Multisensory Integrative Processes and Aging

by

Aysha Basharat

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology (Aging, Health and Well-Being)

Waterloo, Ontario, Canada, 2022

Examining Committee Membership

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner: Annalisa Setti
Lecturer, School of Applied Psychology, University College Cork

Supervisor: Michael Barnett-Cowan
Associate Professor, Dept. of Kinesiology, University of Waterloo

Internal Member: W. Richard Staines
Professor, Dept. of Kinesiology, University of Waterloo

Internal Member: Laura Middleton
Associate Professor, Dept. of Kinesiology, University of Waterloo
Associate Chair, Applied Research, Partnerships and Outreach

Internal-External Member: Myra Fernandes
Professor, Dept. of Psychology, University of Waterloo

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Our sensory systems provide us with distinct impressions of our surroundings which are critical for perception, cognitive processing, and control of action. Indeed, input from multiple sensory stimuli compared to a single sensory stimulus increases the likelihood of detection, sensitivity, and the likelihood of correctly identifying the event. However, this process changes as we age. In this dissertation, I investigate the changes associated with auditory and visual integration in older adults by utilizing various psychophysical tasks. This dissertation aims to determine the following: (1) to understand the relation between behavioural tasks that are commonly utilized to investigate multisensory integration, (2) to investigate how performance on these tasks changes when the central nervous system is aroused or stressed through the use of exercise (both in-person and virtually), and (3) to investigate the limitations and shortcomings of the current practices in the multisensory integration literature. Results indicate that older adults are impaired in judging temporal order of events, however they also exhibit greater performance gains in response time to multisensory, compared to uni-sensory stimuli. Further, results reveal that the integration process is malleable and thus physical activity, both in-person and virtually, may be a useful intervention that can help to improve the speed, accuracy, and precision with which older adults integrate multisensory information. A scoping review concludes the dissertation, which reveals that only 60% and 50% of studies measure for age-abnormal hearing and vision respectively and that within these studies a consistent definition of what constitutes normal hearing and vision is not found.

Acknowledgements

The existence of this dissertation is a testament to the wisdom, labour, love, and support of many people. Firstly, I am forever indebted to my supervisor, Dr. Michael Barnett-Cowan, for his continuous patience, guidance, and encouragement throughout my PhD. Michael, I have benefited greatly from your wealth of knowledge and from your scientific rigour. I am extremely grateful that you took me on as a student and continued to have faith in me over the years, even when I did not have faith in myself. You consistently allowed this thesis to be my work by giving me room to be independent, while steering me in the right direction whenever I needed your help.

I would additionally like to thank all my collaborators including Dr. Jeannette Mahoney, Dr. Jennifer Boger, Dr. Shi Cao, Dr. John E. Muñoz, Samira Mehrabi, and Archana Thayanithy. Further, I would like to thank Dr. Laura Middleton for being not only a supportive committee member, but also a wonderful collaborator. The skills that I was able to acquire while working with all of you have made me the researcher that I am today.

I would also like to thank my examination committee, Dr. W. Richard Staines and Dr. Laura Middleton for providing thoughtful and detailed feedback throughout my PhD. I would additionally like to thank Dr. Myra Fernandes and Dr. Annalisa Setti for being a part of my committee.

Furthermore, I would like to thank the entire Multisensory Brain and Cognition lab for providing an environment that was always open to new ideas. I would also like to thank all those who graciously volunteered their time to participate in my research.

This thesis was carried under the financial assistance of the Ontario Graduate Student Scholarship and the Waterloo Interdisciplinary Trailblazer Fund. I would like to thank these agencies as well as Dr. Barnett-Cowan for helping to fund my research.

Lastly, I would like to express my sincerest gratitude to my lovely partner in life, Matthew, for always providing unfailing support and continuous encouragement. Thank you for editing my code, for your meticulous editing of my thesis, and for all the sacrifices you made so I could obtain my PhD. I hope that I have been, or now that this journey is complete, will be able to express my gratitude more fully than I ever could on this page.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Overview

Imagine you are at a party, you are surrounded by many friends and family members, and at one point, a friend walks over and initiates a conversation with you. You direct your attention to your friend, intuitively tilt your head in their direction, and find yourself using your lip-reading skills in order to facilitate word and sentence comprehension in an attempt to make sense of and contribute meaningfully to the conversation. This situation illustrates how many of our experiences involve multiple sensory modalities, making our perception of the world naturally multisensory. As each sensory system carries and transmits a separate report of any given event, a more accurate representation of the event and appropriate behavioural response can be made through the synthesis of different sensory signals. Indeed, the ability to use sensory information from multiple modalities is a fundamental aspect of brain function, and integration across modalities has been shown to produce significant behavioural benefits that include, but are not limited to, faster and more accurate responses to external stimuli relative to the sum of their individual parts [440, 129]. However, the process of integrating sensory information is far from simple as the central nervous system (CNS) must overcome the binding problem, where at any given moment, there is an abundance of incoming sensory information and the CNS must be able to correctly bind sensory information that originates from a single source while correctly segregating sensory information that stems from different sources [213, 466].

The intrinsic and extrinsic differences in transmission time can make it difficult for the CNS to determine the temporal coincidence of two events. For example, light travels faster than sound (300,000,000 m/s and 330 m/s respectively) thus arriving at the eyes before sound arrives at the ears [435]. Transduction times complicate this process furthermore as they differ between sensory modalities [237]; the transduction of auditory stimuli is much faster than the transduction of visual stimuli due to the dynamics of the hair cells that have transduction latencies of approximately 40 µs [102]. In contrast, the transduction latencies of photoreceptors found in the retina are 15-93 ms [244]. The time for information to reach the CNS from the transducer [44] also makes it difficult for the CNS to accurately perceive simultaneity. In humans, activity in the auditory cortex after the presentation of suprathreshold stimuli starts at approximately 10-15 ms post stimulus presentation [268, 172, 326, 67]. While activity in the primary visual cortex starts at approximately 40-55 ms [94, 159] (see also [410, 170] for non-human, animal model studies) post-stimulus presentation.

Much of the seminal work examining the ability of the CNS to integrate multisensory information was conducted by Stein, Meredith and colleagues who examined the neurons in the superior colliculus (SC), which can be divided into two separate regions: the unisensory and multisensory regions. The superficial layers (I-III) are thought to be unisensory in nature as they have been found to respond only to visual stimuli [443]. The deeper layers (IV-VII) have been considered multisensory as they contain not only auditory, visual, and somatosensory neurons, but also groups of multisensory neurons with the capability of combining signals from all three of the sensory modalities mentioned [443, 440]. Working with the neurons within the deeper layers, early researchers were able to discover three basic principles of multisensory integration (MSI; [311, 312, 313, 441, 442, 439, 485]). Two of these principles relate to the spatio-temporal heuristics where single cell recordings showed an interaction between stimuli in two or more modalities such that responses in the multisensory neurons located within the deeper layers of the SC showed greatest integration when the unisensory cues were:(1) presented close in space ("spatial rule") and (2) presented close in time ("temporal rule"). These heuristics have been replicated in humans; indeed, behavioural research, primarily in younger adults, has since found that signals that occur together in time [230, 509, 130, 98, 204] or space [486, 434, 433] are more likely to be perceived as simultaneous, while signals that originate from different external events or are presented further in time are less likely to be perceived as such. The third principle relates to the effectiveness of stimuli from multiple modalities to drive a given response whereby stimuli that were close to a cell's detection threshold (i.e., less salient) were more likely to elicit a larger response when integrated compared to their individual unisensory responses [8]. Taken together, these rules indicate that sensory stimuli from multiple modalities that are only weakly effective but are spatially and temporally aligned, combine to elicit a response that exceeds the sum of their parts. Although all three rules provide insight into the workings of MSI, the focus of this dissertation is on the temporal heuristic.

A theory that's been postulated within the literature related to how the CNS may account for intrinsic and extrinsic temporal variability between modalities suggests that although sensory signals that occur at the same time are more likely to be bound together, perfect temporal alignment is not required for the two inputs to be bound [447]. This theory, referred to as the temporal binding window (TBW), posits that inputs from any given sensory modality must fall within a "window" of time to be perceived as simultaneous. The TBW is defined as the maximal asynchrony, or time between stimuli, beyond which they are no longer perceived as synchronous [404]. The TBW is typically measured by presenting pairs of stimuli while varying the time between the stimuli, known as the stimulus onset asynchrony (SOA) [508, 270]. Using this method to obtain the width of the window, a growing body of research has shown that the width of the TBW changes throughout early development [204, 205, 266], following injury [493], disease [399], and aging [36, 43, 370, 418]. Although research relating to the aging population is limited, a variety of experimental approaches have been utilized to characterize changes in the perceived timing of multisensory events for older compared to young adults. Two such tasks include the simultaneity judgment (SJ) and the temporal order judgement (TOJ) tasks which have extensively been used in the literature to investigate timing perception and multisensory integration in both young [6, 29, 30, 275, 323, 476] as well as older adults [36, 43, 279, 415, 416].

1.2 Tasks Utilized to Measure Multisensory Integration in Young and Older Adults

1.2.1 Simultaneity Judgment and Temporal Order Judgment Task

In the SJ task, participants are presented with two stimuli of differing modalities (e.g., audio and visual) and are asked to determine whether the two stimuli are simultaneous, while in the TOJ task, participants are asked to determine which stimulus came first [473]. SOAs are varied across trials and the participant's response is used to construct psychometric functions relating the "probability of simultaneous" and "probability of visual first" for the SJ and TOJ tasks respectively. These tasks have been found to be sensitive to both the TBW as well as the point of subjective simultaneity (PSS), the time at which participants are most likely to perceive stimuli as occurring simultaneously or the point at which they are equally likely to report 'light' or 'sound' first for SJ and TOJ tasks respectively. Although they both provide measures of the TBW and PSS, previous research has shown that these two tasks measure different perceptual processes [29, 30, 275, 323, 476] and are likely to be subserved by different neural mechanisms [3, 6, 36, 126, 270]. Research conducted by Allan [6] investigating the relation between SJs and TOJs suggests that successiveness and temporal order are processed at different stages due to the fact that the perception of successiveness is required prior to temporal order perception. Further, research investigating the relation of PSS obtained from the SJ and TOJ tasks in young adults has found no correlation between the two tasks [473, 275], and has revealed that on average, the SJ task yields visual-leading PSS estimates whereas the TOJ task yields audio-leading PSS estimates [473, 275]. Additional differences between the two tasks arise from the TBW.

The TBW represents a range of tolerances or thresholds within which stimuli from different modalities are integrated together and perceived as being simultaneous, thus, a reliable detection of the temporal order of events is not perceived within the TBW [275]. For audiovisual stimuli, the TBW is typically less than 100 ms in younger adults [416, 508] but is found to be wider in older adults [43, 36, 37, 416]. Previous research indicates that a TOJ task may provide a better estimate of the width of the TBW as compared to the SJ task [404, 231, 418, 353], due to the fact that, for the audiovisual SJ task, the raw data are not symmetric but rather participants are biased towards the "simultaneous" option especially on the "light-first" SOAs [404, 231, 193]. Additionally, in the SJ task, participants may assume that stimuli belong together merely because the "simultaneous" option is available, which may result in more "simultaneous" responses, thus yielding a wide Gaussian [231]. On the contrary, participants may assume that stimuli presented are never simultaneous for the TOJ task because only temporal order responses can be given; this may result in a narrower TBW [231]. Such differences are thought to arise because the two tasks may involve different underlying processes and/or mechanisms (i.e., one related to binding of cues from multiple sensory modalities, while the other is related to temporal order discrimination) [508, 270]. Further, using these two tasks has revealed that the TBW varies with age as it tends to be wider in early childhood, becomes more fine-tuned during middle childhood, and widens again with aging [43, 205, 204, 266, 370, 418]. This widening of the TBW has been interpreted as a deficit by some researchers as it indicates that older adults are more likely to bind temporally disparate cues that don't necessarily belong together [7, 71, 80, 81, 198, 370, 481] and has indeed been associated with inaccurate perception of the world and poor behavioural outcomes [287, 417, 293, 415, 279] for older adults. While the SJ and TOJ tasks paint a picture of deficit, the simple response time (RT) task provides a more hopeful outlook.

1.2.2 Response Time Task

Response time (RT) measures have been used in psychology since the 19th century and the use of response time has grown and persisted into the 21st century [164]. Although many measures of processing duration have been used in the literature, two of the most commonly utilized procedures include the simple response time task and the choice response time task. The simple RT task involves making a response as quickly as possible to one or more stimuli, where the same response is made regardless of stimulus type (e.g., pressing the space bar when either a visual or an auditory stimulus is presented). In the choice RT task on the other hand, participants are required to make appropriate and differing responses to multiple different stimuli (e.g., pressing the right arrow when an auditory stimulus is presented while pressing the left arrow when a visual stimulus is presented). The variables that are typically derived for statistical analyses from both of these tasks involve some measure of central tendency (e.g., mean or median) as well as a measure of variability (e.g., standard deviation or standard error) and can be compared within a group (e.g., young adults) or between groups (e.g., young and older adults). Many researchers have assessed the relation between age and RT and have found a U-shaped function, where RTs are slow in childhood, fastest in adulthood, and reduce in speed once again in older age [78, 123, 136, 124]. Interestingly, this increase in processing time with age, is thought to be associated with age-related declines in higher-level cognitive function and has been shown to be moderately to strongly correlated with general fluid intelligence [401, 400, 478, 218]. Within the multisensory literature, the simple RT task is commonly utilized to assess the perceived timing and consequent response to multimodal versus unimodal stimuli. Here, however, the method of analysing data goes beyond the comparison of central measures (i.e., mean and or median) in order to further ascertain the underlying processes that may subserve multimodal versus unimodal processing.

During the simple multimodal RT task, the observer is presented with unisensory or multisensory stimuli and is asked to press a response key as fast as possible following stimulus presentation. Studies utilizing such a design find that multisensory stimuli are indeed detected faster than unisensory stimuli and indicate that the presentation of two or more stimuli facilitate behaviour [463, 128, 318, 129]. In the pioneering study, Todd [463] proposed that such a redundant signal effect (RSE) was observed because the simultaneous stimuli summate in excitatory effect and discharge down a common tract. Since then, many alternative explanations have been proposed, including the explanation proposed by Raab [379] who suggested that the presentation of a pair of multimodal stimuli produce parallel activations in different sensory channels that initiate a detection race wherein the signal that is processed fastest is the one to produce the observed RT (i.e., the 'winner' of the race). Note, that this race or separate activation model would also predict shorter average RTs for the multimodal compared to unimodal stimuli purely due to statistical facilitation. In other words, the minimum of the winner's time will, by design, be faster than the average time for either of the unimodal stimuli as the slow processing in one channel is compensated by the faster processing in the other channel.

In contrast, instead of separate processing of the two stimuli, coactivation models propose that multimodal stimuli are integrated. The race model inequality (RMI) proposed by Miller [318] is one such model that has become the standard testing tool in many multisensory studies. It provides a way to test whether the observed RT facilitation in multimodal trials can be attributed completely to statistical facilitation. As the race model describes separate, context-invariant processing of redundant information (i.e., external events don't affect perception and that presenting audiovisual stimuli won't change behaviour), a violation of the RMI indicates that either the race model is violated, or the context invariance assumption is not supported. A conventional view of this violation is that separate processing of stimuli is not taking place, rather it indicates synergistic neural mechanisms (but see [349, 350, 348]). RMI is tested by using the response times from each unimodal stimulus category (e.g., audio and visual cues) to create a distribution of RTs where the faster modality (i.e., winner of the race) has the shorter RT of the two processing times and provides the upper bound for the cumulative probability (CP) distribution [179]. If the observed CP distribution of the multimodal trials (e.g., audiovisual cues) is less than or equal to the predicted upper bound at each point the observed and predicted distributions are compared, then RSE is just due to statistical facilitation, and the race model is accepted. If on the other hand, observed CP distribution of the multimodal trials is larger than the predicted CP, then RMI is not satisfied and statistical facilitation cannot be the full explanation of the RSE, and the race model is violated [179].

Researchers have tested the RMI in younger adults and have found that response time facilitation provided from multimodal stimuli indeed violates the race model as it is larger than would be expected from statistical facilitation [326, 425]. Although research comparing MSI effects between young and older adults is limited, it appears that older adults demonstrate greater multisensory RT facilitation effects compared to young adults when presented with multimodal stimuli [106, 132, 255, 291, 361]. The test of the RMI tends to show significantly larger violations in older adults suggesting greater integration of unisensory stimuli as compared to young adults who tend to show reduced integration [255, 291].

1.3 Comparison of SJ, TOJ, and Simple RT Tasks

1.3.1 Neuroanatomical Regions Involved in Multisensory Integration

Although much of the perception literature investigates sensory perception one modality at a time, mounting evidence suggests that behaviour and perception are driven through the integration of multimodal cues. In traditional models of the brain, MSI is thought to occur after unisensory processing has occurred, however, anatomical studies reveal that there are extensive interactions between not only primary sensory cortices but also between primary and association cortices [74, 392, 10]. Several higher order cortical areas such as the superior temporal sulcus (STS), the intraparietal complex, and the frontal cortex have been classified as multisensory, because they have been found to be connected with multiple unisensory areas [221], or because single neuron recordings indicated activity for multisensory stimuli in those regions [66], or because lesions in such areas caused behavioural deficits related to MSI [461]. Through non-human animal studies, it has been found that roughly 36-38% of neurons in the anterior region of STS respond to auditory or visual information, while only approximately 18% respond to auditory or visual cues in the caudal portion of the STS [66, 202, 45]. Further, it has been found that approximately 23% of the STS integrates auditory and visual information [31]. A second region of interest that has been classified as multisensory by nature is the posterior parietal cortex, which contains regions such as the lateral intraparietal (LIP) and the ventral intraparietal (VIP) areas [300, 10, 408]. In a study conducted by Mazzoni and colleagues [300], where macaque monkeys were tasked to move their eyes towards the location of either acoustic or visual targets, it was found that the majority of the neurons in the LIP that responded to the auditory saccade task also responded to the visual saccade task (88-89% of the cells that responded to the auditory stimulus also responded to the visual stimulus), indicating that neurons in the LIP are involved in processing and responding to both auditory and visual stimuli. While the VIP area is primarily thought to be involved in visual, vestibular, and tactile integration, research by Schlack and colleagues [408] showed that neurons in the VIP area are also responsive to auditory stimuli. In their study, electrical activity from 136 neurons in the VIP was recorded while auditory or visual stimuli were presented and they found that 80% of the neurons responded to auditory stimulation, while approximately 92% of these neurons responded to the visual stimulus [408]. Further, visual and auditory neurons were generally found to be in close spatial proximity (approximately 72.8%). Of note, it was found that there was a broad range of response latencies for the auditory stimulus with a mean latency of 103 ms ±7.2 ms, while the minimal latency was only 15 ms. Such a wide range of latencies could be the result of the VIP area receiving auditory inputs from multiple areas including the temporoparietal occipital area, the temporal opercular caudal zone, and the auditory belt region [265]. There was less variability in response latencies for the visual stimulus and the mean latency was found to be 115 ms ±5.9 ms.

In all of these studies, auditory and visual stimuli were either presented separately or simultaneously as is the case with the RT task, however many did not require a behavioural response from the animal. More recently, a limited number of researchers have focused on determining the underlying mechanisms that subserve simultaneity and temporal order perception; we turn our attention to this particular literature now. In a study conducted by Binder and colleagues [50], young adults ($n = 15$) performed audiovisual SJ and TOJ tasks to simple beep and flash stimuli while functional magnetic resonance imaging (fMRI) was recorded and they found that both tasks elicited bilateral activations in the inferior parietal lobules, activations in the supplementary motor area/pre-supplementary motor area, activations within the insular region, and the inferior frontal gyrus. They also found activations in the superior parietal lobule in the left hemisphere and occipital region activation in the right occipital pole. Interestingly, they found that there were no regions that had a stronger activation in the SJ condition compared to the TOJ condition, however, stronger activations in the left hemisphere were found for the TOJ task. These stronger activations in the left hemisphere were found within the middle and inferior frontal gyri, the superior and inferior parietal lobes, and the occipito-temporal junction. In order to assess whether such neural differences are present for more complex audiovisual stimuli, Love and colleagues [276] asked their participants to perform the SJ and TOJ tasks while fMRI was recording, while using a continuous stream of point-light drumming stimulus. Similar to Binder and colleagues [50], they found regions that were activated for both the SJ and TOJ tasks (bilateral putamen, insula, and superior temporal cortex) as well as regions that were activated more during the TOJ task compared to the SJ task, all in the left hemisphere (middle occipital, middle frontal, precuneus, and superior medial frontal cortex). Note that here again, no region was more activated during the SJ as compared to the TOJ task. These studies suggest that TOJs require cognitive processing in addition to what is needed for the SJ task. Indeed, Binder and colleagues [50] argue that the additional activation seen for the TOJ task provides evidence for a two-stage cognitive process for TOJs which require the perception of both synchrony as well as order, while the SJ only requires synchrony perception. Limited neuroimaging research using SJ, TOJ, and RT tasks has been conducted to compare young and older adults, however, the findings provide evidence for differing neural mechanisms subserving the SJ and TOJ tasks even within the aging population [36].

1.3.2 Behavioural Research

A central issue in psychology and cognitive science is to understand how sensory stimulation leads to conscious experience or perception and motor response; researchers in this area seek to understand their relation by studying their durations. One modality where such distinctions have been investigated is within the visual domain, where distinct pathways were initially proposed for perception (ventral pathway) and for action (dorsal pathway), however, the literature now suggests there is a link between these two streams, which work together to produce adaptive behavior [180]. In order to assess the relation between perception and action, past researchers have compared motor and perceptual latencies to the same visual stimuli whereby the difference between RT to two salient stimuli is compared with perceptual outcomes (e., PSS) to the same stimuli. Here, the mean RT obtained during a simple RT (SRT) task is assumed to represent the sum of two components: a detection time (D) and a motor (M) activation component ($\mathrm{SRT} = \mathrm{D} + \mathrm{M}$) [277].

Where D, is thought to represent the time needed to detect the onset of the stimulus, while M, is thought to represent the time needed to initiate and respond to said stimulus [277, 321, 321, 472]. Perceptual tasks such as the SJ and TOJ tasks, provide an alternate method of processing time. For example in the TOJ task, when two stimuli are presented and participants are asked to report which stimulus was detected first, it is assumed that the response represents the stimulus that was detected first by the CNS as well as the decision rules that the CNS was following to make the response [445]. As RT, SJ, and TOJ tasks provide varying measures of processing durations, cross-checking the conclusions reached with one method of processing with the others, can yield useful information related to the inner workings of time perception and sensory integration. One common model that's been used to understand the underlying mechanisms that may subserve time perception and the relation between perception and action posits that both action and perception tasks depend on the same initial perceptual detection stage [321, 131].

Previous research on the relation between RT and TOJ using stimulus onset asynchronies (SOAs) has revealed that the TBWs obtained from the RT task are wider than those corresponding to the TOJ task ([131, 307]; however see [75] where the TBW for the TOJ task was wider than that for the RT task); this can be seen as an observer's strategy to optimize performance, as the TOJ task requires participants to discern small asynchronies in which a narrower window is beneficial, whereas a wider window would maximize multisensory facilitation (as determined by the race model violation) in the RT task. Although such a relation between the RT and SJ tasks has not been investigated, Diederich and Colonius [131] suggest that these results can be further extended to the SJ task, and that a similar relation should be observed. To assess changes in perception within the aging population, researchers have used a similar design of varying the SOAs used in the RT task to extract the TBW. Here, older adults have slower RTs compared to young adults [132, 255], have broader TBWs [132], and they tend to show greater multisensory facilitation as assessed via race model violation [132, 255]. However, there is a lack of research investigating: (a) whether a relation exists between the RT task and the TBWs obtained from the TOJ and SJ tasks and (b) if there are any changes across the lifespan in the relation between these tasks.

If a relation between the width of the TBW and RT exists, one could argue for such a relation between RT and PSS as well. It has been shown that the TOJ task utilizes all available information in order to infer physical onset of the stimuli, thus maximizing the number of correct responses [325]. While simple RTs are characterized by automatic response behaviour, the motor task requires minimization of response time (rather than maximizing correct responses), which is achieved by setting the motor threshold to be as low as possible [75, 445, 490]. Regardless of the different strategies that are utilized by the CNS, it has been suggested that motor and perceptual responses comply with a 'one-system-two-decision' model where the same internal processes are utilized but at distinct decision-making levels [75, 321, 445]. In order to assess such a model, researchers have compared RTs and PSS estimates obtained from the TOJ task from the same pairs of stimuli (i.e., RT to two unequally salient stimuli is compared to TOJ outcomes on the same trial). A significant association between RT and TOJ PSS estimates has been found whereby RTs to pairs of visual stimuli differ with the associated TOJs (i.e., RTs were faster or slower depending on the temporal delay between the two stimuli), indicating that RT to, and TOJ of, two sensory signals may be triggered by the same decision process [75]. However, simple RTs are thought to represent automatic response behaviour and may be independent of subjective decision-making factors, whereas perceptual tasks (such as the SJ and TOJ tasks) are thought to be context-dependent, contingent on factors such as a priori probability, potential pay-off, and the observer's knowledge of noise associated with the task [75]. Nevertheless, the relation between RT and TOJ mentioned above provides evidence against the action-perception dissociation and although further research is required, these findings indicate that the two tasks may be triggered at different decision-processing levels of the same internal signal ('one-system-two-decisions') [75].

Contrary to the 'one-system-two-decisions' model, when auditory and visual RT and TOJ tasks have been compared, it has been found that although the RT for the auditory stimulus is faster than the visual stimulus (by 43 ms), the auditory stimulus has to be delayed compared to the visual stimulus in order to be perceived as simultaneous (e.g., PSS); this has been interpreted as an example highlighting the difference between these two tasks and as potential evidence for different underlying mechanisms subserving the two tasks [398, 445, 217]. In order to further understand the relation between these two tasks, many researchers have manipulated the stimulus intensity [2], stimulus duration [214, 215], and stimulus modality (e.g., auditory vs. visual [217]) and have found the largest difference between the two types of tasks through intensity. Indeed, increases in stimulus intensity produced reductions in simple RTs that were approximately twice as large as the effects seen for the corresponding PSS [215, 216, 309, 398, 396, 406, 407], which has also been interpreted as a reflection of differing underlying mechanisms. Much is left to the imagination regarding the relation between the RT, SJ, and TOJ tasks, as a consensus regarding the relation between the two types of tasks (i.e., similar or differing underlying mechanisms) has yet to be made. In this dissertation, I will investigate the relation between theses tasks, not only in young, but also in older adults.

A key finding from the existing literature on the aging population is that the temporal binding window becomes wider with age [43, 36, 37, 416, 80, 370, 117, 331]. Some researchers have interpreted this widening as a compensatory mechanism for slower and more variable peripheral sensory processing (e.g., RT facilitation that is observed for older adults compared to younger adults), while others have viewed this reversion back to a wider window, as a deficit as it indicates that older adults are more likely to integrate temporally disparate information that does not necessarily belong together, which can lead to an inaccurate representation of the world. Regardless of the underlying reason for why the window of integration widens, some researchers have tried to take advantage of the malleability of this window to train the observer to more accurately perceive and bind incoming sensory information. Although training paradigms are not commonly utilized, the existing training paradigms are quite long, with some spanning multiple days, and most being conducted with younger adults [375, 377, 418, 353, 446, 81]. Even fewer researchers have utilized alternative means to improve perception, including the utilization of exercise interventions in gymnasiums and in virtual settings [351, 314].

1.4 Interventions

1.4.1 Chronic Exercise

As the aging population continues to grow in numbers (one quarter of the population worldwide will be 65 years and over in the 2020s [46]), some researchers have turned towards examining successful aging to understand the type of lifestyle changes that may protect the aging population against cognitive decline and dementia. As such, researchers have investigated behavioural factors such as intellectual engagement, social interaction, physical activity, etc., that may induce or contribute to brain plasticity. Brain plasticity refers to the brain's ability to change and adapt, both physically and functionally throughout life [46]. Evidence suggests that some activities, such as physical activity (PA) and cognitive stimulation, are more likely to induce brain plasticity compared to others in both young and older adults [232, 96, 144, 226]. Further, research related to PA on the human body has found that PA is positively associated with healthy aging [110], and it may prevent the onset of many chronic diseases including cardiovascular disease, type II diabetes mellitus, and cancer [148, 384]. Evidence of the benefits of PA have been found on cognitive function in review articles and through various epidemiological studies where thousands of participants were surveyed over the span of multiple years revealing that those who engage in regular PA have a significantly lower incidence rate of Alzheimer's disease [253, 369, 53], have significantly better cognitive function, and face lower risks of cognitive impairment [491, 256]. Indeed a dose-response relationship between PA and cognitive outcomes has been reported, where some PA is better than none, and more frequent PA confers greater benefits. As such, lower risk of cognitive impairment, Alzheimer's disease, and dementia of any type has been reported for individuals who engage in greater levels of PA [258, 256, 498, 491, 480]. In addition to observational or epidemiological studies, imaging as well as physiological studies with non-human animal models have been conducted to clarify and better understand the underlying mechanisms that correlate with cognitive improvement.

In a seminal study conducted by Colcombe and colleagues [96], the authors aimed to determine whether moderate to intense aerobic exercise could increase brain volume in regions of the brain that were typically associated with age-related decline using fMRI. In their study, 59 older participants were either placed in an aerobic exercise intervention group or in a toning and stretching control group. Further, 20 young adults served as controls but did not participate in the intervention. They found that participation in a 6-month aerobic exercise intervention increased gray matter volume primarily in the prefrontal [anterior cingulate cortex (ACC), supplementary motor area (SMA), and right inferior frontal gyrus (rIFG)] and temporal [dorsal aspect of the left superior temporal lobe (lSTL)] regions. The researchers also found increases in white matter volume in the anterior white matter tracts (AWM). Erickson and colleagues [144] further investigated this relation in a larger sample. In their study, 120 older adults were enrolled in either a control condition (stretching; $n = 60$) or a moderate-intensity aerobic exercise ($n = 60$) condition for one year. They found that exercise increased the size of the anterior hippocampus which led to improvements in spatial memory. Indeed, they observed a hippocampal volume increase of approximately 2%, which the authors argued offset the normal deterioration (1 to 2%) of the hippocampus typically associated with the normal aging process [144, 383]. More recently, similar findings were reported in a meta-analysis consisting of 30 neuroimaging experiments investigating the neural correlates underlying the effects of physical exercise and cognitive improvement in older adults [219]. In this meta-analysis, which consisted of over 2,600 participants, they found that physical exercise was effective in inducing volumetric and functional changes in the hippocampal-medial temporal lobe and the culmen of cerebellum. Further, the medial prefrontal cortex was also found to be affected by exercise and related to cognitive improvement [219]. Additionally, in a recent review by Erickson, Gildengers, and Butters [145], it was reported that greater engagement in physical activity and higher cardiorespiratory fitness at baseline were associated with better cognitive outcomes. Further, those who engaged in more intense exercise earlier in life showed better cognitive function. Their review also revealed that some areas of the brain (e.g., prefrontal cortex, hippocampus) appear to benefit more from exercise as compared to others, especially in older adults, and although research has not yet revealed why this may be the case, one explanation is that exercise may target those areas that show the most atrophy with age, thus making them more sensitive to the effects of exercise [145]. Another possible explanation may be that the areas that benefit the most from aerobic exercise are the regions and networks that are most involved in efficiently communicating among each other to regulate the neurophysiological processes and associated motor output required during exercise [405].

The volumetric changes in the CNS found from human participants are in-line with non-human animal studies that indicate that regular or chronic exercise can lead to growth of new capillaries in the brain [51, 390], increase the length and number of dendritic interconnections between neurons [104], increase cell production in the hippocampus [475], increase resistance to brain injury [452, 76], and increase enhancement in learning [475, 505]. It is thought that these effects are mediated in part by increased production and secretion of brain-derived neurotrophic factor (BDNF), vascular edothelial growth factor (VEGF), and insulin-like growth factor-1 (IGF-1) [96, 144, 475, 76, 477, 141]. Chronic exercise induces greater levels of circulating BDNF, VEGF, and IGF-1, which promote gliogenesis, neurogenesis, synapotgenesis, and angiogenesis [51, 390, 104, 105, 141, 474, 65, 272]. Increased neurogenesis and gliogenesis are thought to mediate increases in grey and white matter volume [144, 419, 141], while synaptogenesis is thought to mediate increases in neural and receptor activity [141, 88, 482]. Finally, angiogenesis is thought to play a role in increasing cerebral blood flow [429, 141]. Such increases in grey matter, white matter, neural activity, and receptor activity have been associated with improvements in cognitive and motor function.

In addition to the growth factors mentioned above, Gamma-Aminobutyric Acid (GABA), the primary inhibitory neurotransmitter of the CNS, is also thought to increase in concentration with chronic exercise [134] and has been found to be related to improvements in cognitive function [372]. Limited research investigating the effects of chronic exercise on multisensory processing has been conducted, however the findings from multisensory literature echos the findings for higher-order cognition in that exercise has been found to positively impact audiovisual sensory integration in [314]. As research continues to reveal the benefits of chronic exercise, some researchers have turned towards investigating whether similar effects can be found for acute bouts of exercise in older adults. Here again, behavioural, imaging, and physiological methods are utilized to determine the underlying mechanisms associated with exercise and cognition.

1.4.2 Acute Exercise

Acute exercise research, similar to chronic exercise research, is based on the premise that physiological responses to exercise impact cognitive performance. Meta-analyses investigating these relationships indicate that the timing of exercise relative to cognitive performance is crucial. Their results indicate that exercise has either a negligible (Cohen's d = 0.06) or detrimental (Cohen's d = -0.14 to -0.18) effect on cognitive performance *during* the first 20 minutes of exercise [84, 250], but support the hypothesis that there is improvement in cognitive performance if the task is administered during exercise but after 20 minutes of activity (Cohen's d = 0.26) or immediately after a single bout of physical activity or after a delay following exercise with effect sizes ranging from 0.1 to 0.26 [84, 147, 250]. Many aspects of cognition have been investigated in acute exercise literature, broadly consisting of **attention** (e.g., oddball, odd-one-out, Posner spatial attention), **executive function or cognitive control** (e.g., flanker task, Digit span (backward), trail-making-task), **memory** (e.g., delayed match-to-sample, delayed recall, free recall), **intelligence and achievement tests** (e.g., verbal fluency/word fluency, Weschler Adult Intelligence Scale, Weschler Test of Adult Reading), **motor speed and learning** (simple reaction time, choice reaction time, continuous tracking task), and **information processing** (e.g., critical flicker fusion, visual field, digit symbol substitution) [371, 84]. In the past decade, more research has been conducted investigating executive function than any other category mentioned above. This category is thought to comprise of inhibition, working memory, and cognitive flexibility and is thought to be supported by the anterior cingulate cortex, prefrontal cortex, basal ganglia, superior frontal sulcus, insula, and parietal cortex [70, 397, 162, 371].

In a recent meta-analysis, approximately 41% of studies in the literature investigated the inhibitory aspect of cognitive control and generally found enhanced interference control following a bout of exercise with effect sizes ranging from 0.2 to 1.16 [371]. Of interest to this dissertation however, are the changes in motor speed and information processing categories. Studies investigating the effect of a single bout of aerobic exercise on motor speed (e.g., simple or choice reaction times) have typically observed enhancements in speed with effect sizes of Cohen's d ranging from 0.2 to 0.5 [371, 101, 228, 208]. Alternatively research investigating the effects of exercise on information processing is inconsistent, with some researchers observing enhancements in performance with effect sizes ranging from 0.2 to 0.5 [84, 371, 142, 329] while others have failed to find any effect following exercise [450]. In addition to timing and type of task tested, the intensity at which an acute bout of exercise is performed is also crucial. In a meta-analysis conducted by Chang and colleagues [84], they reported an enhancement in cognition when the cognitive task was performed immediately after termination of very light to moderate activity whereas enhancements in cognition following higher intensity were more beneficial after a delay (e.g., a cool-down period) of at least 1 minute [84]. These findings suggest that higher intensity exercise may be necessary for effects to be maximized if there is a delay between the exercise session and cognitive task administration. However, very light exercise can also result in cognitive enhancement immediately following exercise, suggesting that lower intensity could result in appropriate level of physiological mechanisms (typical physiological responses of interest for this literature include change in heart rate, BDNF concentration, and plasma catecholamine concentration) post exercise. In addition to dose (intensity), the duration of exercise and timing of cognitive task administration, as mentioned above, also impact the outcome. Chang and colleagues [84] found that at least 20 minutes of exercise was necessary to see cognitive enhancements and that cognitive tests that were administered 11-20 minutes following exercise resulted in maximal enhancement. Further, they reported that these effects subsided following a delay longer than 20 minutes post-exercise. In addition to physical bouts of exercise, exergaming has also shown to have an effect on cognition and perception [314, 351, 113, 250]. We will use the methods as well as the findings from the literature mentioned above in chapter 3 to construct a study that is best suited to further evaluate the effects of a single bout of exercise on multisensory processing.

1.4.3 Exergaming

Both physical exercise and cognitive training are non-pharmaceutical interventions that are thought to benefit cognitive function and brain health [95, 241, 252, 280]. Physical exercise is thought to induce physiological and metabolic changes that facilitate cognition through structural and functional changes (see the subsections above for more information; [95, 241, 144, 49]) while cognitive training appears to benefit the trained cognitive ability with limited transfer to untrained cognitive domains [243, 252, 280, 49]. Based on the individual benefits of physical exercise and cognitive training, researchers have begun to investigate the effects of combining these forms of interventions with the hopes to maximize cognitive benefits. Review articles investigating the effects of combining physical exercise and cognitive training find that either simultaneous or subsequently combined physical and cognitive training is more successful (larger effect on cognitive function) compared to exercise and cognitive training individually [254, 512]. Engaging in exergames defined as "experiential activity ... that requires physical exertion or movements that are more than sedentary activities and also include strength, balance, and flexibility activities" [339], are a novel form of exercise that have gained the interest of many researchers as many combine physical and cognitive exercise in an "interactive, digital, augmented, or virtual game-like environment" [449]. Indeed, some commercial exergame systems such as Nintendo Wii, Xbox Kinect, or Dance Dance Revolution include exergames that are able to achieve light to moderate physical energy expenditure [324, 283, 354, 460], suggesting that time spent engaging with exergames can count towards the weekly amount of physical activity recommended by the Canadian Society for Exercise Physiology (CSEP) as well as the American College of Sport Medicine (ACSM) [158, 389]. Further, engaging with exergames seems to be beneficial for cognitive function (e.g., improvements in reaction time, attention, working memory, etc.) and some researchers have argued that it may be a more engaging and enjoyable substitute for traditional cognitive training [465, 23]. A meta-analysis conducted by Toril, Reales, and Ballesteros [465] investigating the the effects of cognitive training with video games on cognitive function in healthy older adults found that multiple variables impacted the expected outcome for cognitive function. This included the age of the participant and the number of sessions or duration of the training program. They found that oldest adults (71-80 years) showed greater cognitive improvements as compared to more younger older-adults (60-70 years). Further, they found that the observed cognitive effects were more enhanced when the exergame training was of short duration (1-6 weeks) as compared to when it was longer (7-12 weeks). Considering the surprising nature of their findings regarding the duration of the exergame intervention, the authors explained that training sessions may be exciting and interesting at first but older adults may be getting bored by the end of the last session. A potential explanation may be that as the environment of the exergames becomes more predictable and less salient, the concentration of the neurotransmitter, dopamine, is reduced, hence increasing feelings of boredom and reducing motivation [57, 438, 360, 60].

Virtual reality (VR) exergames may be a more engaging and innovative approach to promote physical activity in older adults. They combine physical exercise with computer-simulated environments to increase the overall appeal of exercise by shifting the observer's attention away from averse aspects of exercise (e.g., discomfort from increased heart rate) towards more motivating features (e.g., three-dimensional scenery of a forest or lake). As commercial VR exergames have become more popular, affordable, and accessible, many researchers have turned their attention towards determining whether VR exergames may be a useful tool to improve cognitive function and physical health. Researchers have found that VR exergames improve not only general cognitive function in older adults but also memory, orientation, comprehension, naming, attention, and judgment [79, 85, 502, 341]. Indeed in recent meta-analyses, reviews, and randomized control trials, researchers found that VR exergames achieved moderate effect sizes for overall cognitive function (*Cohen's d* = 0.48; *Hedge's g* = 0.525), small to moderate effect sizes for executive function (*Cohen's d* = 0.3; *Cohen's d* = 0.5), moderate to large effect sizes for memory (*Cohen's d* = 0.7;*Hedge's g* = 0.507), and small to moderate effect on visuospatial memory (*Cohen's d* = 0.44) [502, 341, 13]. As was the case with non-VR exergaming literature, here too a meta-analysis by Yen and colleagues [502] found that VR exergame interventions should be conducted for at least 6 weeks. Yen and colleagues [502] differed however from Toril and colleagues [465] in suggesting that a longer duration should be utilized for greater efficiency, especially against depressive outcomes. We will utilize the existing literature for developing our exergame protocol in chapter 4.

1.5 Hypotheses

The limited literature described above indicates that exercise can potentially improve the accuracy and precision of perceptual responses [351, 314], and that further research utilizing in-person and virtual exercise interventions is pertinent to better understand and investigate the relation and maleability of some of the most commonly utilized tasks in the multisensory integration literature. As limited research has been conducted with older adults, the inclusion of the aging population can further improve our understanding of the underlying mechanisms that subserve multisensory integration. Inclusion of older adults is especially relevant as the limited research conducted with the aging population has yielded mixed results regarding how the aging CNS integrates multimodal information between the RT (i.e., response time facilitation from multimodal cues) and the SJ and TOJ (i.e., impaired perception of time) tasks. In addition to a lack of research comparing how the most common methods of ascertaining sensory integration may differ between young and older adults, there is also a general lack in utilizing novel methods to improve timing perception using various interventions. The aim of this dissertation is not only to better understand and potentially improve the multisensory integration process in older adults, but to also investigate the methods utilized to screen for normal sensory acuities by multisensory integration researchers. The motivation for such an investigation stemmed from research showing that changes in audition and vision (e.g., ocular disease, hearing loss), which are typically associated with aging, can impact temporal perception and multisensory integration [153, 154, 182, 188, 115, 299, 233, 247, 415, 301, 366, 169, 163] and are yet not always accounted for in research studies. Therefore, accounting and screening for age-abnormal changes in the auditory and visual modalities is necessary for researchers to draw more reliable conclusions related to how audiovisual integration changes with age. Thus, a scoping review was conducted for this dissertation to determine the methodology, or lack thereof, that multisensory integration researchers are currently utilizing to screen for age-abnormal auditory and visual acuity. The aim of this dissertation is thus three-fold: (1) to further understand the relation between audiovisual tasks that are commonly utilized to investigate multisensory integration, (2) to investigate how performance on these tasks changes when participants are stressed or aroused through the use of exercise (both in-person and virtually), and (3) to investigate the limitations and shortcomings of the current practices in the multisensory literature, all through the lens of aging.

The following research questions and hypotheses will be investigated in each of the chapters enclosed in this dissertation:

1.5.1 The association between Simultaneity Judgment, Temporal Order Judgement, and Response Time Tasks (chapter 2):

The work presented within chapter 2 has been published [37]. The following research question was asked within this publication:

Is there a relation between the multisensory integration outcomes (e.g., TBW, PSS, and the magnitude of race model violation) and how do age-related differences impact this relation? Here, we hypothesized that:

1. Older adults would have slower response times as compared to young adults.
2. Older adults would demonstrate larger race model violations compared to young adults.
3. Increased race model violations would be positively correlated with wider TBWs.

4. Increased race model violations would be positively correlated with PSS falling farther away from true simultaneity.

1.5.2 The effect of rest, a cognitively demanding task, and aerobic exercise on the SJ, TOJ, and RT tasks in community-dwelling older adults (chapter 3):

The work presented within this chapter is currently under review [34]. The following research questions were asked within this chapter:

Do multisensory integration outcomes change with a single bout of aerobic exercise? Do effects observed after the aerobic exercise condition differ from reading and performing a cognitively demanding task? Here, we hypothesized that:

1. A single bout of aerobic exercise would improve multisensory processing as measured through the RT, SJ, and TOJ tasks (i.e., narrower TBW, PSS closer to true simultaneity, and increased integration as assessed through the area under the curve).
2. The effects observed for the single bout of aerobic exercise would be significantly better than the effects observed for resting and performing a cognitively demanding task.

1.5.3 The effects of virtual exergaming on the SJ, TOJ, RT, and SIFI tasks in community-dwelling older adults (chapter 4):

The following research question was asked within this chapter:

Do multisensory integration outcomes change with 6-weeks of VR exergame use in community-dwelling older adults? Here, we hypothesized that 6-weeks of participation in the exergame intervention would:

1. Reduce the response time and increase race model violations compared to the control group.
2. Reduce the width of the TBW for both the SJ and TOJ tasks compared to the control group.
3. Reduce the susceptibility to the sound-induced flash illusion (SIFI) compared to the control group.

1.5.4 A Scoping Review of Audiovisual Integration Methodology: Screening for Auditory and Visual Impairment in Younger and in Older Adults (chapter 5):

The work presented within chapter 5 has been published [38]. The research question asked within this publication was as follows:

1. What is known from existing literature about how auditory and visual acuities are being taken into account within the field of multisensory integration, especially within the aging population?
2. What is the feasibility of whether a meta-analysis can be conducted in the future to further quantitatively evaluate the results of this scoping review? Therefore, based on the results obtained in this scoping study, a recommendation of whether or not a meta-analysis can be conducted to determine if significant differences exist in the findings and or conclusions drawn in studies that used self-reported vision and hearing impairment screening methods compared to studies that measured vision and hearing impairment in the laboratory will be made.

Due to the fact that scoping reviews are observed as a hypothesis generating exercise, we did not explicitly create hypotheses for this review. We however believed that many researchers were failing to collect or account for visual and/or auditory acuities and assessed this hypothesis through the data obtained from existing literature.

Chapter 2

The association between Simultaneity Judgment, Temporal Order Judgement, and Response Time Tasks

Adapted from: Basharat A, Mahoney JR, Barnett-Cowan M (2019). Temporal Metrics of Multisensory Processing Change in the Elderly. Multisensory Research. 32(8), 715-744 [37]. DOI: https://doi.org/10.1163/22134808-20191458

2.1 Abstract

Older adults exhibit greater multisensory response time (RT) facilitation by violating the race model more than young adults; this is commonly interpreted as an enhancement in perception. Conversely, older adults typically exhibit wider temporal binding windows (TBWs) and points of subjective simultaneity (PSS) that fall further from true simultaneity as compared to young adults when simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks are utilized; these outcomes are commonly interpreted as an impairment in perception. Here we explore the relation between these three tasks in order to better assess audiovisual multisensory temporal processing in both young and older adults. Our results confirm previous reports showing that audiovisual RT, TBWs, and PSSs change with age; however, we show for the first time a significant positive relation between the magnitude of race model violation in young adults as a function of the PSS obtained from the audiovisual TOJ task (r: 0.49, p: 0.007), that is absent in older adults (r: 0.13, p: 0.58). Furthermore, we find no evidence for the relation between race model violation as a function of the PSS obtained from the audiovisual SJ task in both young (r: -0.01, p: 0.94) and older adults (r: 0.1, p: 0.66). Our results confirm previous reports that i) audiovisual temporal processing changes with age; ii) distinct processes are likely involved in simultaneity and temporal order perception; and iii) common processing between race model violation and temporal order judgment is impaired in the elderly.

2.2 Introduction

The central nervous system (CNS) is constantly presented with information from multiple modalities that must be efficiently combined in order to form a coherent representation of the world. There is an evolutionary advantage to integrating sensory information from multiple modalities as it allows the observer to respond to external events more quickly and accurately relative to processing unisensory information alone [440]. One important factor that the CNS must consider when determining whether to bind multisensory information is the relative timing of events. Studies have shown that there is a window in time within which multisensory events are judged to have occurred simultaneously. Interestingly, a growing body of research has shown that this temporal binding window (TBW) changes throughout early development [204, 205, 266], or following injury [493], disease [399] and aging [36, 43, 370, 418]. With respect to aging, a variety of experimental approaches have been utilized to characterize changes in the perceived timing of multisensory events for older compared to young adults. Here we seek to assess the relationship among some of these approaches in order to better understand the underlying mechanisms that may subserve them.

A classic psychophysical method used to assess the relative perceived timing of multisensory events is response time (RT), in which the observer is presented with unisensory or multisensory stimuli and asked to press a response key as quickly as possible following stimulus presentation. Early work conducted by Raab [379] suggested that the presentation of a pair of stimuli initiates a detection race wherein the winner's time determines the observed RT. The race model inequality (RMI) proposed by Miller [318] tests whether the observed RT facilitation for multimodal stimuli is too large to be attributed to statistical facilitation; RMI has become the standard testing tool in many multisensory studies. Context invariance, an assumption of the RMI, states that the processing times for one signal (i.e., individual or redundant signals) is unaffected by the presentation of another signal, meaning, the processing time for lets say the auditory signal of an audiovisual stimulus, would follow the same distribution as the processing time for the auditory stimulus alone [179, 320]. The race model describes separate, context-invariant processing of redundant information; thus, a violation of the RMI indicates that either the race model is violated, or the context invariance assumption is not supported. A conventional view of this violation is that separate processing of the stimuli is not taking place, indicating synergistic neural mechanisms (but see [349, 350, 348]). Research comparing multisensory integration (MSI) effects in young and older adults is limited; however, it appears that older adults demonstrate greater multisensory RT facilitation effects compared to young adults when presented with multimodal stimuli [106, 132, 255, 291, 361]. The test of the RMI tends to show significant violations in older adults suggesting integration of unisensory stimuli while young adults tend to show reduced or no violation suggesting minimal integration [255, 291]. More recently, however, it has been argued that the magnitude of the race model violation [i.e., area under the curve (AUC) obtained from the RMI] could provide further information regarding age-related alterations of multisensory integration [288, 289].

Various other tasks can be found in the literature that are commonly utilized to assess multisensory processing. One such task is the sound-induced flash illusion (SIFI; [420, 421, 422]), where a single flash accompanied by two beeps in close temporal proximity leads to the perception of two flashes. The perception of the illusion is determined by the stimulus onset asynchronies (SOAs) between the beeps and the flash. It has been found that healthy younger adults generally perceive the illusion when the SOA is less than or equal to 70-150 ms, whereas older adults are susceptible over a wider range of temporal SOAs. In a study conducted by Setti and colleagues [415], it was found that young adults showed maximal susceptibility to the illusion at the SOA of 70 ms and a decrease in susceptibility to the illusion with increasing delay between the stimuli such that they were no longer susceptible to the illusion at the SOA of 270 ms. Older adults, however, did not show as much of a decrease in susceptibility to the illusion. As the travel and transduction time for auditory and visual stimuli are considered too great for optimal integration beyond 100-150 ms, a departure from integration over this time may represent deficient sensory integration. To determine whether temporal perception can be modified, Setti and colleagues [418] investigated whether training temporal perception through the temporal order judgment (TOJ) task would reduce susceptibility to the SIFI in older adults. Overall, a high proportion of error on the illusory trials was found even after 5 consecutive days of training on the TOJ task, however, the results did reveal a significant improvement for the SOA of 270 ms in the trained group, indicating that not only are the improvements specific to the longer SOAs, but that older adults maintain a large temporal discrimination threshold even after training.

Another task used to measure multisensory integration is the stream/bounce illusion, where a two-dimensional visual display is used to present two identical objects moving toward one another, coinciding, and moving apart [414]. After the point of coincidence, the movement of the objects can be interpreted as if they continued in their original direction or as if they bounced off one another and reversed directions. A brief beep is presented 150 ms before, after, or at the point of coincidence which increases bounce perception compared to the control condition in which no beep is presented. Previously, Roudaia and colleagues [394] demonstrated that older adults did not have an increased perception of the bounce illusion when the auditory stimulus was presented at the point of coincidence, suggesting an age-related reduction in multisensory integration. Bedard and Barnett-Cowan [43], however, found that older adults were more susceptible to the illusion, indicating that they were integrating auditory and visual cues over a large window of time. One of the concerns for both the SIFI and the stream/bounce illusion, is that they are not sensitive to the full parameterization of the temporal window during which multisensory information is integrated (i.e., TBW) and they only provides an indirect method of assessing such a window [394, 418].

Simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks are extensively used in the literature not only with young adults [6, 29, 30, 275, 323, 476] but with the aging population as well [36, 43, 279, 415, 416]. In both these tasks, participants are provided with the same pairs of audiovisual stimuli and they're either asked to determine if the stimuli occurred at the same or different times (SJ) or which stimulus appeared first (TOJ) [473]. These tasks have been found to be sensitive to both the TBW as well as the point of subjective simultaneity (PSS), the point at which participants are most likely to perceive stimuli as occurring simultaneously for the SJ task, and the point of maximal uncertainty for the TOJ task. Although both tasks utilize the same stimuli and both provide measures of the PSS and TBW, it is thought that they measure different perceptual processes [29, 30, 275, 323, 476] and are likely to be subserved by different neural mechanisms [3, 6, 36, 126, 270]. Past research investigating the relation of PSS obtained from the SJ and TOJ tasks in young adults has found no correlation between the PSS for the two tasks [473, 275], and has found that on average, the SJ task yields visual-leading PSS estimates whereas the TOJ task yields audio-leading PSS estimates (see [473] for review; [275]). Such differences are thought to arise because the two tasks may involve different processes/mechanisms [508]. For example, the SJ task assesses the judgment of 'simultaneous' versus 'non-simultaneous' whereas the TOJ task assesses the perception of 'order' which requires the correct perception of successiveness [6, 206, 508].

Interestingly, using the SJ and TOJ tasks, it has been found that the TBW varies with age as it tends to be wider in early childhood, becomes more fine-tuned during middle childhood, and widens again with aging [43, 205, 204, 266, 370, 418]. A wider TBW in older adults indicates that they are more likely to perceive synchrony and thus have more trouble differentiating temporally offset stimuli [7, 71, 80, 81, 198, 370, 481]. Widening of the TBW with aging is of concern given that information that should be encoded as arising from separate events is more likely to be integrated, which can result in decreased speech comprehension [287, 417], an inability to dissociate from distracting or inaccurate information [497], and increase the susceptibility to falls ([293, 415]; but see [288]) and fall awareness [279]. Furthermore, age-related impairments in driving performance and speech comprehension have been associated with temporal processing deficits within the auditory [21, 182] and visual [248, 494] domains. In order to address this concern, psychophysical training regimens have been designed to recalibrate the TBW that may address deficits associated with temporal order perception [80, 81, 375].

SJ, TOJ, and RT are different methods of assessing temporal perception of events; however, no study to date has compared all three tasks. This comparison is important as it provides us with a better understanding of how multisensory information is processed and whether or not there is a relation between the different decision-making processes that underlie the behaviour associated with these tasks. In this study, we aim to explore the relation between these three tasks in young and older adults in order to better understand the underlying mechanisms that subserve multisensory temporal processing and to determine whether they change with age. When comparing the relation between RT and TOJ tasks, some researchers have varied the stimulus onset asynchronies used in the RT task to extract the TBW from both of these tasks. Research using such a design has revealed that the TBWs obtained from the RT task tend to be wider than those obtained from the TOJ task [131, 307] and this has been interpreted as a strategy to optimize performance on each task. The TOJ task requires participants to discern small temporal asynchronies and thus benefits from a narrower TBW, whereas the RT task benefits from having a wider TBW as it allows for maximum multisensory facilitation. Using such a design (i.e., by varying the SOAs in the RT and TOJ tasks), researchers have found that older adults have slower RTs compared to young adults [132, 255], they also have broader TBWs [132], and they tend to show greater multisensory facilitation as assessed via the race model violation [132, 255]. Further, if a relation exists between the TBW and response time, one could argue for such a relation between RT and PSS as well. It has been shown that the TOJ task utilizes all available information in order to infer physical onset of the stimuli, thus maximizing accuracy [325], while RTs are characterized by automatic response behaviour, the motor task requires minimization of response time (rather than maximizing correct responses), which is achieved by setting the motor threshold to be as low as possible [75, 445, 490]. As was the case with the TBW, researchers have also compared RTs and PSS estimates obtained from the TOJ task from the same pairs of stimuli (i.e., participants performed RT and TOJ tasks within the same trial), in order to gain a deeper understanding of the relation between the two variables. The results have revealed a significant association between RT and TOJ PSS estimates whereby RTs of pairs of visual stimuli differ with the associated TOJs, indicating that the two tasks may be triggered at different decision-processing levels of the same internal signal (i.e., 'one-system-two-decision' model) [75]. Note, however, that TOJ was found to be less sensitive to stimulus intensity as compared to the RT task, thus providing some evidence for distinct decision criteria for perceptual and motor responses [75].

The studies mentioned above provide initial evidence for a relation between a wider TBW, slower mean RT, and a larger violation of the race model, as well as a relation between mean RT and PSS. However, research comparing race model inequality (RMI) [quantified as the AUC from the cumulative distribution function (CDF) difference wave] to measures obtained from the SJ and TOJ tasks (i.e., TBW and PSS) from older adults is lacking . As multisensory processing changes with age (i.e., requiring light to appear much earlier than sound to perceive simultaneity as compared to young adults), assessing these relations within the aging population provides further information related to whether the underlying mechanisms associated with these tasks maintain their relation. The main objective of the current study is to determine age-related differences in auditory–visual (AV) integration using a unique experimental design that encompasses aspects of AV RT, SJ, and TOJ tasks. Here, we aimed to determine age-related differences in TBW, PSS, and the magnitude of race model violation. We hypothesize that (1) older adults will have slower mean RTs as compared to young adults; (2) older adults will demonstrate larger race model violations compared to young adults; (3) increased race model violations will be positively correlated with wider TBWs; and that (4) increased race model violations will be positively correlated with PSS falling farther away from true simultaneity.

2.3 Materials and Methods

2.3.1 Participants

Participants (n = 56) were recruited from the University of Waterloo (young adults; YA) and from the Waterloo Research in Aging Participant Pool (WRAP; older adults; OA). The WRAP program ensures that all recruited participants are healthy older adults over the age of 60 with no significant medical concerns (i.e., Alzheimer's disease, Parkinson's disease, stroke, epilepsy, etc.). Participants were further screened for mild cognitive impairment and dementia using the Montreal Cognitive Assessment (MoCA; mean score = 27, SD =

0.47) where a score of 26 or above out of 30 indicates normal cognition [334]. Self-reported data acquired from medical history questionnaires was also assessed in order to ensure that the eligibility criteria was met.

Male and female participants between 19 and 79 years of age were included in this study. Participants included 30 young (17 females, mean age = 22.93, s.e. = 0.66) and 26 older (19 females, mean age = 70.80, s.e. = 0.90) adults. All participants were required to have normal or corrected-to-normal vision and hearing. Prior to study inclusion, participants completed a self-reported clinical information form where they indicated (yes/no) if they had normal or corrected-to-normal vision and if they had normal or corrected-to-normal hearing (yes/no). If participants answered no to any of the above questions, they were subsequently excluded from the study. In appreciation of their participation, participants received a $10 per hour remuneration. This study was approved by the University of Waterloo's Human Research Ethics Committee in accordance with the Declaration of Helsinki, and written informed consent was obtained from all participants before participation.

2.3.2 Experimental Setup

Each participant completed three experimental tasks while seated in front of a 23.6-inch ViewSonic V3D245 computer monitor (resolution 1920 × 1080, 120 Hz) in a soundproof booth with his/her head stabilized on a chin rest. Visual stimuli were presented on the monitor at a viewing distance of 57 cm, in the form of white circles (0.4°). Auditory stimuli were emitted from two speakers (Altec Lansing Multimedia computer speaker system, ACS95W) adjacent to the monitor such that they were 66 cm apart. A Macbook Pro (OS 10.9 Mavericks) that resided outside of the booth was used to run the tasks. VPixx Technologies ProPixx hardware and DataPixx software version 3.01 were utilized for this experimental procedure to ensure synchrony of the audio and visual stimuli (depending on condition) with <1 ms accuracy. Participants were able to record their response for each trial by using the RESPONSEPixx handheld five-button response box.

2.3.3 Procedure

Participants completed the SJ, TOJ, and RT tasks in a randomized order. For all tasks, a central fixation cross (visual angle = 0.5°) was presented on the screen, and participants were instructed to fixate on this cross throughout the experimental procedure. For all three tasks, response from the participant initiated the next trial. In order to reduce temporal predictability, each trial began with the stimulus being presented after a delay of 1000–3000 ms. Participants were presented practice trials prior to commencement of each of the experimental tasks. Test performance during the actual experiment was monitored on a laptop from outside the booth.

Simultaneity Judgment

In the SJ task, participants were instructed to report, using different response buttons, whether they perceived the auditory and visual stimuli as occurring simultaneously (right button) or not (left button). Participants were explicitly told to respond as accurately as possible as opposed to responding quickly. Visual stimuli were presented in the form of a 0.4° white circle [49.3 Candela per meter squared (cd/m^2)] against a black background (0.3 cd/m^2), which appeared 2° below the fixation cross for 17 ms. They were either preceded or followed by an auditory beep (1850 Hz, 7 ms, 71.7 decibels) at the following SOAs: 0, 25, 50, 100, 150, 200, 300 ms. Ten trials were presented in a randomized order for each condition for a total of 130 trials (see Fig. 2.1).

Temporal Order Judgment

The experimental design of the TOJ task was identical to the SJ task with the exception of the task instructions. Here, participants were asked to report, using the response buttons, whether they perceived the visual (right button) or the auditory (left button) stimulus as appearing first; 'synchronous' or 'I don't know' responses were not acceptable for this task (see Fig. 2.1). Again, participants were explicitly told to respond as accurately as possible as opposed to responding quickly.

Response Time Task

In the RT task, participants were told that they would either see a flash of light, hear a beep, or a combination of the two. Participants were instructed to press the response button as soon as they detected any one of the three experimental conditions: unisensory Visual (V), unisensory Auditory (A) or multisensory audiovisual (AV). In order to maintain consistency across all three tasks, the exact same stimuli and stimulus durations were employed; however, for this task all AV stimuli were presented simultaneously. Each stimulus was presented 100 times in a randomized order (300 trials in total). Trials were divided into two blocks and participants were given a break in between blocks to reduce fatigue (see Fig. 2.2).

2.4 Statistical analysis

2.4.1 Simultaneity and temporal order judgment tasks

To estimate the accuracy (PSS values) and the precision (TBW) with which participants made their judgments for SJ and TOJ, psychometric functions were fitted to the participant's responses as a function of SOA using SigmaPlot version 12.5. Each task was analyzed individually for each participant, with participant data fit to both Gaussian (for

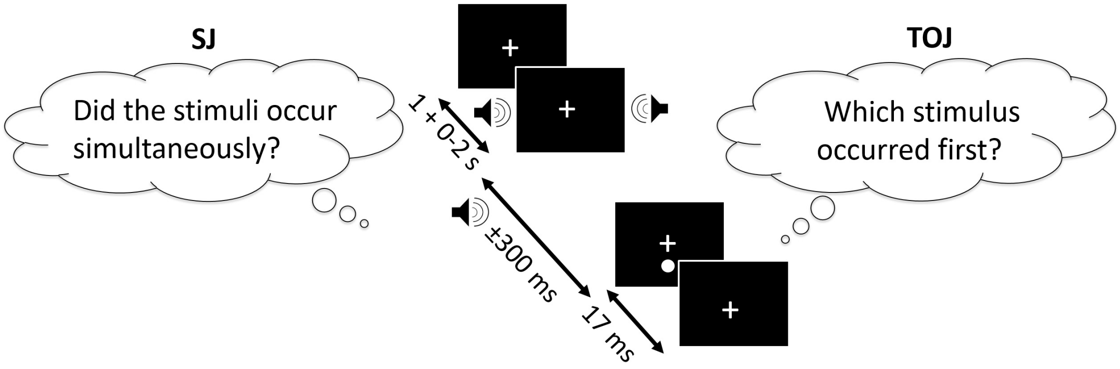


Figure 2.1: SJ task (left) and the TOJ task (right), presented with the SOAs of ±0, ±25, ±50, ±100, ±150, ±200, ±3000 ms (-ve = sound appeared before light). In both tasks, the first stimulus of the audiovisual pair can appear 1-3 sec following the fixation cross and the second stimulus appears between 0 – 300 ms after the first stimulus. The figure depicts the auditory stimulus (i.e., beep) as presented before the visual stimulus (i.e., flash). Note, that the experimental design for the SJ and TOJ is identical, however the instructions vary by task.

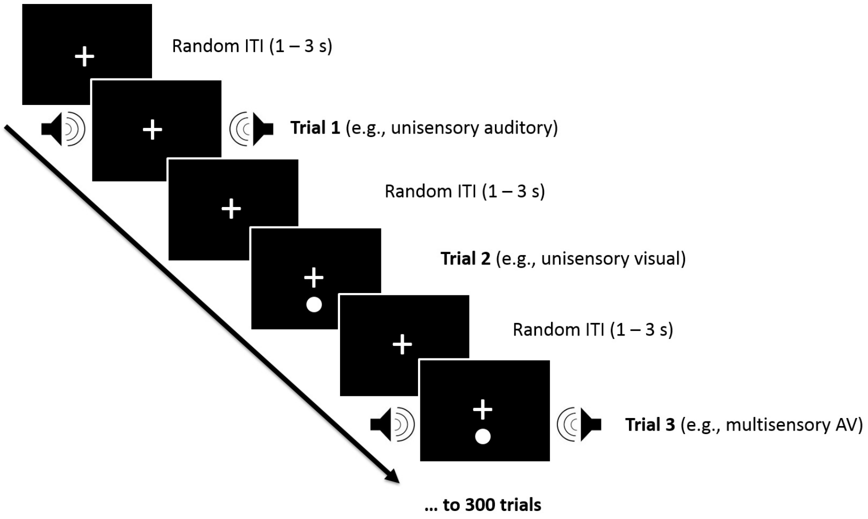


Figure 2.2: Participants were presented with unimodal [auditory (A) or visual (V)] or bimodal [audiovisual (AV)] stimuli and were asked to make speeded responses to all stimuli, regardless of sensory modality by pressing a RESPONSEPixx button which triggered the next trial. Two blocks of A, V, and AV stimuli (150 trials per block) were randomly presented with random inter-trial-intervals (ITIs) of 1 – 3 s.

the SJ task; Eq. 1) and logistic (for the TOJ task; Eq. 2) functions:

$$Eq.1 : y = a \cdot e^{(-0.5((x-x0)/b)^2)} \tag{2.1}$$

Where a is the amplitude, $x\o$ is the PSS and b is the standard deviation.

$$Eq.2 : y = 100/(1 + e^{(-(x-x\emptyset)/b)})\% \tag{2.2}$$

Where a is fixed to 1, $x\o$ is the PSS and b is the standard deviation.

The best fit parameters corresponding with the PSS and TBW were identified for each participant separately, and those participants whose data was poorly estimated were excluded from further analysis ($r^2 \leq 0.2; YA = 1; OA = 3$).

As we were interested in the relationships between TBWs obtained from the two tasks and not their absolute size, we chose to analyze the b values (i.e., standard deviation) of these psychometric functions as a proxy for the size of the TBW to avoid discrepancies in the literature that differ when defining the absolute size of the TBW.

Using a within-subjects design, paired t-tests were conducted to assess differences between TBWs and PSSs within each group. Independent t-tests were used in accordance with Leven's test for equality of variance to further assess differences between young and older adults. Pearson's correlations ($\alpha = 0.05$) were assessed between the two tasks for all participants while controlling for age. Furthermore, Pearson's correlations ($\alpha = 0.05$) were conducted to determine age-specific relations.

2.4.2 Response time task

Error analysis, outlier removal, and mean RT analysis

As previously mentioned, participants responded to 300 trials in total (100 per condition). Given recent reports implicating the use of RMI over RT facilitation for investigating MSI effects [106, 288, 295], we applied a similar approach. RMI was first tested using Gondan's permutation test over the fastest quartile (0-25%) of responses and violation was indeed observed for both young ($t_{max} = 4.42, t_{crit} = 2.21, p < 0.001$) and older ($t_{max} = 5.71, t_{crit} = 2.08, p < 0.001$) adults [178, 179]. Data trimming procedures were not applied (see[178, 179, 288, 295]); however very fast responses, slow responses, and misses (defined as < 100 ms or > 1500 ms or not registered by the program respectively [$< 3\%$ for each condition]) were set to infinity rather than excluded (see also [289] for a RMI tutorial). To be consistent with other MSI studies, RT facilitation (multisensory condition – most efficient unisensory condition) was also calculated.

Mean RT analysis

A 2 (age group: young or older) x 3 (condition: auditory, visual, or audiovisual) repeated-measures mixed-design ANOVA was conducted to determine whether age and condition significantly affected RT. Mauchly's test of sphericity was conducted and the Greenhouse-Geisser was used if necessary. Planned pairwise comparisons were also made to assess the differences between young and older adults by condition.

Test of the race model

As previously mentioned, the race model posits that the response to redundant signals is produced by the modality that processes its respective signal the fastest and thus is the "winner" of the race [379]. Race model violations are typically tested using cumulative distribution function (CDF) models which compare the *observed* CDF distribution to the *predicted* CDF distribution [318]. Here, to compute the CDFs, each participant's data was sorted in ascending order for all three conditions (A, V, AV). Each participant's RTs were then quantized into 5th percentile bins until the 100th percentile was reached, yielding 21 bins in total.

Observed CDF distributions were formed using the following equation (Eq. 3):

$$Eq.3 : CDF_{observed} = P(RT_{AV} \leq t) \tag{2.3}$$

Where RT_{AV} represents the RT *observed* for the multisensory condition for any latency, t [97, 291]. *Predicted* CDF models were formed using the following equation (Eq. 4):

$$Eq.4 : CDF_{predicted} = Min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{2.4}$$

Where RT_A and RT_V represent the RTs *observed* for unisensory condition A (e.g., auditory) and V (e.g., vision), for any time, t [97, 291].

Differences between the *observed* CDF distribution and the *predicted* CDF distribution were calculated for every participant across all percentile bins as follows (Eq. 5):

$$Eq.5 : RT_{AV} = P(RT_{AV} \leq t) - min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{2.5}$$

When the *observed* CDF is less than or equal to the *predicted* CDF, the race model is accepted. However, the race model is violated when the *observed* CDF is greater than the *predicted* CDF. Thus, a negative value (or zero) indicates acceptance of the race model while values greater than zero provide evidence for multisensory integration as they are indicative of race model violations [97, 293].

Although many researchers have previously utilized t-tests (i.e., paired t-tests comparing *observed* versus *predicted* CDF or one sample t-tests along the difference curve) to determine race model violations, it has been argued, that these tests are too conservative [179]. As mentioned above, we used a data-driven approach to determine RMI violations by conducting Gondan's permutation test over the fastest quartile (0-25%) of responses, where robust violations were evident for both young and older adults (see also Figure 2.7 below). In addition to performing Gondan's permutation test of race model (Gondan & Minakata, 2016), we calculated the AUC (which served as our independent variable) in an effort to further quantify the magnitude of RMI violation over the first quartile of responses. As described in Mahoney & Verghese [289], the AUC was calculated for each time bin over the 0-25th percentile, where the difference value obtained from the *observed* CDF and the *predicted* CDF from the first time bin (i.e., 0%) was summed with the difference value obtained from the second time bin (5%) and divided by two. This was repeated for the subsequent time bins until 25^{th} percentile was reached. All the values obtained were summed to generate a total AUC of the CDF difference wave during the 25^{th} percentile. To compare the AUC obtained from young and older adults, a Kruskal-Wallis test was conducted in order to account for the non-normal distribution of the AUC data.

Relation between the SJ, TOJ, and RT tasks

In order to assess the relation between race model violations obtained from the RT task, as well as the TBWs and PSSs obtained from the SJ and TOJ tasks, Pearson's correlations ($\alpha = 0.05$) were determined between the AUC values, TBWs, and PSSs for young adults. While Spearman's correlations ($\alpha = 0.05$) were determined between the AUC values, TBWs, and PSSs within older adults in order to account for the non-normal AUC data distribution. In addition to the correlations, multiple regression analyses were conducted while controlling for age in order to further assess the relation between AUC, TBWs, and PSSs for the two tasks.

2.5 Results

2.5.1 Simultaneity and temporal order judgment tasks

Participants' responses were fitted to either a Gaussian or a Sigmoidal logistic curve for SJ and TOJ respectively using equations 1 or 2 from which PSSs and TBWs were extracted for analysis. Figure 2.3 shows the average Gaussian functions (SJ) and Figure 2.4 shows the average logistics function (TOJ) for young and older adults. The goodness of fit from the SJ task for young (r^2 Mean: 0.85, Median: 0.88, SD: 0.09, s.e.: 0.02) and older adults (r^2 Mean: 0.80, Median: 0.84, SD: 0.13, s.e.: 0.03) were similar [independent t-test: t(55) = 1.68, $p = 0.1$; Cohen's $d = 0.46$)]. The goodness of fit from the TOJ task for young (r^2 Mean: 0.76, Median: 0.82, SD: 0.18, s.e.: 0.03) and older adults (r^2 M: 0.75, Median: 0.81, SD: 0.21, s.e.: 0.042) were also similar [independent t-test: t(53) = .53, $p = 0.6$; Cohen's $d = 0.14$].

In line with our previous work [36], within the young group, the paired t-test revealed that the TBW obtained from the SJ task (M = 160.07, s.e. = 8.39) was significantly wider than the TOJ task (M = 103.04, s.e. = 10.51); ($t(27) = 6.69$, $p < 0.001$, Cohen's $d = 1.13$; Figures 2.3 and 4). Furthermore, a paired t-test between the two tasks for the PSS revealed that the visual stimulus was required to appear before the auditory stimulus earlier in the SJ task (M = 56.36, s.e. = 7.77) than the TOJ task (M = 10.31, s.e. = 14.17) in order for simultaneity to be perceived; ($t(28) = 2.81$, $p < 0.01$; Cohen's $d = 0.75$; Figures 2.3 and 2.4). Similarly, within older adults, a paired t-test revealed that the TBW was wider in the SJ task (M = 186.26, s.e. = 14.35) compared to the TOJ task (M = 117.01, s.e. = 13.12); ($t(22) = 4.74$, $p < 0.001$; Cohen's $d = 1.05$; Figures 2.3 and 2.4). No significant difference was found between the PSS for the SJ task (M = 82.70, s.e. = 9.36) compared to the TOJ task (M = 53.91, s.e. = 23.52); ($t(22) = 1.16$, $p = 0.26$; Cohen's $d = 0.34$; Figures 2.3 and 2.4).

Planned independent t-tests were conducted to determine age-related differences between the two tasks. While the TBWs were not significantly different between the two groups (for both SJ ($t(50)$ = -.95, p = 0.35; Cohen's d = 0.26) and TOJ ($t(49)$ = -.84, p = 0.40; Cohen's d = 0.23)), on average, older adults (M_{SJ} = 179.20, s.e. = 16.46; M_{TOJ} = 117.01, s.e. = 13.13) exhibited wider TBWs compared to young adults (M_{SJ} = 162.59, s.e. = 8.48; M_{TOJ} = 103.04, s.e. = 10.51). In line with previous literature, no significant effects of PSS were found between the young (M_{SJ} = 56.35, s.e. = 7.76; M_{TOJ} = 10.31, s.e. = 9.25) and older adults (M_{SJ} = 79.26, s.e. = 14.17; M_{TOJ} = 53.91, s.e. = 23.51) for SJ ($t(50)$ = -1.84, p = 0.07; Cohen's d = 0.51) and TOJ ($t(50)$ = -1.66, p = 0.10; Cohen's d = 0.45).

Age controlled partial correlations were first conducted on all participants for the TBW as well as the PSS. In line with previous literature [43], a significant positive correlation was found between the TBWs obtained from both the tasks ($r(49)$ = 0.50, $p < 0.001$). As expected, no significant correlations were observed for PSS ($r(49)$ = 0.03, p = 0.84). Pearson's correlations were then conducted within each group and the TBWs from the two tasks within both young ($r(28)$ = 0.61, $p < 0.001$) and older ($r(23)$ = 0.44, p = 0.04) adults were found to be significantly positively correlated. PSSs were not correlated between the two tasks in both young ($r(29)$ = -0.04, p = 0.85) and older adults ($r(23)$ = 0.06, p = 0.77).

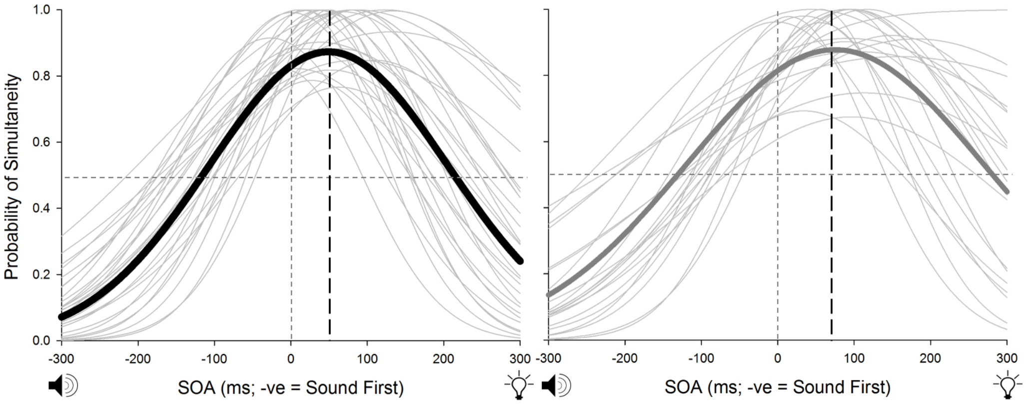


Figure 2.3: SJ: here the Gaussian function is fit to the average (thick lines) and individual (thin lines) data. Young adults (black) require the visual stimulus to occur approximately 58 ms before sound while older adults (grey) require the visual stimulus to occur approximately 82 ms before sound in order to perceive the two stimuli as simultaneous.

2.5.2 Response time task

Error analysis, outlier removal, and mean RT analysis

Both young and older adults made few errors with an overall accuracy of 99.98% and 99.99% in each group respectively. Young adults maintained an accuracy of 99.4% in the auditory

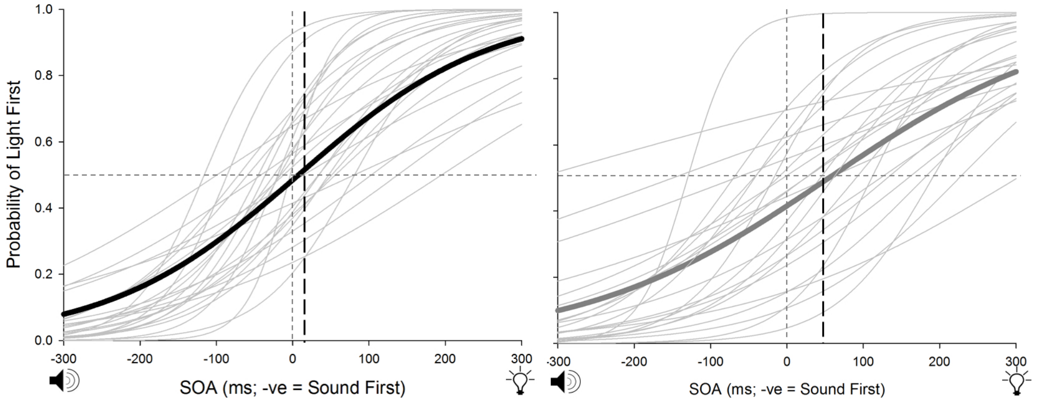


Figure 2.4: TOJ: the sigmoidal function is fit to average (thick lines) and individual (thin lines) data. Here, young adults (black) require the visual stimulus to appear approximately 10 ms before sound while older adults (grey) require the visual stimulus to appear approximately 49 ms before light in order to perceive the two stimuli as being simultaneous.

trials, 99.6% in visual stimuli, and 97.9% in the audiovisual trials. Older adults achieved an accuracy of 99.6% in auditory trials, 99.8% in visual trials, and 98.0% in audiovisual trials. In line with Couth and colleagues [106] our data also revealed most outliers to be the slower responses (>1500 ms) with very few misses (<1% for all conditions). Outliers were converted to infinity and only correct responses were included in the analyses.

Mean RT analysis

Results from the 2 (age group: young, older) x 3 (condition: audio, visual, audiovisual) RM ANOVA revealed a significant main effect of group ($F(1, 25) = 25.97$, $p < 0.001$; $\eta_p^2 = 0.51$; Figure 2.5) and condition ($F(1.30, 32.4) = 129.37$, $p < 0.001$; $\eta_p^2 = 0.84$). The interaction between group and condition was also significant ($F(1.54, 38.48) = 21.49$, $p < 0.001$; $\eta_p^2 = 0.46$). In line with our hypothesis, planned pairwise comparisons revealed that older adults (M = 369.26 ms, s.e. = 17.68) demonstrated significantly longer RTs compared to young adults (M = 280.85 ms, s.e. = 14.03; $p = 0.001$). The pairwise comparisons also revealed that responses to audiovisual trials (276.35 ms, s.e. = 12.02) were significantly faster than auditory (324.80 ms, s.e. = 17.45) and visual trials (374.00 ms, s.e. = 11.23; $p < 0.001$; see Figure 2.5).

The race model violation

The difference waveform, calculated by subtracting the predicted CDF from the observed CDF, is indicative of whether or not the race model has been violated [97]. Evidence for the co-activation model and thus support for multisensory integration is provided if a positive value is obtained regardless of the significance of the magnitude [97, 291, 294]. Figure 2.7 indicates a violation of the race model and provides evidence for the co-activation model

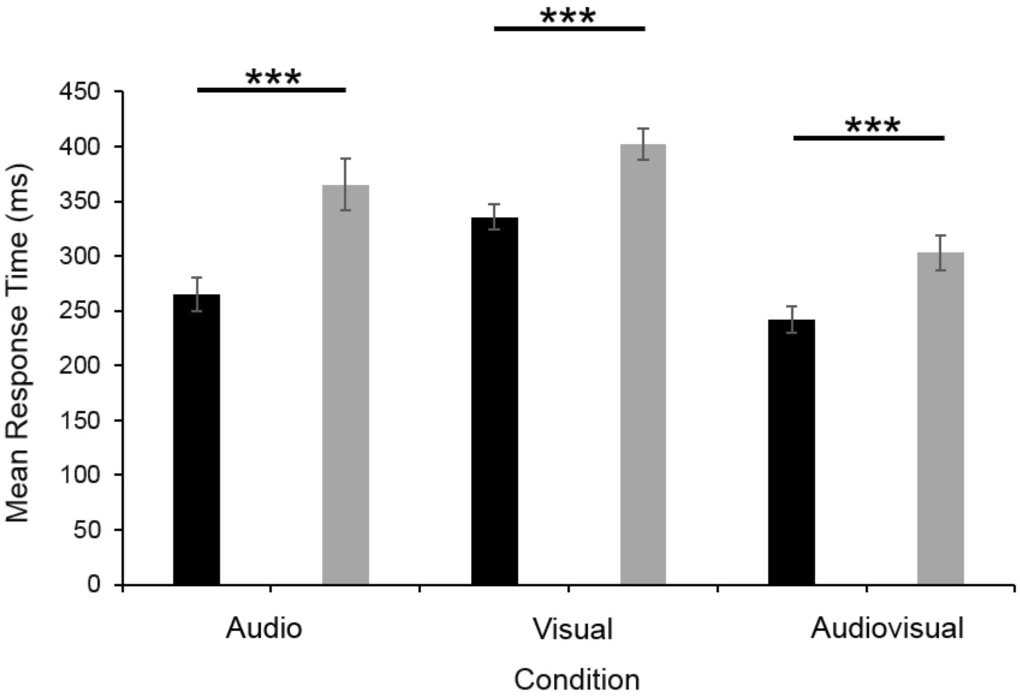


Figure 2.5: Averaged response time data (with Standard Error of Mean; SEM] from the auditory, visual, and audiovisual conditions for both young (black) and older (grey) adults. Error bars are ±1 SEM. Asterisks indicate statistical significance at $p < 0.001$ level.

over the first 25th percentile (highlighted in grey) in both young and older adults. These findings are consistent with the main effect of condition (i.e., audio, visual, audiovisual) and group (young and older) as found through the RM ANOVA conducted above with mean RT. However, as mentioned above, Gondan's permutation test was also conducted to statistically assess race model violations and was significantly violated in both young and older adults. We also conducted a Kruskal-Wallis test comparing the AUC values to determine group differences; here, the AUC data obtained from older adults violated the Shapiro-Wilk test due to two outliers; D(23) = 0.87, $p < 0.01$. A statistically significant difference between the groups was determined (χ^2 (1) = 8.48, $p < 0.01$) where young adults showed a smaller mean rank score (21.05) compared to older adults (33.37) thus indicating larger race model violations in older adults (see Figures 2.6 and 2.7).

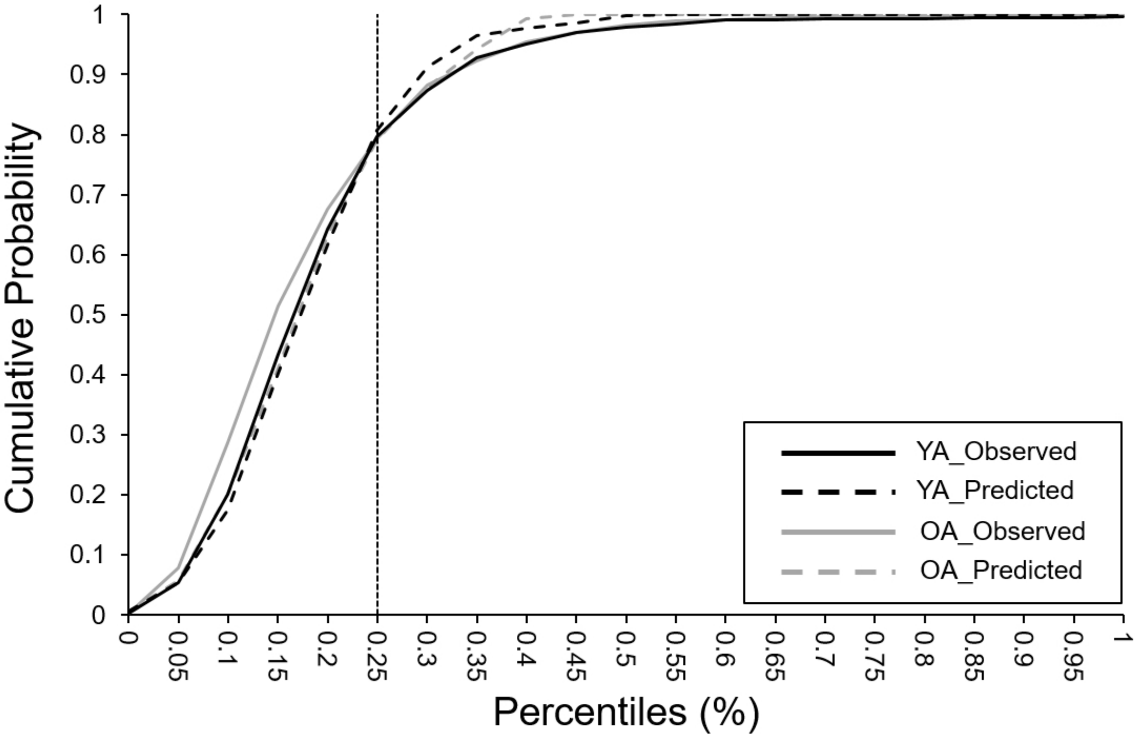


Figure 2.6: Cumulative probability graphs where the solid lines represent the *observed* cumulative probability while the dashed lines represent the *predicted* cumulative probability for young (black) adults and older (grey) adults.

2.5.3 Relation between the SJ, TOJ, and RT tasks

Prior to conducting the correlation analysis, data was checked for normality. All data was normally distributed except for the AUC values obtained from older adults which consisted of 2 outliers (females); even when removed, the data continued to be non-normally distributed. Thus, Pearson's correlations ($\alpha = 0.05$) were determined between the PSSs and the TBWs obtained from the SJ and TOJ tasks with the average AUC values obtained from the RT task over the fastest (0-25%) percentiles within the young adults while Spearman's correlations ($\alpha = 0.05$) were conducted for older group. A significant positive correlation was found between the PSS obtained from the TOJ task and the AUC ($r(29) = 0.49$, $p < 0.01$) in the young group. No other correlations were found for both the young and older group (see Figures 2.8 and 2.9). Multiple regressions were conducted in order to further substantiate these findings and in line with the results obtained from the correlation analysis, it was found that the PSS estimates obtained from the TOJ task ($\beta = 1.19$, $p = 0.01$) and age ($\beta = 0.49$, $p < 0.01$) were significant predictors of AUC (see Figure 2.10). Furthermore, a significant interaction between PSS obtained from TOJ and age was also found ($\beta = -1.06$, $p = 0.02$; see Figure 2.10).

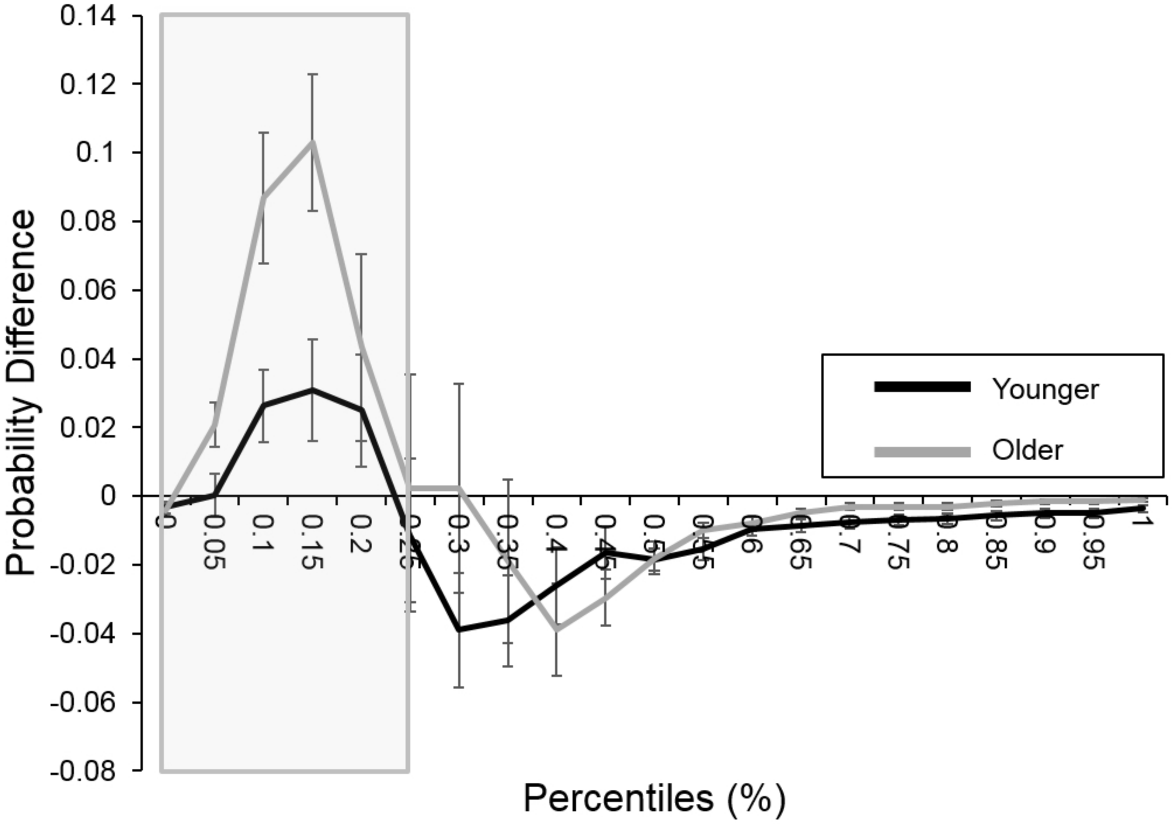


Figure 2.7: Test of the race model by group. The graph represents the probability difference wave where the *predicted* CDF is subtracted from the *observed* CDF for young (black line) and older (grey line) adults. They grey box indicates the area over which the analyses were conducted. Error bars are ±1 SEM.

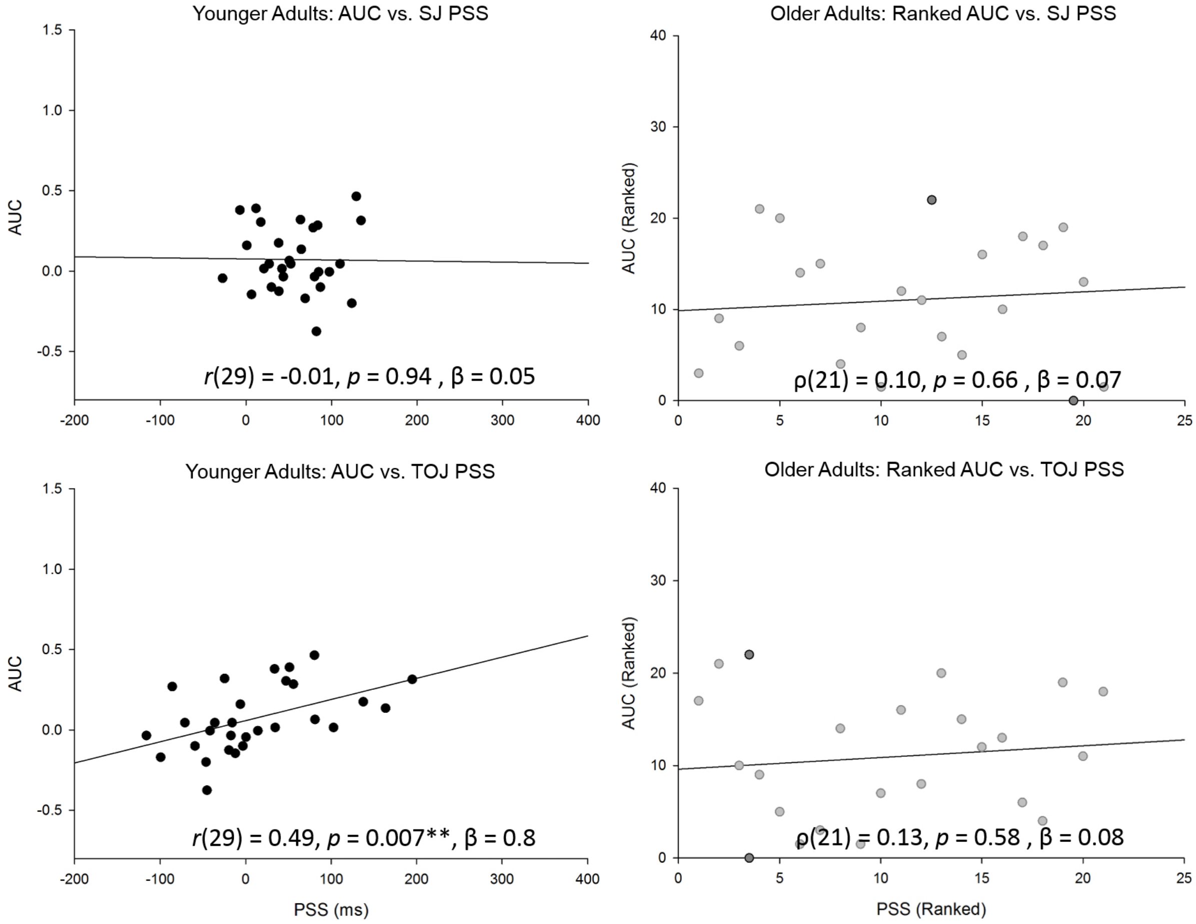


Figure 2.8: Scatter plots of correlations between the AUC and the PSS for both young (left) and older (right) adults. Notice that Spearman's correlations were conducted for older adults and thus the ranked data is reported for the group; note the two outliers (dark grey) found within the older adult group. Pearson's correlations were conducted for young adults. Note: only the PSS obtained from the TOJ task is positively correlated with the AUC. ** $p < 0.01$.

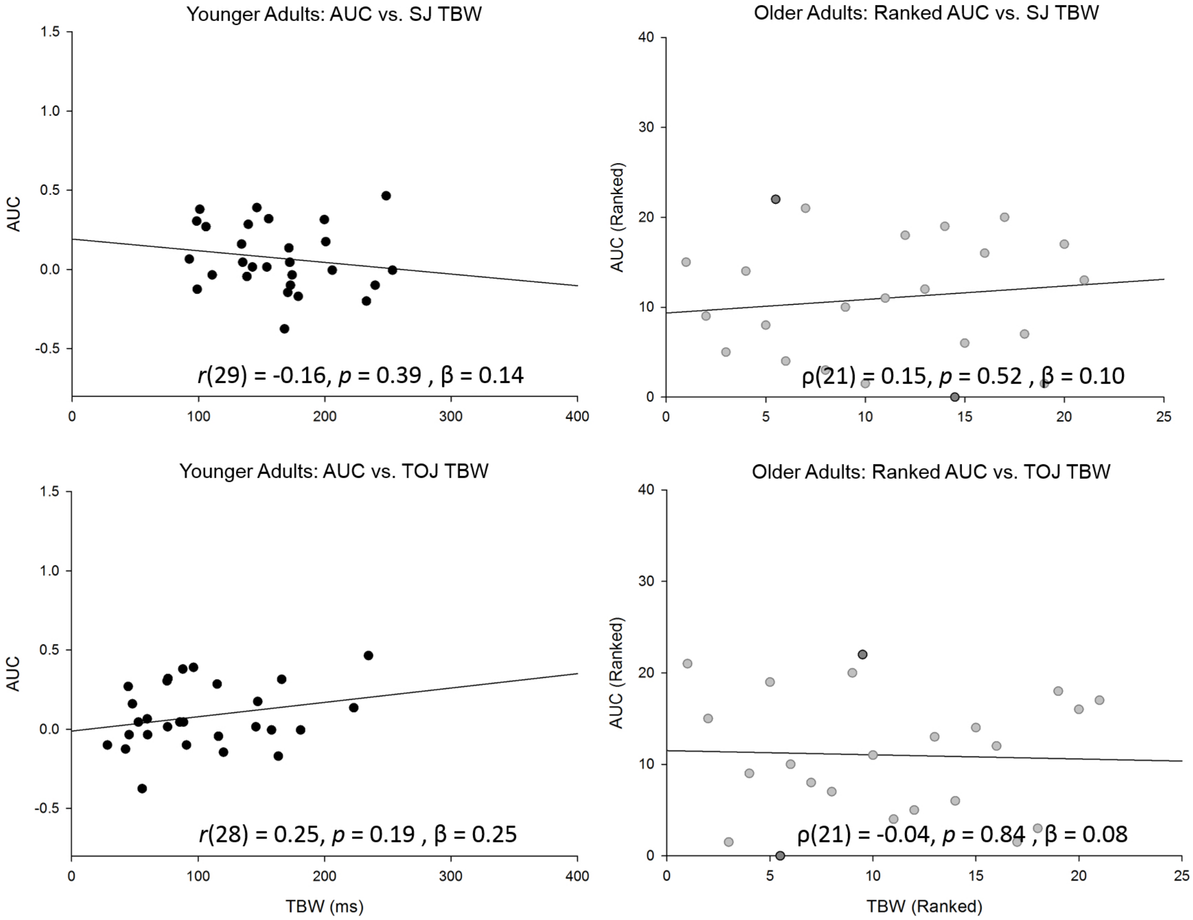


Figure 2.9: Scatter plots of correlations between the AUC and the TBW for both young (left) and older (right) adults. Notice that Spearman's correlations were conducted for older adults and thus the ranked data is reported for the group; two outliers found within this group are highlighted in dark grey. Note that Pearson's correlations were conducted for young adults.

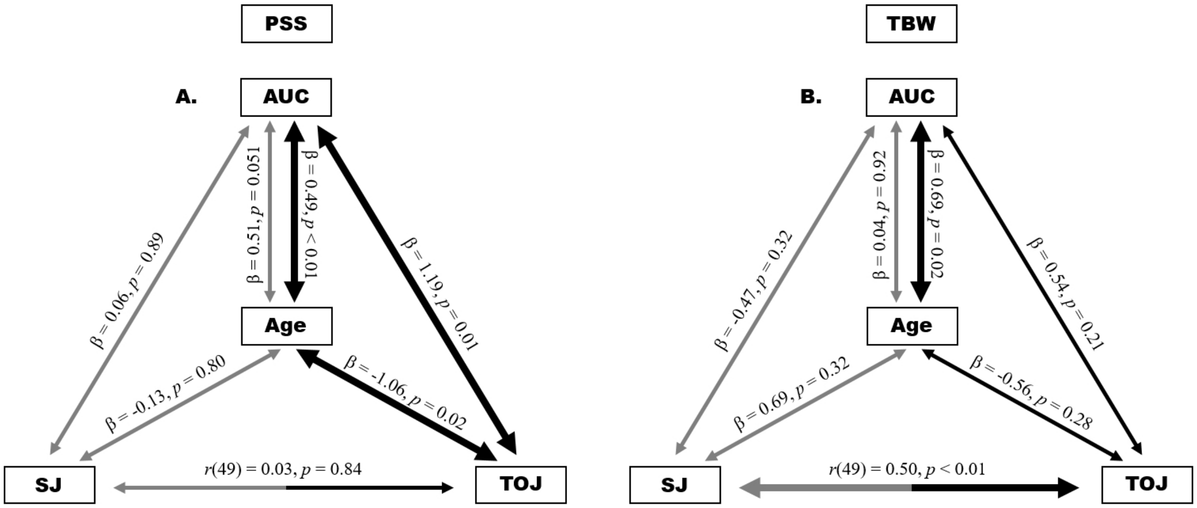


Figure 2.10: Significant relations found between PSS (a) and TBW (b) obtained from the SJ, TOJ, and AUC obtained from the RT task have been emphasized in this figure. Black lines represent the analyses conducted with the TOJ task while grey lines represent the analyses conducted with the SJ task. The regression analysis indicates that the average PSS estimates obtained from the TOJ task and age are significant predictors of AUC obtained from the RT task. Notice that such a relation does not exist for the SJ task. Age controlled partial correlations conducted between SJ and TOJ are reported here; note that the average TBWs from the two tasks are significantly correlated whereas the PSS estimates from the two tasks did not reach significance. Thicker lines indicate significant ($p \leq 0.05$) results from the regression and correlation analyses.

2.6 Discussion

The main objectives of this study were to identify whether an association exists between the race model violation (as assessed via AUC) and measures obtained from the SJ and TOJ tasks (i.e., PSS and TBW). We found a highly significant positive correlation between race model violation and the PSS from the TOJ task in young adults, however, there was no evidence of an association between the AUC and the PSS for the SJ task. Figure 2.8 clearly shows that within the young group, those who did not violate the race model were more likely to require the sound to be presented before light in order to perceive the two as being simultaneous for the TOJ task. Whereas those who required the light to be presented before sound in order to perceive simultaneity were more likely to violate the race model; however, for SJ, we found that all but one individual required the light to be presented prior to the sound in order to perceive simultaneity and yet approximately 60% violated the race model while the remaining 40% did not. This suggests that there is a discrepancy regarding the underlying mechanisms such that race model violation is related to audiovisual integration and perception for TOJ but not necessarily for SJ. This is in line with previous literature which suggests that SJ and TOJ are subserved via different neural mechanisms and therefore differ from one another [3, 126, 416, 36].

What do our results reveal regarding changes in multisensory processing among older adults? The very strong positive correlation that was found between AUC and PSS from the TOJ task for young adults was not found for the older group. This could be related to the fact that temporal order perception seems to be impaired with aging while simultaneity perception may be preserved [43]. Additionally, given that our current study as well as previous research [43, 36] have not found significant differences in PSS estimates between young and older adults, this could suggest that PSS may also be preserved with aging. Thus, based on current and previous literature, one may speculate that if a relation between PSS and AUC was to be found for the SJ task in young adults, such a relation may have been found to persist with aging and may have been present in the older group. However, this assertion must be specifically tested in larger studies with sufficient power. Of further interest is the fact that not only do we not find a relation between PSS estimates and AUC in older adults, we also find two non-integrators in the older adult group who demonstrate that some older adults fail to integrate audiovisual information. This is immensely interesting given that older adults tend to benefit more from multisensory integration compared to their young counterparts [255, 361, 132, 291, 106], but perhaps is not surprising given Mahoney and colleagues recent reports of differential multisensory integration patterns in aging [293, 294, 288, 295]. Recent research [349, 350, 212, 348] may provide further insight into the lack of "integration" that is observed in some of our older and young participants. These authors [349, 350, 212, 348] argue that the definition of multisensory integration that is commonly utilized in studies assessing the redundant signal effect (RSE) assumes that the race model needs to be violated in order to demonstrate integration when this is not necessarily the case [350]. However, a potential limitation of this proposed model is that it assumes that a ceiling effect (i.e., all participants respond with a high accuracy rate, making few anticipatory or late responses) will be achieved. Previous literature, however, indicates that a ceiling effect is not always achieved by older adults as they tend to show more early, anticipatory, or late responses [291, 292, 293, 294, 106]. In our current study, which uses a forced choice design, this is less of a concern as participants approached ceiling performance (i.e., less than 1% misses). Future studies should further investigate the relation between the current models being utilized as well as the proposed model, especially as the adaptation of a common model would allow for a more nuanced comparison not just between studies but also between different tasks (i.e., SJ, TOJ, RT).

SJ, TOJ, and RT tasks are three of the most common tasks utilized in the literature to assess multisensory integration, however, no other study has compared measures obtained from all three tasks (i.e., TBW, PSS, and RMI). We argue that understanding the relation between race model violation, as assessed via the RT task, and TBW and PSS, as assessed via SJ and TOJ tasks, can provide further information regarding MSI and the underlying mechanisms that may change with age. Interestingly, literature from the SJ and TOJ tasks argues that there is an impairment in older adult's ability to perceive the temporal order of events from multiple modalities due to a widening of the TBW (i.e., less precision) and a larger shift from true simultaneity (i.e., less accuracy; [370, 415, 416, 80, 81, 43]. Whereas studies testing RT argue that there is a greater enhancement in performance (i.e., faster RTs) for multimodal stimuli especially in the aging population [255, 361, 132, 291, 106]. This suggests that different decision-making processes may be at play for the two categories of tasks (i.e., SJ/TOJ vs. RT).

What might explain these similarities and differences in temporal metrics of multisensory processing? We know from early research that the superior colliculus is implicated in processing both unisensory (i.e., audio or visual) and multisensory (i.e., audiovisual) stimuli for simple RT tasks [310, 311, 237]. We also know from more recent research that the superior colliculus is involved in assessing temporal order of auditory and visual cues (in addition to the superior colliculus, the posterior parietal cortex, the superior temporal sulcus, and frontal cortices were also involved) [73, 167]. However, we find differences in cortical activation between simple RT and temporal order perception as well. From literature using simple RT tasks, we find evidence for early multisensory convergence in cortical areas that were previously considered as being ‘unisensory’ [168, 326, 409]. For example, using a simple RT task, Giard and Peronnet [168] found ERP activations representing multisensory processing as early as 40 ms post-stimulus presentation over the occipital region, indicating that multisensory integration takes place much earlier than expected. Forced-choice paradigms exploring synchrony and asynchrony perception on the other hand provide evidence for activation in higher order regions. For example, in a study conducted by Dhamala and colleagues [126], participants were asked to judge whether audiovisual stimuli were presented simultaneously, whether a sound was presented first, a light was presented first, or if they could not tell. They found that while the primary visual sensory cortices, parietal, and prefrontal cortices were involved in asynchrony perception, only the left temporal and parietal cortices, as well as the right frontal cortex and superior colliculus were involved in synchrony perception, with no activation of the visual cortex [3, 126]. Our results align with previous research indicating that although there is a relation between race model violation and asynchrony perception, such a relation may not exist for synchrony perception. The different neural mechanisms that underlie the behaviour observed for an RT task and synchrony perception may explain why no such relation is found with aging. It is important to note however, that some behavioural models posit that perception (as measured by TOJ) and automatic response (as measured by RT) may be subserved via similar internal mechanisms [75, 321, 445]. Our results provide further evidence for a relation between the PSS estimates obtained from the TOJ task and AUC from the RT task as found in young adults but also provide the critical information that this relation fails to exist in older adults. Such a relation between race model violation and PSS estimates indicates that the mechanisms that may be shared between perception (as measured through TOJ) and action (as measured through RT) in young adults change with age. Future research should assess these findings in greater depth; one method is to add multiple SOAs to the RT task in order to make the three tasks more similar.

It has previously been reported that a wider TBW is associated with slower RT [255, 370, 132], however we failed to find such an association. This lack of correlation may be explained by the design of the tasks as both the SJ and TOJ tasks consist of multiple SOAs while in the RT task audiovisual stimuli were presented only simultaneously. As mentioned previously, the addition of the same SOAs to the RT task may have increased the similarities between the paradigms and would have allowed for a more nuanced comparison. However, the aim of this study was to assess if a relation exists between the most commonly utilized paradigms, thus, the design of the tasks used reflects what is commonly found in the literature. Future studies should consider the inclusion of SOAs for the RT task in order to assess if the lack of relation found in our results changes with the design. Another explanation for the lack of relation between TBW and the AUC in older adults was the lack of a significantly wider TBW in older adults as compared to young adults. The predicted relation was precedented on the idea that not only would older adults violate the race model more so than young adults, but that they would also have significantly wider TBWs. It is important to note that this lack of difference between young and older adults has been seen before. Previously, with a similar sample size, Basharat and colleagues [36] yielded similar results where older adults exhibited wider TBWs compared to young adults but they were not statistically significant. Whereas Bedard and Barnett-Cowan [43] found that older adults had significantly wider TBWs compared to young adults on the TOJ task but not on the SJ task. Their findings suggest that simultaneity perception may be preserved with aging while temporal order perception is not. As the study conducted by Bedard and Barnett-Cowan [43] had a larger sample size and was well-powered, we speculate that the larger sample size contributed to the significant differences observed for the TBW values between the two groups.

In agreement with previous literature, the mean analysis of the response time data indicates that older adults had significantly longer RTs compared to young adults regardless of modality and that providing stimuli from multiple modalities significantly decreased response time [255, 361, 291]. Furthermore, providing evidence for our hypothesis, the results showed that although both young and older groups violated the race model, older adults were more likely to do so. Various theories have been proposed to explain such improvements in multisensory integration in the elderly. One possible explanation is the principle of inverse effectiveness; it states that reduced sensitivity in the individual sensory systems (i.e., decreased visual acuity [431], increased auditory thresholds [273])combined with age-related alterations in cognitive processing (i.e., decline in executive function, working memory, and attention [150, 149]) increases the magnitude of multisensory enhancement [192, 161]. Mozolic and colleagues [330] have provided another explanation for the improvement observed in the older group; they state that older adults do not adequately filter sensory noise and hence are more prone to distractions compared to young adults. However, as the background sensory information becomes more relevant, older adults benefit from enhanced processing of such information. It is clear that the neural networks involved in multisensory integration change with age and these alterations directly impact multisensory processing in the aging population. Using magnetoencephalography, Diaconescu and colleagues [127] compared neural activity of young and older adults to unimodal and multimodal audiovisual stimuli and found that young adults showed increased activity in sensory-specific regions after multimodal stimuli were presented whereas older adults showed activity in the inferior parietal and medial prefrontal areas. These results provide evidence for posterior to anterior shift with aging (PASA) indicating that older adults engage frontal brain areas to a greater extent than young adults in order to compensate for impaired function in other brain areas [186, 112]. Age-related changes clearly have large implications on multisensory processing and this study has provided further evidence that older adults benefit more from multimodal cues.

Given that poor multisensory processing has been correlated with speech comprehension deficits [287, 417], an inability to dissociate from irrelevant information [497], and poor driving performance [381], measures of MSI present an easy assessment tool to be utilized in the clinical setting. However, prior to the inclusion of these tasks in the clinic, it is important for researchers to understand the relation between them. Our results indicate that there is a relation between the point at which participants perceive simultaneity and the likelihood of violating the race model which may change with age. Knowing this information suggests that the 'impairment' and the 'enhancements' observed here may be subserved by similar mechanisms, but further research is required to untangle why these differences arise as we age. One explanation for the differences observed between young and older adults may be related to a general cognitive decline due to structural changes and loss of brain mass [330]. However, if general cognitive decline could completely explain the differences in performance between the two groups, older adults would consistently perform poorly regardless of whether unimodal or multimodal cues were presented. As indicated by our results and previous research, older adults demonstrate greater multisensory enhancement from bimodal cues compared to young adults and thus age-related changes cannot fully be explained by general cognitive slowing [361]. Another explanation for why such differences arise may be associated with age-related changes in gamma-aminobutyric acid (GABA), the principal inhibitory neurotransmitter in the CNS [457, 166, 372]. Previous research has found a reduction of approximately 5% in GABA concentration per decade of aging after adolescence in the frontal cortex leading to a decline in inhibitory signals [166]. This reduction in GABA may be associated with an inability to inhibit binding of erroneous cues, thereby resulting in an increased inability to determine temporal order of stimuli. In addition to between group differences, our results also indicate a large variation in multisensory perception within each group. In the future, this inter-individual variability can be further investigated through genetic factors which may contribute to the heterogeneity of the results and may explain the differences observed in young and older adults.

2.7 Conclusion

Here, we have demonstrated that older adults are impaired in judging temporal order and simultaneity, due to an extended TBW. However, older adults also exhibit greater enhancement in performance on the RT task as indicated by a higher likelihood of race model violation. Correlations conducted to assess the relation between the three tasks reveal that the likelihood of violating the race model is associated with the point at which simultaneity is perceived but only for the TOJ task. No such relation was found in the older group. By utilizing the RT, SJ, and TOJ tasks, our work provides further evidence that the underlying mechanisms that subserve these tasks change with age. Future studies should attempt to determine the underlying neural mechanisms that subserve these three tasks and to develop training paradigms that increase the accuracy and precision with which the elderly bind multisensory information in order to reduce errors in temporal order and simultaneity judgments.

Chapter 3

Assessing the effects of exercise, cognitive demand, and rest on audiovisual multisensory processing in older adults: a pilot study

Under review: Basharat A, and Barnett-Cowan M. Assessing the effects of exercise, cognitive demand, and rest on audiovisual multisensory processing in older adults: a pilot study. Multisensory Research (MSR-1686R1; [34]).

3.1 Abstract

A single bout of aerobic exercise is related to positive changes in higher-order cognitive function among older adults, however, the impact of aerobic exercise on multisensory processing remains unclear. Here we assessed the effects of a single bout of aerobic exercise on commonly utilized tasks that measure audiovisual multisensory processing: response time (RT), simultaneity judgment (SJ), and temporal order judgment (TOJ) in a pilot study. To our knowledge this is the first effort to investigate the effects of three well-controlled intervention conditions on multisensory processing: resting, completing a cognitively demanding task, and performing aerobic exercise for 20 minutes. Our results indicate that the window of time within which stimuli from different modalities are integrated and perceived as simultaneous (temporal binding window; TBW) is malleable and changes after each intervention condition for both the SJ and TOJ tasks. Specifically, the TBW consistently became narrower post-exercise while consistently increasing in width post-rest, suggesting that aerobic exercise may improve temporal perception precision via broad neural changes rather than targeting the specific networks that subserve either the SJ or TOJ tasks individually. The results from the RT task further support our findings of malleability of the multisensory processing system, as changes in performance, as assessed through cumulative probability models, were observed after each intervention condition. An increase in

integration (i.e., greater magnitude of multisensory effect) however, was only found after a single bout of aerobic exercise. Overall, our results indicate that exercise uniquely affects the central nervous system and may broadly affect multisensory processing.

3.2 Introduction

Humans are constantly presented with information regarding our external environment that must be transduced and processed by different sensory modalities. The integration of such information is necessary not only for the formation of a coherent representation of the world but also for perceptual, motor, and higher-order cognitive systems to function and adapt. There are multiple factors that the central nervous system (CNS) must take into consideration when determining whether information should be integrated or segregated and one such factor is the relative timing of events. Optimal integration from different sensory modalities occurs when signals from these modalities are in close temporal register [444] and their temporal structures are correlated [359]. Researchers have found that the aging process can impact how the CNS integrates multimodal information and many have turned towards better understanding this relation, especially as the aging population continues to increase in Canada and worldwide. It is expected that the aging population will comprise approximately 22% - 28% of the Canadian population and approximately 16% of the world population by 2050 [342, 42].

Various tasks have been utilized in the literature to investigate the differences in multisensory processes in younger and older adults including a simple response time task (RT) [255, 361, 132, 291, 106] as well as the simultaneity judgment (SJ) and the temporal order judgment (TOJ) tasks [416, 415, 43, 279, 36]. As indicated in the prior chapters, older adults, as compared to younger adults, are more likely to integrate and thus benefit more from the presentation of multimodal as compared to unimodal cues (i.e., RT facilitation) [255, 361, 132, 291, 106]. The magnitude of such facilitation in integration has been found to be related to cognitive function [290], balance [293, 288, 295], and habitual physical activity [294]. On the contrary, research using the SJ, TOJ, and various other temporal perception tasks indicate a deficit in temporal order perception as it reveals that older adults are more likely to integrate and perceive temporally disparate information from different sensory modalities as being simultaneous [43, 36, 37], which, as mentioned previously, can effect everyday functions and has been associated with decreased speech comprehension [287, 417], poor driving [381], and increased susceptibility to falls [416]. Given the challenges associated with multisensory integration (MSI) in the aging population, some researchers have turned towards designing rehabilitative interventions that may help to improve the speed, accuracy, and precision with which older adults integrate multimodal information and may thus improve the quality of life of this population.

While there are many training paradigms focused on improving cognitive and perceptual function, only few studies have focused primarily at improving multisensory processing. Training paradigms focused on improving multisensory processing, performed in a controlled environment typically led to improvements in performance on the trained task, however, there have also been some instances of transfer effects of training on one task leading to improvements in a different task when feedback was provided in both young and older adults [375, 377, 376, 418, 446, 353]. Such research using perceptual training paradigms shows that not only is multisensory integration a malleable process, but that the effects of training persist for at least a week [375] and that the effects of training can affect performance on other perceptual tasks that are not directly trained [418, 446]. Although promising, such training paradigms require participants to complete training in a controlled lab setting over long periods of time. As such, the applicability of such rehabilitation paradigms is limited; thus, adopting strategies that utilize training paradigms which can be performed at home or outside of a lab setting should be prioritized.

As adults age, so too do their auditory, visual, somatosensory, and vestibular systems. Indeed, many researchers have demonstrated a robust association between sensory and cognitive function where sensory acuities reliably explain large amounts of variance in age-related cognitive decline [271, 25, 401, 402, 16]. Thus, sensory degradation can not only affect how the CNS integrates and responds to sensory information, but can also affect the amount of resources available for cognitive functioning and complex motor activity [294]. A growing body of literature indicates that physical activity is beneficial for brain health and cognitive function throughout the lifespan [96, 424, 316, 203, 105], and indeed protects the brain from the effects of aging by enhancing mental resources [49], by reducing depression, anxiety, and chronic stress as well as by improving self-efficacy [436]. Physical activity (PA), which refers to any bodily movement that is produced by the skeletal muscles and results in energy expenditure, is recommended for all age groups and genders and is a key predictor of healthy aging [110]. Note that exercise is a subset of physical activity as it is a planned, structured, and repetitive process that aims to maintain and improve physical fitness [77]. The vast body of literature relating to PA indicates numerous physical and psychological health benefits of PA for older adults including improvements in cognition, working memory, mood, functional abilities, quality of life, and maintenance of independence [86, 459, 333]. As such, PA has been recognized as a valuable strategy to promote healthy aging, as well as a therapeutic and preventative strategy for older adults living with mild cognitive impairment (MCI) and dementia [118, 201, 56]. The World Health Organization (WHO), Canadian Society for Exercise Physiology (CSEP), as well as the American College of Sport Medicine (ACSM) recommend that all healthy adults (young and older) should participate in moderate aerobic activity for 150 minutes per week or 75 minutes of vigorous aerobic activity per week or a combination of both [364, 158, 347, 389]. However, despite strong evidence supporting broad physical and cognitive benefits of physical activity, older adults tend to be the least physically active population with very low percentages of older adults being sufficiently active [467].

Although much of the literature investigating the link between exercise and cognitive function has focused on chronic exercise, literature from single-bouts of aerobic exercise is also promising. One of the most researched mechanisms attributed to cognitive function enhancement after a single bout of physical activity is arousal [250, 84, 371]. Changes in heart rate, skin conductance, and changes in plasma catecholamines are typically utilized in human participants to measure arousal, which is associated with the activation of the sympathetic nervous system [371, 351]. Behavioural arousal is controlled by a group of brainstem nuclei, sometimes referred to as the ascending arousal system, that consist of neuronal cell bodies which project axons to various brain regions and influence CNS activity by secreting modulatory neurotransmitters (NT) [99, 133]. Indeed, nonhuman animal model studies have found increases in modulatory NT concentration during and after exercise in various regions. A single session of aerobic exercise influences norepinephrine concentration or metabolism in the parietal [245] and frontal cortex [357, 358], as well as in the anterior hypothalamus [510, 195], and the striatum [306] but not in the hippocampus [173]. Aerobic exercise influences dopamine concentration or metabolism in the striatum [306, 196, 197] as well as in the anterior hypothalamus [510, 195, 194], and the hippocampus [173]. Finally, aerobic exercise influences serotonin concentration or metabolism in the parietal [245] and frontal cortex [176] and the hippocampus [176, 305, 177] but not the in anterior hypothalamus [510, 195, 194]. Of interest to this dissertation are the changes in norepinephrine, serotonin, and acetylcholine in the parietal cortex, a region that is thought to play a crucial role in MSI [245, 3, 327, 229]. Additional physiological changes that are thought to induce the effects related to exercise include increased production and concentration of neurotrophic factors including brain-derived neurotrophic factor (BDNF), insulin-like growth factor (IGF-1), and vascular endothelial growth factor (VEGF) which play a neuromodulatory role in promoting and maintaining synaptic connectivity, learning and memory formation [105, 84, 371].

As there may be common underlying neural mechanisms that are responsible for age-related declines in sensory, cognitive, and motor function (i.e., common cause hypothesis) [271, 25], physical activity, including a single bout of aerobic exercise, may positively impact integration from multimodal cues in addition to improving higher-order cognitive function [96, 203, 84, 303, 371]. Indeed, Mahoney and colleagues [294] showed a relation between the amount of physical activity an individual engaged in over a month and the amount of RT facilitation that was observed on multimodal compared to unimodal stimuli. In their study [294], 147 older participants completed a visuosomatosensory RT task where they were asked to respond to the unimodal (asterisk on the screen or electrical pulse) and multimodal (combined asterisk and electrical pulse) stimuli as quickly as possible. They found that older adults who reported less engagement in physical activity showed a larger magnitude of multimodal facilitation compared to those who reported a higher degree of participation in physical activity. These results however were somewhat counter-intuitive, especially given that previous research has shown that physical activity is beneficial for cognitive performance in physically fit individuals [84, 96], yet Mahoney and colleagues [294] found that those who were less physically active tended to benefit more from multisensory integration. Note that those who benefited more from the presentation of the multimodal cues (i.e., those who reported less PA) showed non-significant faster response times to the multimodal and the unimodal somatosensory conditions. The response time profiles differed primarily for the unisensory visual condition, where those who benefited more from sensory integration had significantly longer response times to the visual cues as compared to those who benefited less (i.e., those who reported more PA). However, there was no statistically significant difference between the two groups. To further assess this possible relation, here, we conducted an exploratory analysis to determine whether a similar relation exists between the amount of physical activity reported and the magnitude of RT facilitation.

Few studies have explored the direct effect of exercise on perception and those that have assessed this relationship have focused on the visual modality [113, 114, 251], with one study recently conducted that focused primarily on audiovisual modalities [351]. Davranche and Audiffren [113] (n = 16) as well as Davranche and Pichon [114] (n = 7) showed that critical flicker fusion (CFF) is improved with aerobic exercise. Furthermore, Lambourne and colleagues [251] (n = 19) found that CFF also improved during a 40-minute exercise session and returned to baseline within 30 minutes of exercise cessation. The work done by Lambroune and colleagues [251] along with the studies mentioned above suggest that enhancements in perceptual processes may be related to exercise induced arousal in younger adults. In a more recent study conducted by O'Brien and colleagues [351], healthy older adults (n = 58) completed the audiovisual sound induced flash illusion (SIFI) before and after an exercise session and found that 60 to 80 minutes of exercise improved sensitivity to the perceptual task but only if participants completed "open skill" exercises (i.e., activities that are unpredictable and demanding such as tennis and badminton; n = 18) compared to the control group (n = 21). They did not find such an effect for participants who performed "closed skill" exercises (i.e., sports that are more predictable such as swimming and running; n = 19). This however may be related to a lack of control over the intensity of the exercise sessions, as participants completed the physical activity on their own accord and returned to the lab to be tested once they had completed their exercise session. Furthermore, participants in the control group played card games, which requires the involvement of cognitive function that may also be utilized in "closed skill" exercise; this may partially explain the lack of an effect found for the "closed exercise" group. Nevertheless, the existing literature indicates that a single bout of aerobic exercise can impact cognitive and perceptual processes and potentially result in improved multisensory processing. Thus, we aimed to conduct a pilot study that can be used by future researchers to determine the feasibility of designing and implementing an aerobic exercise study to guide their work. Here, we predicted that a single bout of aerobic exercise would improve audiovisual multisensory processing as measured through the RT, SJ, and TOJ tasks (i.e., narrower TBW, point of subjective simultaneity (PSS) closer to true simultaneity, and increased RT facilitation as assessed through the area under the curve; AUC). Furthermore, we explored the effects of our control conditions including completion of a cognitively demanding task and reading on the RT, SJ, and TOJ tasks to determine how they impact perception and multisensory processing. Additionally, there is evidence to suggest that chronic exercise habits impact integration processes and thus we conducted an exploratory analysis to investigate this relation with the hypothesis that partaking in physical activity more frequently will be associated with better integration.

A repeated measures, within factors power analysis was conducted to determine the sample size required to reach a small to moderate effect with the population of interest (older adults). This analysis revealed that for 1 group of participants, where data was collected across three sessions, with an alpha of 0.05, and a power of 0.80, we would need to collect data from 27 to 161 participants for a medium (η^2 = 0.01) or small (η^2 = 0.06) effect, respectively [371, 249]. We were however restricted, due to the pandemic, with respect to participant recruitment; initially we recruited 31 participants and collected data from 14 of the eligible participants, alas, we were able to include data from only 11 participants just prior to not having access to this population, as the remaining participants either did not meet the inclusion criteria for our study ($n = 17$) or the quality of their data was compromised and could not be included ($n = 3$).

3.3 Materials and Methods

3.3.1 Participants

Participants (n= 31) were recruited from the Waterloo Research in Aging Participant Pool (WRAP; older adults; OA). The WRAP program ensures that all recruited participants are healthy older adults over the age of 60 years with no significant medical concerns (i.e., Alzheimer's disease, Parkinson's disease, stroke, epilepsy, etc.) via self-reported medical history and we further verified health status by screening for mild cognitive impairment and dementia using the Montreal Cognitive Assessment (MoCA; A score $\geq$ 26/30 would screen out most people with MCI) [334] and by reviewing self-reported information acquired from medical history questionnaires. In addition to self-reported declaration of normal or corrected-to-normal vision and hearing, visual and auditory acuity tests were conducted using the Freiburg Visual Acuity and Contrast Test (FrACT; [22]) and the UHear application [455, 59] to ensure that all participants could perceive the auditory and visual stimuli as suprathreshold.

Male and female participants between the ages of 60 and 80 years were included in this study ($n = 31$; females = 19, mean age = 71.53, s.e. = 0.82). All participants were required to have self-declared normal or corrected-to-normal vision and hearing and normal cognition. Prior to study inclusion, participants completed a self-reported clinical information form where they indicated (yes/no) if they had normal or corrected-to-normal vision [do you have normal or corrected-to-normal vision (yes or no)], if they had normal or corrected-to-normal hearing [do you have normal or corrected-to-normal hearing (yes or no)], and if they had normal cognition [do you have any neurological conditions including stroke, epilepsy, Parkinson's disease, cognitive impairment, or dementia (yes or no)]. If participants answered no to any of the above questions, they were subsequently excluded from the pilot study. Furthermore, participants were required to complete an auditory acuity, visual acuity, and cognitive (MoCA) test in order to participate. Participants were required to have visual acuity that was better or equal to 20/32 (or Logarithm of the Minimum Angle of Resolution (LogMAR) score of 0.2 or lower) in both eyes as measured through the Freiburg Visual Acuity & Contrast Test (FrACT; Bach, 1996; mean score right eye = 0.131, s.e. = 0.047; mean score left eye = 0.12, s.e. = 0.047; mean score both eyes = -0.017, s.e. = 0.036). Additionally, hearing was tested using the UHear application in a sound-proof booth, and following the definition of the application for normal hearing, individuals who were unable to hear a 2000 Hertz (Hz) tone at 25 decibels (dB) in both ears were excluded. After exclusion, including the MoCA assessment (mean = 28.89, s.e. = 0.42), the eligible sample consisted of 14 older adults (females = 8, mean age = 69.29, s.e. = 1.06). Participants were also screened for their ability to perform physical activity within the lab using the Get Active Questionnaire (GAQ; average minutes/week = 200.79, s.e. =

30.56) and the Physical Activity Scale for the Elderly (PASE; mean score = 148.33, s.e. = 17.67). The GAQ and PASE also provide self-reported measures of each participant's habitual exercise habits. In appreciation of their participation, participants received a $10 per hour remuneration. This study was approved by the University of Waterloo's Human Research Ethics Committee in accordance with the Declaration of Helsinki, and written informed consent was obtained from all participants before participation.

3.3.2 Study Design

Participants completed three sessions in the lab, each including a different intervention (exercise, cognitive task, or rest) in a randomized order; the randomization function in Microsoft Excel was utilized to ensure that the sessions were completed in a randomized order by each participant. The sessions were held in the mornings and in order to reduce learning and training effects, the sessions were each held approximately one week apart. Participants were asked to refrain from caffeine consumption if they didn't normally consume caffeine in the morning and from engaging in any physical activity they wouldn't normally engage in, the morning of each session.

3.3.3 Intervention Sessions

The experimental measures (SJ, TOJ, RT) were consistent across the three sessions and only the intervention (exercise, cognitive task, or rest) differed. In the first session, participants were required to provide written informed consent and had their eligibility confirmed. After this, participants completed the PASE and the GAQ to assess their baseline physical activity status. Participants were then asked to complete the SJ, TOJ, and RT tasks in a randomized order before and after they completed the intervention. Each intervention was approximately 20 minutes long. In the exercise intervention condition, participants completed a 3-minute warm-up, 20 minutes of cycling at a moderate intensity (40-60% Heart Rate Reserve; HRR; Eq. 1, 2, 3, and 4), and a 3-minute cool-down on a recumbent bike. Participants were asked to wear a Polar Heart Rate monitor in order to obtain their resting heart rate and to monitor their heart rate throughout the exercise session. Ratings of perceived exertion (RPE) were recorded every 60 seconds using the Borg's 20-point scale [55] to ensure that the participants' perceived exertion fell within the range of moderate exertion (RPE of 12-15). The effort level and peddling rate were modified accordingly if the RPE reported by the participant did not fall within the desired range (12-15).

$$Eq.1 : HRR = (Age - predictedHR_{max} - HR_{rest}) \tag{3.1}$$

Eq. 1 Calculation for Heart Rate Reserve (HRR) where the formula "220 – HR (heart rate)" was used to estimate the age-predicted HR_{max} for each participant. Note, the resting heart rate [HR_{rest}] was obtained using the Polar Heart Rate monitor prior to exercise.

$$Eq.2 : \%HRR = (desiredintensityxHRR) \tag{3.2}$$

Eq. 2 Calculation of exercise intensity as % HRR. As our target intensity was between 40% - 60% HRR, this calculation was performed twice, once for the lower limit of the desired intensity and once for the upper limit of the desired intensity range, for each participant.

$$Eq.3 : THR = [(\%HRR) + HR_{rest}] \tag{3.3}$$

Eq 3. Calculation of the Target Heart Rate (THR). This calculation, like the calculation above was calculated twice for both the 40% and 60% HR.

$$Eq.4 : THR = [(0.4(Age - predictedHR_{max} - HR_{rest})) + HR_{rest}] \tag{3.4}$$

to

$$[(0.6(Age - predictedHR_{max} - HR_{rest})) + HR_{rest}] \tag{3.5}$$

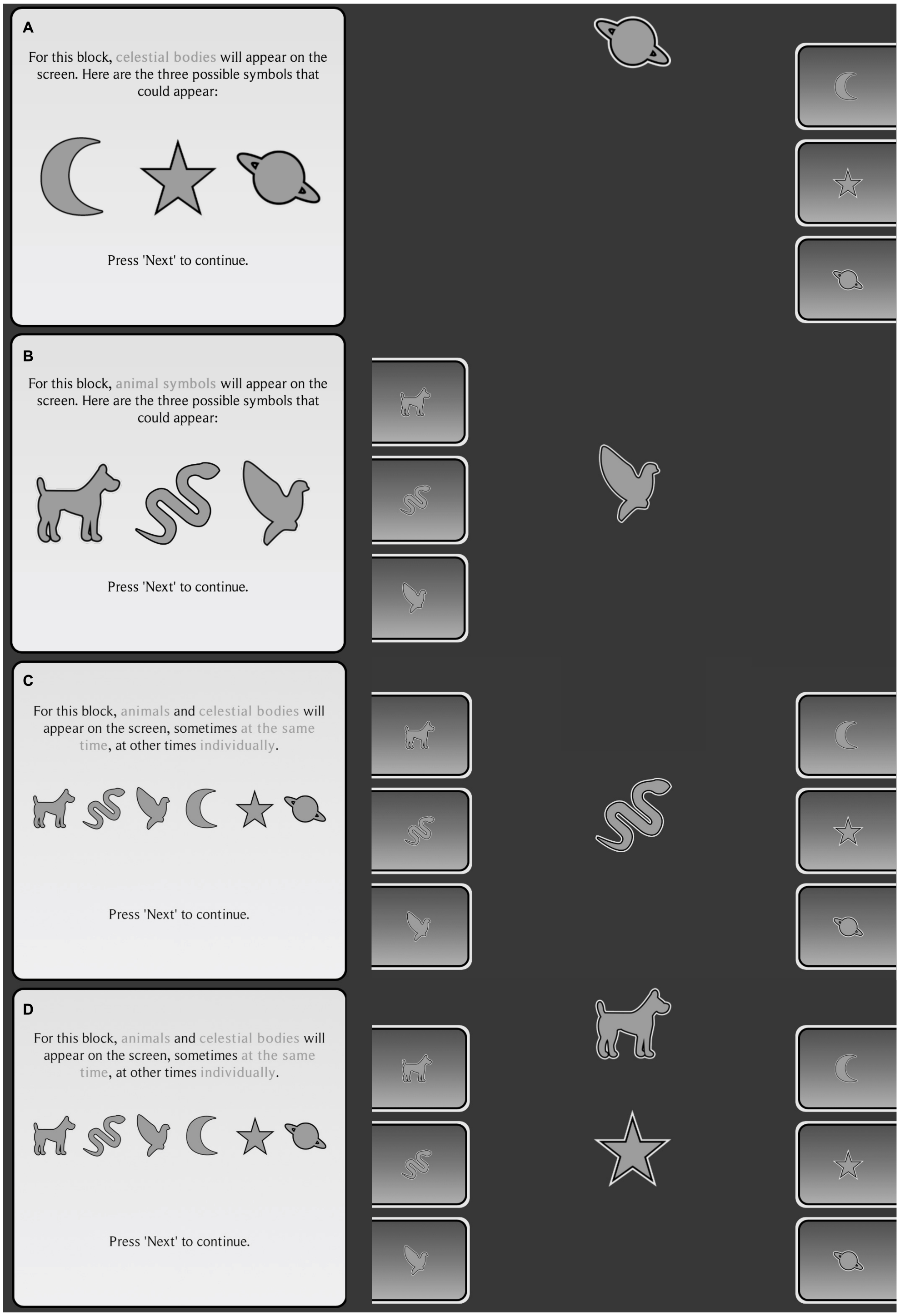
Eq. 4 and 5 The combination of the equations above to showcase the calculations conducted for moderate intensity of 40% and 60% HRR.

In the cognitive task condition, participants completed a dual-task paradigm for 20 minutes where they were asked to identify which celestial body (planet, star, or sun) and/or animal (snake, dog, or bird) appeared in the centre of the screen. The paradigm involved three different trial types; single-pure (SP), single-mixed (SM), and dual-mixed (DM) [47, 48, 46, 209]. In the SP trials, a single stimulus consisting of either an animal or a celestial body was presented and participants were asked to match the image presented in the centre of the screen to the corresponding animal (always presented on the left side of the screen) or celestial body (always presented on the right side of the screen). In the SM trials, both an animal and celestial bodies appeared on the left and right side of the screen, however, only one image appeared in the centre of the screen that participants were asked to match to its corresponding image on either the left or right side of the screen. In the DM condition, two stimuli were presented at the same time in the centre of the screen (one animal and one celestial body; see Figure 3.1). Participants were asked to respond as quickly and accurately as possible to both the stimuli without prioritizing responding to either animal or celestial body images. They were also asked to avoid grouping their answers (e.g., selecting images on the right and left side of the screen at the same time for the DM task), as that would suggest that they waited to recognize both the stimuli prior to making their response. The task was completed on an ipad and each stimulus was presented for 2750 ms, and the next trial appeared regardless of whether a response was recorded or not [209].

In the rest condition, participants read a chapter titled ‘Aging: the Wise Way’ from a book titled ‘Spark: the Revolutionary New Science of Exercise and the Brain’ for 20 minutes.

3.3.4 Measures

Similar to the methods mentioned in chapter 2, each participant completed three experimental tasks while seated in front of a 23.6-inch ViewSonic V3D245 computer monitor



For this block, celestial bodies will appear on the screen. Here are the three possible symbols that could appear:

Press 'Next' to continue.

For this block, animal symbols will appear on the screen. Here are the three possible symbols that could appear:

Press 'Next' to continue.

For this block, animals and celestial bodies will appear on the screen, sometimes at the same time, at other times individually.

Press 'Next' to continue.

For this block, animals and celestial bodies will appear on the screen, sometimes at the same time, at other times individually.

Press 'Next' to continue.

Figure 3.1: Screenshots of the Cognitive task. Panel A and B represent the single-pure (SP) trials, panel C represents single-mixed (SM) trials, and panel D represents dual-mixed (DM) trials. Participants were asked to respond as quickly and accurately as possible by pressing the images on the left and right side of the iPad screen that matched with the images presented in the center of the screen. See text for further details.

(resolution 1920 x 1080, 120 Hz) in a sound-proof booth with his/her head stabilized on a chin rest before and after each intervention. Visual stimuli were presented on the monitor at a viewing distance of 57cm, in the form of white circles (0.4°). Auditory stimuli were emitted through two speakers (Altec Lansing Multimedia computer speaker system, ACS95W) adjacent to the monitor such that they were 66 cm apart. A Macbook Pro (OS 10.9 Mavericks) that resided outside the booth was used to run the tasks. VPixx Technologies, ProPixx hardware, and DataPixx software version 3.01 was utilized for this experimental procedure to ensure the synchrony of the audio and visual stimuli (depending on task and condition) with <1 millisecond (ms) accuracy. Participants were able to record their response for each trial by using the RESPONSEPixx handheld 5-button response box.

3.3.5 Procedure

Participants completed the SJ, TOJ, and RT tasks in a randomized order. For all tasks, a central fixation cross (visual angle = 0.5°) was presented on the screen, and participants were instructed to fixate on this cross throughout the experimental procedure. For the SJ and TOJ tasks, response from the participant initiated the next trial. In order to reduce temporal predictability, each trial began with the stimulus being presented after a delay of 1000 – 3000 ms. Participants were presented practice trials prior to commencement of each of the experimental tasks. Test performance during the actual experiment was monitored on the Macbook pro that resided outside the booth.

Simultaneity Judgement

In the SJ task, participants were instructed to report, using different response buttons, whether they perceived the auditory and visual stimuli as occurring simultaneously (right button) or not (left button). Participants were explicitly told to respond as accurately as possible as opposed to responding quickly. Visual stimuli were presented in the form of a 0.4° white circle [49.3 Candela per meter squared (cd/m^2)] against a black background (0.3 cd/m^2), which appeared 2° below the fixation cross for 17 ms. They were either preceded or followed by an auditory beep (1850 Hz, 7 ms, 71.7 dB) at the following stimulus onset asynchronies (SOAs): 0, 25, 50, 100, 150, 200, 300 ms. Ten trials were presented in a randomized order for each condition for a total of 130 trials (see Figure 3.2).

Temporal Order Judgement

The experimental design of the TOJ task was identical to the SJ task with the exception of the task instructions (see Figure 3.2). Here, participants were asked to report, using the response buttons, whether they perceived the visual (right button) or the auditory (left button) stimulus as appearing first. Again, participants were explicitly told to respond as accurately as possible as opposed to responding quickly.

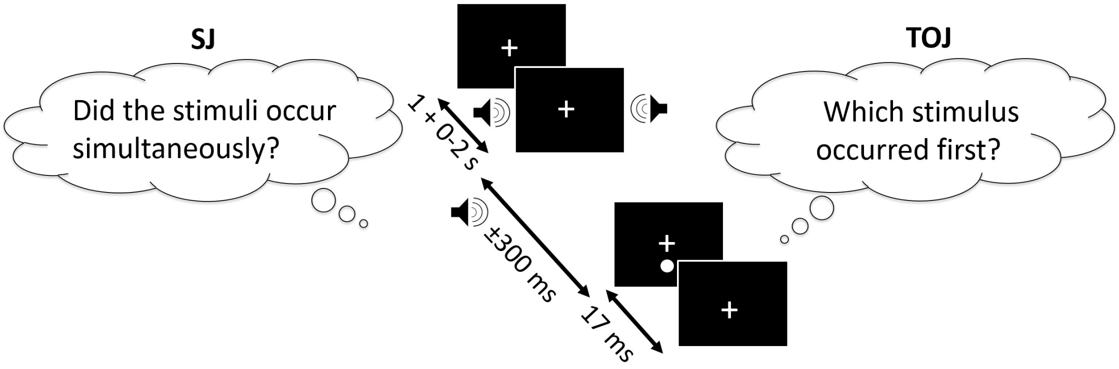


Figure 3.2: SJ task (left) and the TOJ task (right), presented with the SOAs of 0, ±25, ±50, ±100, ±150, ±200, ±300 ms (-ve = sound appeared before light). In both tasks, the first stimulus of the audiovisual pair can appear 1-3 sec following the fixation cross and the second stimulus appears between 0 – 300 ms after the first stimulus. The figure depicts the auditory stimulus (i.e., beep) as presented before the visual stimulus (i.e., flash). Note, that the experimental design for the SJ and TOJ is identical, however the instructions vary by task.

Reaction Time Task

In the RT task, participants were told that they would either see a flash of light, hear a beep, or a combination of the two. Participants were instructed to press the response button as soon as they detected any one of the three experimental conditions: unisensory visual (V), unisensory auditory (A), or multisensory audiovisual (AV). In order to maintain consistency across all three tasks, the exact same stimuli and stimuli durations were employed, however, for this task all AV stimuli were only presented simultaneously. Each stimulus type was presented 100 times in a random order (300 trials in total). Trials were divided into 2 blocks and participants were given a break in between blocks to reduce fatigue (see Figure 3.3).

3.4 Statistical Analysis

Note, that the same analysis procedures were utilized in this chapter as the chapter before. The primary difference will be the impact of the intervention (e.g., cognitive task, exercise, rest) on the parameters obtained from the SJ, TOJ, and RT tasks (a pre- and post-intervention comparison).

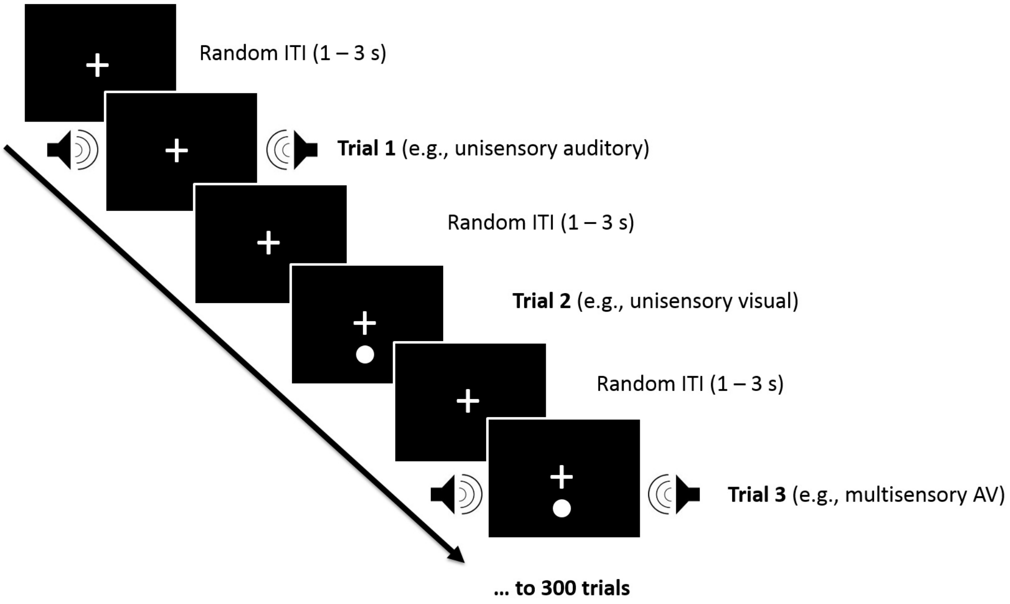


Figure 3.3: Participants were presented with unimodal [auditory (A) or visual (V)] or bimodal [audiovisual (AV)] stimuli and were asked to make speeded responses to all stimuli, regardless of sensory modality by pressing a RESPONSEPixx button. Two blocks of A, V, and AV stimuli (150 trials per block) were randomly presented with random inter-trial-intervals (ITIs) of 1 – 3 s.

3.4.1 Simultaneity and Temporal Order Judgement Tasks

The same methods of analyses from chapter 2 were followed in this chapter to obtain psychometric parameters. To estimate the accuracy (PSS values) and the precision (TBW) with which participants made their judgments for SJ and TOJ tasks, psychometric functions were fitted to each participant's responses as a function of SOA using SigmaPlot version 12.5. Each task was analyzed individually for each participant, with participant data fit to both Gaussian (for the SJ task; Eq. 6) and logistic (for the TOJ task; Eq. 7) functions:

$$Eq.6 : y = a \cdot e^{(-0.5((x-x\emptyset)/b)^2)} \tag{3.6}$$

Where a is the amplitude, *xø* is the PSS and *b* is the standard deviation.

$$Eq.7 : y = 100/(1+e^{(-(x-x\emptyset)/b)})\% \tag{3.7}$$

Where a is fixed to 1, xø is the PSS and b is the standard deviation.

The best fit parameters corresponding with the PSS and TBW were identified for each participant separately, and those participants whose data was poorly estimated were excluded from further analysis ($r^2 \leq 0.2; n = 3$).

As we were interested in the relationships between TBWs obtained from the two tasks and not their absolute size, we chose to analyze the b values (i.e., standard deviation) of these psychometric functions as a proxy for the size of the TBW to avoid discrepancies in the literature when defining the absolute size of the TBW.

Using a within subject design, a 2 (task: SJ or TOJ) x 2 (time: pre- versus post-intervention) x 3 (intervention: exercise or cognitive task or rest) repeated measures (RM) ANOVA was conducted to assess the impact of task, time, and intervention type for the TBW and PSS. Mauchley's test of sphericity was conducted, and if the dependent variables were not proportional to the identity matrix, the Greenhouse-Geisser adjustment was used. Planned pairwise comparisons were made to assess differences between the tasks and intervention.

3.4.2 Response Time Task

Error analysis, outlier removal, and mean RT analysis

As previously mentioned, participants responded to 300 trials in total (100 per condition). Data trimming procedures were not applied (see [178, 179, 288, 295, 289, 37]; however responses faster than 100 ms, slow responses (>1500 ms), and misses (not registered by the program) were set to infinity rather than excluded (see [289] for a RMI tutorial and [37] where this method of data trimming was recently used).

Mean RT Analysis

A 2 (time: pre- versus post-intervention) x 3 (modality: auditory, visual, or audiovisual) x 3 (intervention: exercise or cognitive task or rest) RM ANOVA was conducted to determine whether time, modality, or type of intervention significantly affected RT. Mauchly's test of sphericity was conducted and the Greenhouse-Geisser was used if necessary. Planned pairwise comparisons were also made to assess the differences between time, modality, and interventions.

Test of the Race Model

For the RT task utilized in our pilot study, we presented participants with auditory and visual cues either separately or concurrently and asked participants to respond as quickly as possible, regardless of the stimulus. The presentation of simultaneous signals provides redundant information to the CNS, which typically yield faster response times (i.e., RT facilitation) as compared to their unimodal counterparts. To understand why this may be the case, we utilized the race model inequality (RMI), as proposed by Miller [318], to test whether a 'race' was occurring between the pair of multimodal stimuli wherein the winner's time determined the observed response time [379] or if integration, rather than separate processing of the two stimuli was taking place. As the race model describes separate, context-invariant (i.e., processing time of one signal is unaffected by the presentation of another signal) processing of redundant signals, a violation of the RMI suggests that either the race model is violated or that the context invariant assumption is not supported. Thus, a violation has been interpreted to indicate that redundant sensory cues were combined by the CNS to elicit RT facilitation. Given that RMI may be violated at any latency, RMI has typically been tested using t-tests at different time points and the race model has been rejected if the test is significant for at least one of the tested time points; the utilization of multiple t-tests, however, results in increased risk of Type I error. Therefore, permutation tests have been suggested by Gondan and Minakata [179] to control for this error. Gondan and Minakata [179] argue that if the permutation is significant, it indicates that either the race model is wrong, the context invariance assumption is indefensible, or both. In this study, RMI was first tested over the fastest quartile (0 - 25%) of responses using Gondan's permutation (see Table 3.1; [178, 179]). More recently, however, it has been argued that the magnitude of the race model violation (i.e., AUC) obtained from the RMI can provide further information regarding age-related alterations of multisensory integration [288, 289].

Condition	**Before Intervention**	**After Intervention**
Rest	$t_{max} = 5.37$, $t_{crit} = 2.61$, $p < 0.01$	$t_{max} = 3.27$, $t_{crit} = 2.61$, $p < 0.05$
Cognitive	$t_{max} = 6.09$, $t_{crit} = 2.49$, $p < 0.01$	$t_{max} = 5.06$, $t_{crit} = 2.51$, $p < 0.01$
Exercise	$t_{max} = 5.35$, $t_{crit} = 2.61$, $p < 0.01$	$t_{max} = 4.24$, $t_{crit} = 2.67$, $p < 0.01$

Table 3.1: Gondan's permutation test results obtained for the rest, cognitive, and exercise intervention conditions.

In order to determine the AUC, cumulative distribution function (CDF) models must be computed, which compare the observed CDF distribution to the predicted CDF distribution [318].

Here, each participant's data was sorted in ascending order for all three conditions (A, V, AV). Each participant's RTs were then quantized into 5th percentile bins until the 100th percentile was reached, yielding 21 bins in total.

Observed CDF distributions were formed using the following equation (Eq. 8):

$$Eq.8 : CDF_{observed} = P(RT_{AV} \leq t) \tag{3.8}$$

Where 'P' represents the probability and RT_{AV} represents the RT *observed* for the multisensory condition for any latency, t [97, 291].

Predicted CDF models were formed using the following equation (Eq. 9):

$$Eq.9 : CDF_{predicted} = Min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{3.9}$$

Where RT_A and RT_V represent the RTs *observed* for unisensory condition A (e.g., auditory) and V (e.g., vision), for any time, t [97, 291].

Differences between the *observed* CDF distribution and the *predicted* CDF distribution were calculated for every participant across all percentile bins as follows (Eq. 10):

$$Eq.10 : RT_{AV} = P(RT_{AV} \leq t) - min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{3.10}$$

When the *observed* CDF is less than or equal to the *predicted* CDF, the race model is accepted. However, the race model is violated when the *observed* CDF is greater than the *predicted* CDF. Thus, a negative value (or zero) indicates acceptance of the race model while values greater than zero provide evidence for multisensory integration as they are indicative of race model violation [97, 293].

As mentioned above, instead of using conservative tests (i.e., t-tests), a data-driven approach was utilized to determine RMI violations by conducting Gondan's permutation test over the fastest quartile (0-25%) of responses, where robust violations were evident for all the intervention conditions (see above for calculations and Table 3.1 and Figure 3.11 below).

In addition to performing Gondan's permutation test of race model [178, 179], we also calculated the AUC (which served as our independent variable) to further quantify the magnitude of RMI violation over the first quartile of responses. As described in Mahoney and Colleague's work [289], the AUC was calculated for each time bin over the 0-25th percentile, where the difference value obtained from the observed CDF and the predicted CDF from the first time bin (i.e., 0%) was summed with the difference value obtained from the second time bin (5%) and divided by two. This was repeated for the subsequent time bins until 25th percentile was reached. All the values obtained were summed to generate a total AUC of the CDF difference wave during the 25th percentile. A 2 (time: pre- versus post-intervention) x 3 (intervention: exercise or cognitive task or rest) RM ANOVA was conducted with AUC values in order to compare the effect of time and different interventions on the AUC.

3.4.3 Relation Between the Race model and Multisensory Processes

In order to assess the relation between race model violations, SJ, and TOJ, Pearson's correlations ($\alpha = 0.05$) were determined between the AUC values, TBWs, and PSSs before and after each intervention.

3.4.4 Relation between Physical Activity and Multisensory Processes

In order to assess whether one's habitual exercise habits were related to multisensory processes, exploratory correlational analyses ($\alpha = 0.05$) were conducted between the PASE scores, the GAQ, and the TBW, PSS, and AUC values obtained from the SJ, TOJ, and RT task for each intervention condition.

3.4.5 Relation between the Cognitive Dual-Task and Multisensory Processes

In order to assess whether performance on a cognitively demanding dual task was related to multisensory processes, exploratory correlational analyses ($\alpha = 0.05$) were conducted between the score on the dual-task, and the TBWs and PSSs obtained before and after each intervention.

3.4.6 Bayes Factors

Bayes factors (BFs), can be interpreted as the relative evidence of one hypothesis (i.e., alternative) over another (i.e., null; [484]), were calculated for the SJ, TOJ, and RT tasks as an additional means to determine whether exercise was significantly different from the other interventions. A BF can be any positive number ranging from 0 to infinity where a BF of 1/3 - $<$ 1/100 provides moderate to extreme evidence for the null hypothesis while a BF of 3 - $>$ 100 provides moderate to extreme evidence for the alternative hypothesis [259, 484].

3.5 Results

3.5.1 Simultaneity and Temporal Order Judgment Tasks

Participants' responses were fitted to either a Gaussian or a sigmoidal logistic curve for SJ and TOJ respectively using equations 2 or 3. The PSS and TBWs were extracted for analysis; figure 3.4 shows the Gaussian functions (SJ) while figure 3.5 shows the logistics function (TOJ) for all the intervention conditions. Figures 3.6 and 3.7 show the average Gaussian and logistic functions respectively for all three of the conditions; as expected, pre- and post-intervention goodness of fit were not significantly different from one another for all the conditions. See Tables 3.2, 3.3, and 3.4 for the goodness of fits for the rest, cognitive task, and exercise interventions, respectively.

A 2 (task: SJ or TOJ) x 2 (time: pre- versus post-intervention) x 3 (intervention: exercise or cognitive task or rest) RM ANOVA was conducted for the TBW which revealed a main effect of task (F(1,10) = 16.93, $p < 0.01$, $\eta_p^2 = 0.63$, observed power = 0.96; BF_{10} = 289.304). As expected [36, 37], planned pairwise comparison showed wider TBWs for the SJ (mean = 153.99, $s.e.$ = 13.0) compared to the TOJ (mean = 78.46, $s.e.$ = 18.57; $p < 0.01$) task. The interaction between intervention and time was non-significant post Greenhouse-Geisser correction (F(1.17, 11.73) = 3.25, $p = 0.09$, $\eta_p^2 = 0.24$, observed power = 0.406), and there was no main effect of intervention (F(1.18, 11.84) = 1.11, $p = 0.33$, η_p^2

= 0.10, observed power = 0.17 ; BF_{10} = 0.202) or time (F(1, 10) = 0.340, p = 0.573, η_p^2 = 0.03, observed power = 0.08; BF_{10} = 1.877). Note, however, that the best model with the largest Bayes Factor (BF_{10} = 3.355 x 10^8) was one that included all three factors of task, time, intervention, and interactions between these factors: task and time, task and intervention, time and intervention, and finally task time, and intervention. This provides 'extreme evidence' [259] for the alternative hypothesis that performance on the SJ and TOJ tasks is affected by exposure to various intervention types. Figure 3.8 was thus created to further understand the relation between the TBWs obtained pre- and post-intervention for both the SJ and TOJ tasks respectively. A comparison of the means obtained for each intervention condition revealed the largest TBW for the rest condition, followed by the exercise condition, with the narrowest TBW found for the cognitive task condition for the SJ task (see Table 3.5). For the TOJ task, however, the exercise condition yielded the narrowest TBW followed by the rest condition, and the cognitive task yielded the widest TBW (see Table 3.5). Further, a comparison of the TBWs obtained before and after each intervention revealed that the TBWs only narrowed consistently after exercising for 20 minutes, while consistently increasing in width after resting for 20 minutes for both the SJ and TOJ Tasks (see Table 3.6).

A 2 (task: SJ or TOJ) x 2 (time: before completing the intervention or after the intervention) x 3 (intervention: exercise or cognitive task or rest) RM ANOVA analysis was conducted for the PSS, which failed to reveal a main effect of task task (F(1, 10) = 2.68, p = 0.13, η_p^2 = 0.21, observed power = 0.32; BF_{10} = 348.81), intervention (F(1.29, 12.88) = 1.33, p = 0.29, η_p^2 = 0.12, observed power = 0.25; BF_{10} = 0.109) and time (F(1, 10) = 1.85, p = 0.20, η_p^2 = 0.16, observed power = 0.23; BF_{10} = 0.219; see also Tables 3.7 and 3.8). Note here that although significant main effects of time and intervention were not found, the pre-intervention PSS scores for the TOJ task indicate that participants required sound to be presented before the flash to perceive simultaneity and this shifted after exercising where participants required the flash to be presented before sound to perceive simultaneity. As task was found to have the largest Bayes factor, we created figure 3.8 for a further comparison between the pre- and post- PSS scores obtained by subtracting the pre-intervention scores from the post-intervention scores for each condition for both the SJ and TOJ tasks to better understand the changes associated with each task and intervention.

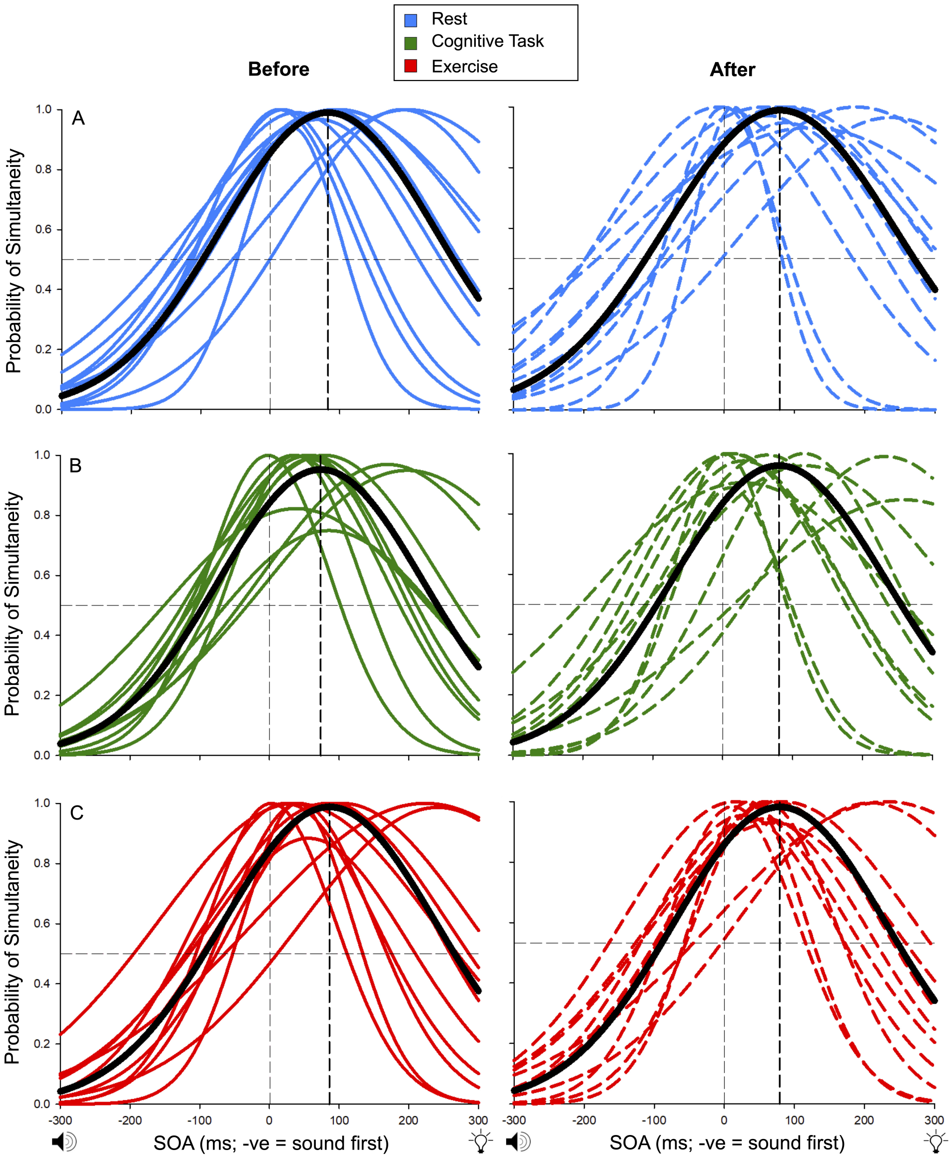


Figure 3.4: SJ: Gaussian function is fit to the average (thick black lines) and individual (thin coloured lines) data. Data from before (solid fits) and after (dashed fits) the rest condition (blue) is represented in panel A, while data from the cognitive task (green) and exercise (red) conditions are presented in panels B and C, respectively. The PSS is represented in the dashed (black) vertical line for each condition. Before rest, participants required the visual stimulus to occur 83 ms before sound, while requiring the visual stimulus to occur 79 ms before sound after rest in order to perceive the two stimuli as simultaneous. Before participating in the cognitive task, participants required the visual stimulus to occur 74 ms before sound, while requiring the visual stimulus to occur 81 ms before sound after the cognitive task in order to perceive the two stimuli as simultaneous. Before aerobic exercise, participants required the visual stimulus to occur 86 ms before sound, while requiring the visual stimulus to occur 79 ms before sound after aerobic exercise in order to perceive the two stimuli as simultaneous.

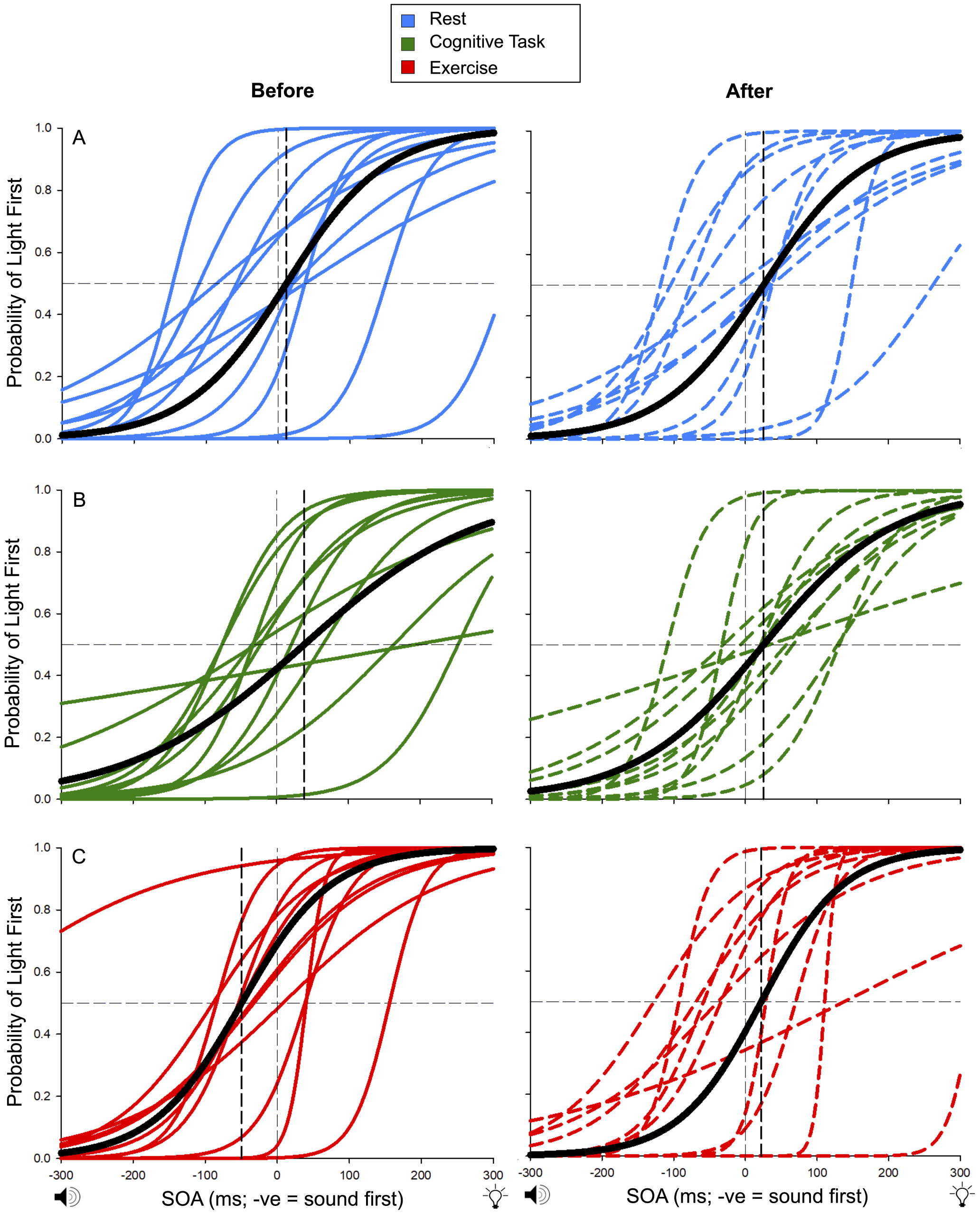


Figure 3.5: Sigmoidal function is fit to the average (thick black lines) and individual (thin coloured lines) data. Data from before (solid fits) and after (dashed fits) the rest condition (blue) is represented in panel A, while data from the cognitive task (green) and exercise (red) conditions are presented in panel B and C respectively. The PSS is represented in the dashed (black) vertical line for each condition. Before rest, participants required the visual stimulus to occur 12 ms before sound, while requiring the visual stimulus to occur 25 ms before sound after rest in order to perceive the two stimuli as simultaneous. Before participating in the cognitive task, participants required the visual stimulus to occur 38 ms before sound, while requiring the visual stimulus to occur 25 ms before sound after the cognitive task in order to perceive the two stimuli as simultaneous. Before aerobic exercise, participants required the auditory stimulus to occur 50 ms before light, while requiring the visual stimulus to occur 22 ms before sound after aerobic exercise in order to perceive the two stimuli as simultaneous.

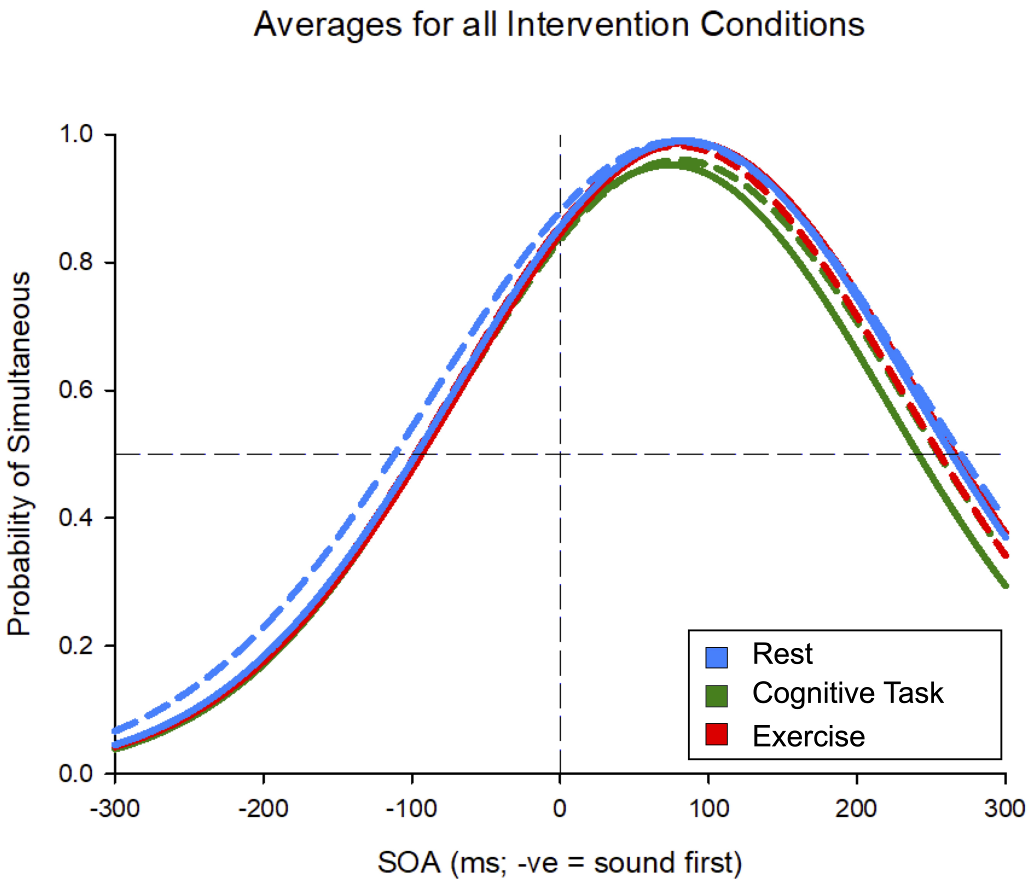


Figure 3.6: Average SJ Gaussian fits from the rest (blue), cognitive (green), and exercise (red) conditions. Where solid lines represent pre- and dashed lines represent post-intervention fits. Note the overlap between the conditions.

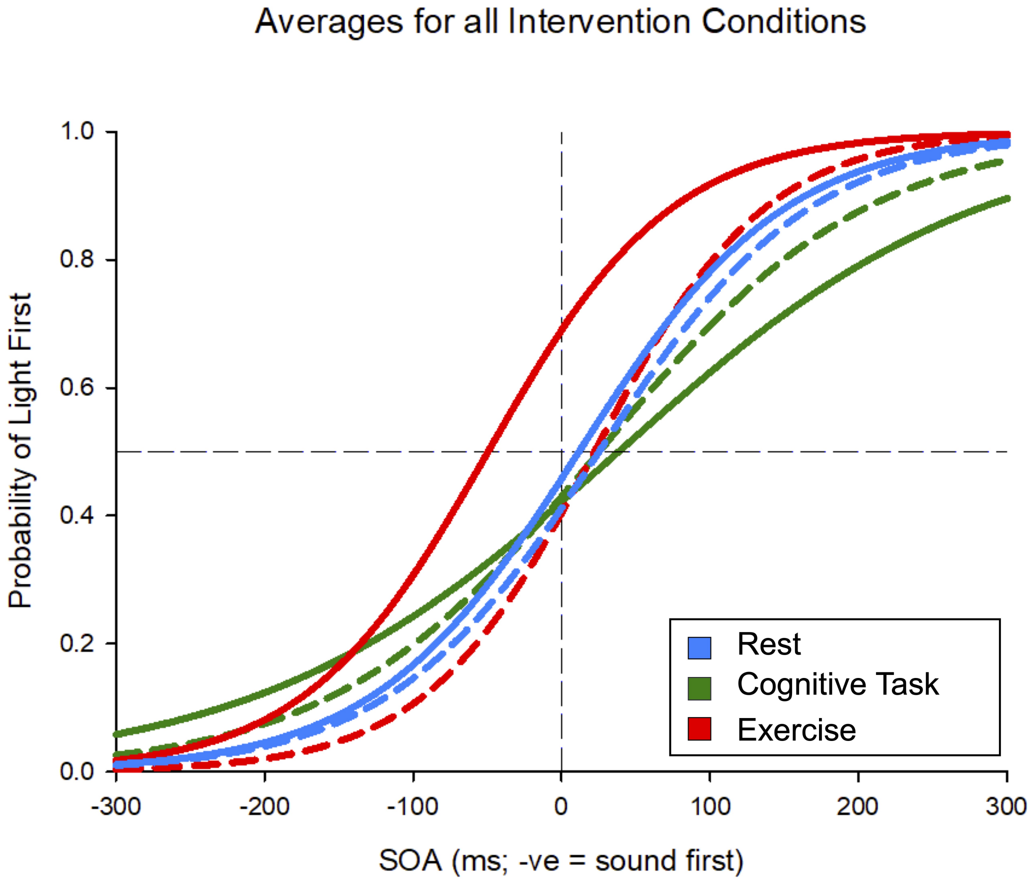


Figure 3.7: Average TOJ sigmoidal fits from the rest (blue), cognitive (green), and exercise (red) conditions. Where solid lines represent pre- and dashed lines represent post-intervention fits. Notice that pre-exercise fits are different from the remaining conditions (i.e., requiring sound to be presented prior to light compared to all the other conditions that required the light to be presented before sound to perceive simultaneity).

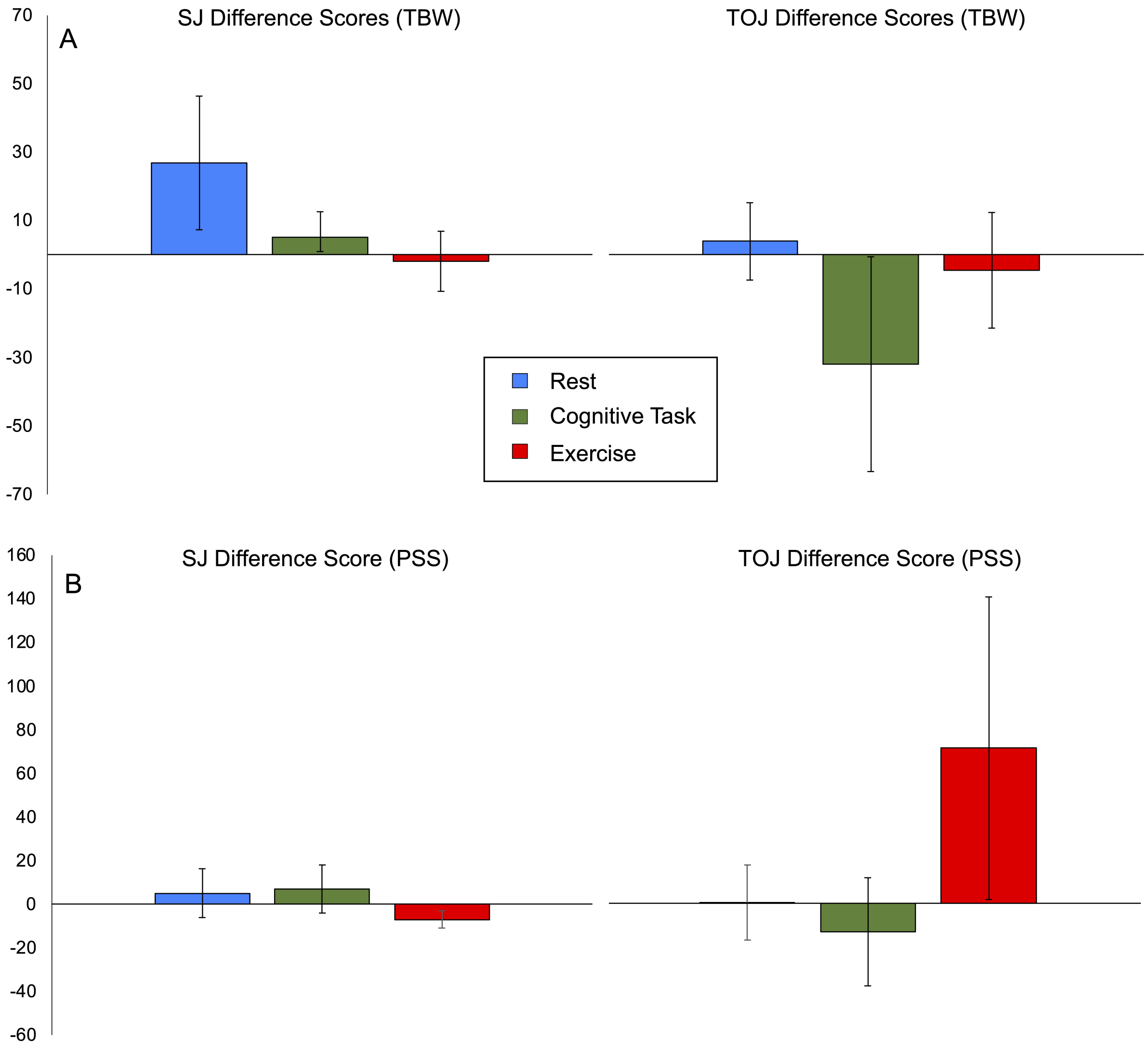


Figure 3.8: Difference scores for the rest (blue), cognitive (green), and exercise (red) conditions obtained for the SJ and TOJ tasks. Both TBWs (A; top two panels) and PSSs (B; bottom two panels) are presented here, where a positive value indicates a widening of the TBW and a negative value indicates a reduction in TBW post intervention completion, while a positive value indicates the PSS moving further away from zero or true simultaneity and a negative value indicates the PSS moving closer to zero or true simultaneity post intervention completion.

Condition	SJ Task	TOJ Task
Before Rest	r^2 Mean = 0.91, Median = 0.91 SD = 0.03, s.e. = 0.01	r^2 Mean = 0.87, Median = 0.93, SD = 0.12, s.e. = 0.04
After Rest	r^2 Mean = 0.91, Median = 0.91, SD = 0.05, s.e. = 0.01	r^2 Mean = 0.88, Median = 0.91, SD = 0.09, s.e. = 0.03
T-test	$t(10) = 0.05$, $p = 0.96$; *Cohen's* $d = 0.00$; $BF_{10} = 0.30$	$t(10) = -0.26$, $p = 0.80$; *Cohen's* $d = 0.09$; $BF_{10} = 0.31$

Table 3.2: Comparison of goodness of fits obtained before and after the rest condition for the SJ and TOJ tasks. T-tests reveal no significant differences between the pre- and post-rest intervention for both the SJ and TOJ tasks. Bayesian paired sample t-tests further reveal Bayes factors of less than 1, providing additional evidence for the null hypothesis that there are no differences between the psychometric fits obtained pre- and post-reading.

Condition	SJ Task	TOJ Task
Before Cog.	r^2 Mean = 0.90, Median = 0.91, SD = 0.05, s.e. = 0.01	r^2 Mean = 0.84, Median = 0.91, SD = 0.20, s.e. = 0.06
After Cog.	r^2 Mean = 0.88, Median = 0.91, SD = 0.08, s.e. = 0.02	r^2 Mean = 0.86, Median = 0.88, SD = 0.18, s.e. = 0.05
T-test	$t(10) = 1.50$, $p = 0.16$; *Cohen's* $d = 0.30$; $BF_{10} = 0.72$	$t(10) = -0.39$, $p = 0.71$; *Cohen's* $d = 0.10$; $BF_{10} = 0.32$

Table 3.3: Comparison of goodness of fits obtained before and after completion of the cognitive task for the SJ and TOJ tasks. Bayesian paired sample t-tests further reveal Bayes factors of less than 1, providing additional evidence for the null hypothesis that there are no differences between the psychometric fits obtained pre- and post-exposure to the cognitive task. Note that 'Cog.' = Cognitive Task.

Condition	SJ Task	TOJ Task
Before Exer	r^2 Mean = 0.90, Median = 0.89, SD = 0.04, s.e. = 0.01	r^2 Mean = 0.80, Median = 0.93, SD = 0.25, s.e. = 0.08
After Exer	r^2 Mean = 0.89, Median = 0.90, SD = 0.05, s.e. = 0.01	r^2 Mean = 0.87, Median = 0.92, SD = 0.12, s.e. = 0.03
T-test	$t(10) = 1.35$, $p = 0.21$; *Cohen's* $d = 0.22$; $BF_{10} = 0.62$	$t(10) = -0.85$, $p = 0.41$; *Cohen's* $d = 0.36$; $BF_{10} = 0.40$

Table 3.4: Comparison of goodness of fits obtained before and after aerobic exercise for the SJ and TOJ tasks. Bayesian paired sample t-tests further reveal Bayes factors of less than 1, providing additional evidence for the null hypothesis that there are no differences between the psychometric fits obtained pre- and post-exercising. Note 'Exer' = Exercise.

Condition	SJ TBW	TOJ TBW
Rest	Mean = 158.83, s.e. = 13.91	Mean = 70.16, s.e. = 11.71
Cognitive Task	Mean = 150.19, s.e. = 12.90	Mean = 105.60, s.e. = 36.54
Exercise	Mean = 152.94, s.e. = 14.30	Mean = 59.63, s.e. = 12.56

Table 3.5: Comparison of the mean TBWs obtained for the SJ and TOJ tasks for each intervention condition.

Condition	SJ TBW	TOJ TBW
Before Rest	Mean = 154.35, s.e. = 13.531	Mean = 69.43, s.e. = 14.14
After Rest	Mean = 163.32, s.e. = 16.29	Mean = 70.88, s.e. = 11.67
Before Cognitive Task	Mean = 147.66, s.e. = 11.43	Mean = 121.59, s.e. = 50.63
After Cognitive Task	Mean = 152.71, s.e. = 15.15	Mean = 89.61, s.e. = 24.45
Before Exercise	Mean = 153.90, s.e. = 15.33	Mean = 61.92, s.e. = 12.01
After Exercise	Mean = 151.97, s.e. = 14.60	Mean = 57.34, s.e. = 17.74

Table 3.6: Comparison of the mean TBWs obtained before and after each intervention for the SJ and TOJ tasks for each intervention condition.

Condition	SJ PSS	TOJ PSS
Rest	Mean = 81.30, s.e. = 20.36	Mean = 18.50, s.e. = 38.83
Cognitive Task	Mean = 77.05, s.e. = 22.51	Mean = 31.90, s.e. = 25.87
Exercise	Mean = 82.59, s.e. = 22.87	Mean = -13.68, s.e. = 22.91

Table 3.7: Comparison of the mean PSSs obtained for the SJ and TOJ tasks for each intervention condition.

Condition	SJ PSS	TOJ PSS
Before Rest	Mean = 83.35, s.e. = 18.85	Mean = 11.69, s.e. = 39.36
After Rest	Mean = 79.25, s.e. = 22.54	Mean = 25.31, s.e. = 39.31
Before Cognitive Task	Mean = 73.61, s.e. = 17.95	Mean = 38.43, s.e. = 34.56
After Cognitive Task	Mean = 80.48, s.e. = 27.41	Mean = 25.36, s.e. = 21.38
Before Exercise	Mean = 86.13, s.e. = 23.65	Mean = -49.58, s.e. = 44.44
After Exercise	Mean = 79.04, s.e. = 22.24	Mean = 22.22, s.e. = 39.10

Table 3.8: Comparison of the mean PSS values obtained before and after each intervention for the SJ and TOJ tasks for each intervention condition.

3.5.2 Reaction Time Task

Error Analysis, Outlier Removal, and Mean RT Analysis

The group maintained an **overall** accuracy of 99.76% for the auditory trials, 96.81% for visual trials, and 99.76% for the audiovisual trials. Refer to table 3.9 for the accuracy achieved before and after each intervention for auditory, visual, and audiovisual trials.

Intervention	Auditory Accuracy (%)	Visual Accuracy (%)	Audiovisual Accuracy (%)
Before Rest	99.72	97.64	99.72
After Rest	99.91	97.82	99.91
Before Cognitive Task	99.50	95.50	99.70
After Cognitive Task	99.70	95.20	99.80
Before Exercise	99.72	97.96	99.72
After Exercise	100	97.09	99.72

Table 3.9: The accuracy achieved for auditory, visual, and audiovisual trials before and after each intervention condition (rest, cognitive task, aerobic exercise).

Mean RT Analysis

A 2 (time: pre- versus post-intervention) x 3 (modality: auditory, visual, or audiovisual) x 3 (intervention: rest or cognitive task or exercise) RM ANOVA revealed a main effect of modality ($F(1.30, 11.54) = 75.06$, $p < 0.0001$, $\eta_p^2 = 0.89$, observed power = 0.99; $BF_{10} = 8.137 \text{ x } 10^{31}$). In line with previous research, planned pairwise comparisons revealed significant differences at the level of $p < 0.01$ between the RTs for each modality, with the longest RT for the visual modality (mean = 363.16 ms, *s.e.* = 17.05), followed by the auditory modality (mean = 313.02 ms, *s.e.* = 19.08), and the shortest RT for the audiovisual modality (mean = 271.70 ms, *s.e.* = 15.19; $p < 0.0001$; see Figure 3.9). No other main effect or interactions were significant. A main effect of time ($F(1, 9) = 2.09$, $p = 0.18$, $\eta_p^2 = 0.189$; observed power = 0.25; $BF_{10} = 0.340$) and intervention ($F(1.28, 11.53) = 1.56$, $p = 0.24$, $\eta_p^2 = 0.15$; observed power = 0.23; $BF_{10} = 0.437$) were not found. Note that the Bayes Factor analysis revealed that although modality provided decisive evidence that the mean response time was impacted by modality type, intervention and modality combined were found to be the best model with a BF_{10} of $1.933 \text{ x } 10^{34}$, suggesting that the intervention type also impacted performance on the task.

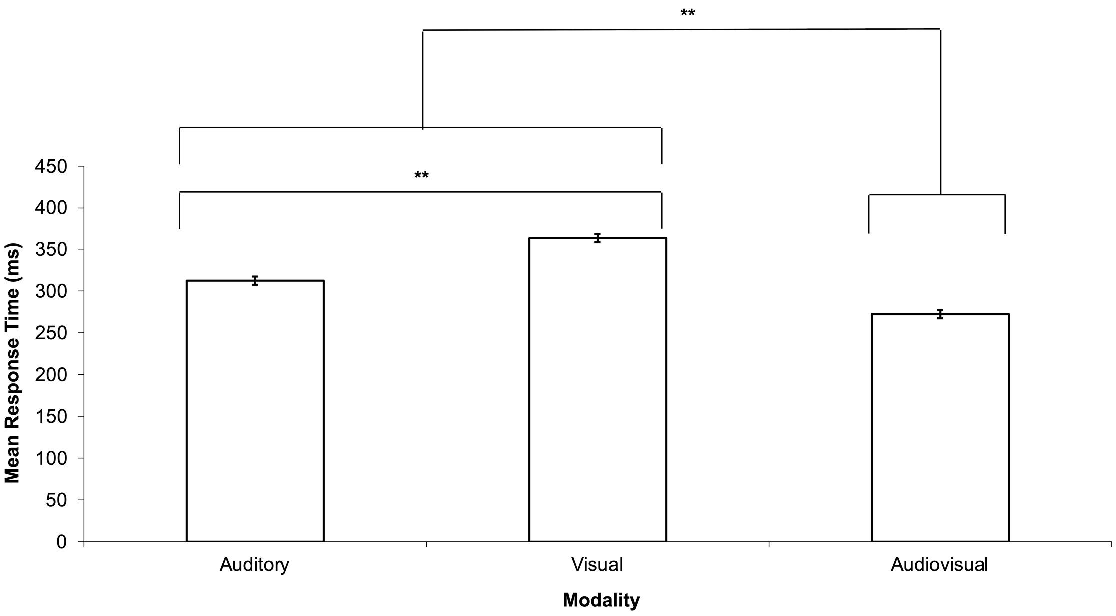


Figure 3.9: Average response time (RT) data (with SEMs) from the auditory, visual, and audiovisual conditions from the rest, cognitive task, and exercise interventions. Error bars are ± 1 SEM. Asterisks indicate statistical significance at $p < 0.01$ level.

The Race Model Violation

To assess the RMI, the difference waveform was calculated by subtracting the predicted CDF from the observed CDF for all the intervention conditions ([97]; see Figure 3.10). Evidence for the co-activation model and thus support for multisensory integration is provided if a positive value is obtained, regardless of the significance of the magnitude ([97, 291, 294, 37]; see Figure 3.11). The figure below indicates violation of the race model and provide evidence for the co-activation model over the first 25th percentile (highlighted in grey) for all the intervention conditions. Further, in order to statistically assess race model violations, Gondan's permutation tests [179] were conducted and significant violations were found for all the intervention conditions (see 'error analysis, outlier removal, and mean RT analysis' section above). We then conducted a 2 (time: pre- versus post-intervention) x 3 (intervention: rest or cognitive task or exercise) RM ANOVA comparing the AUC values between the interventions, however, no significant differences were found for time ($p = 0.12$, $\eta_p^2 = 0.22$, observed power $= 0.33$; $BF_{10} = 1.261$), intervention ($p = 0.92$, $\eta_p^2 = 0.009$, observed power $= 0.062$; $BF_{10} = 0.128$), and the interaction between time and intervention ($p = 0.31$, $\eta_p^2 = 0.11$, observed power $= 0.24$).

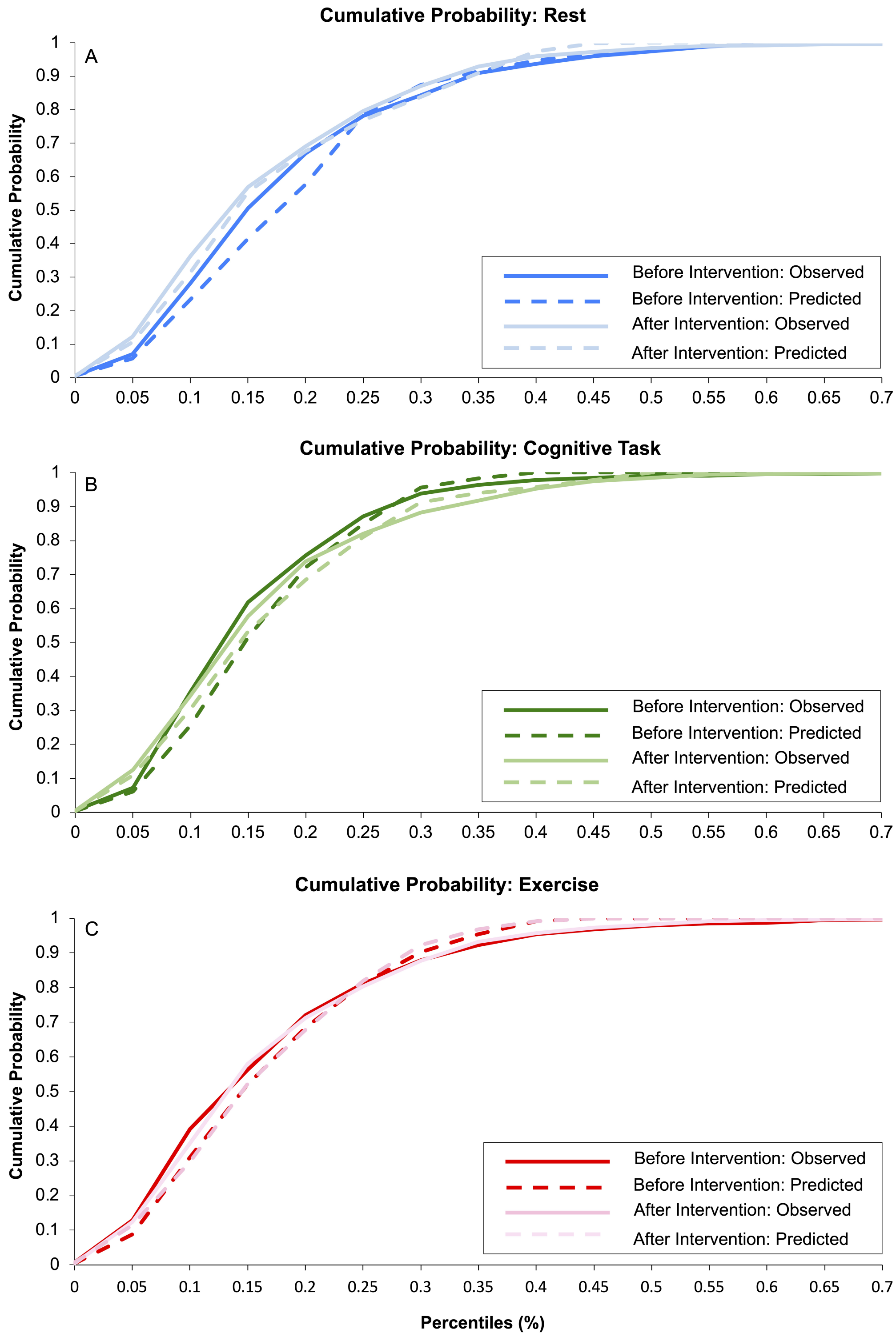


Figure 3.10: Cumulative probability graphs where the solid lines represent the observed cumulative probability while the dashed lines represent the predicted cumulative probability before (darker colour) and after (lighter colour) each intervention condition; panel A represents rest (blue), panel B represents the cognitive task (green), and panel C represents exercise (red).

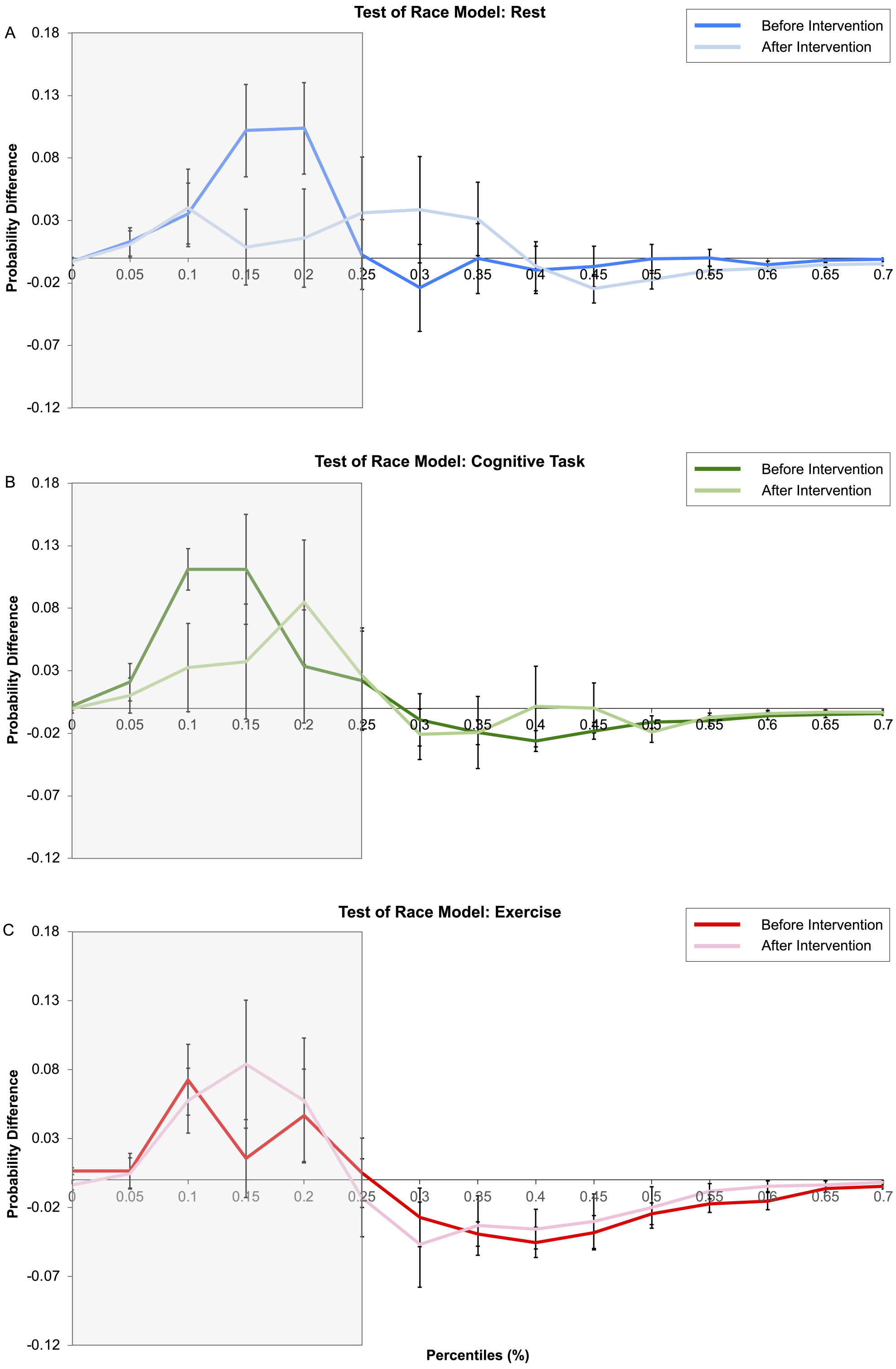


Figure 3.11: Test of the race model before (darker colour) and after (lighter colour) each intervention condition; panel A represents rest (blue), panel B represents the cognitive task (green), and panel C represents exercise (red). The graphs represent the probability difference waves which were obtained by subtracting the predicted CDFs from the observed CDFs for each intervention condition. The grey box indicates the area over which the analyses were conducted. Error bars are ± 1 SEM.

3.5.3 Relation between the SJ, TOJ, and RT tasks

In order to assess the relation between race model violations, SJ, and TOJ, Pearson's correlations ($\alpha = 0.05$) were determined between the AUC values, TBWs, and PSSs for all participants. Multiple significant relations were found between the AUC scores and the TBW and PSS values obtained from both the SJ and TOJ tasks, however, these relations were deemed non-significant once the Bonferroni correction was applied ($\alpha = 0.05/24 = 0.0021$). Examples of correlations deemed non-significant post-Bonferroni correction include relations found between the AUC score from before completing the cognitive task and the TBW ($r(11) = 0.733$, $p = 0.010$; $BF_{10} = 6.80$) and the AUC score after the cognitive task and the PSS ($r(11) = 0.739$, $p = 0.009$; $BF_{10} = 7.355$) obtained from the SJ and TOJ tasks respectively.

3.5.4 Relation between Physical Activity and Multisensory Processes

In order to assess whether one's habitual exercise habits were related to multisensory processes, exploratory correlational analyses ($\alpha = 0.05$) were conducted between the PASE scores, the GAQ, and the TBW, PSS, and AUC values obtained from the SJ, TOJ, and RT task for each intervention condition. Although no significant relation was found between the PASE and the TBW, PSS, and AUC values, a significant relation was found between the GAQ score and the TBW obtained from the TOJ task before participating in the exercise intervention ($r(11) = 0.685$, $p = 0.020$; $BF_{10} = 4.08$). Note however that the relation between GAQ and the TBW was deemed non-significant once the Bonferroni correction was applied ($\alpha = 0.05/32 = 0.0016$).

3.5.5 Relation between the Cognitive Dual-Task and Multisensory Processes

In order to assess whether performance on a cognitively demanding dual task was related to multisensory processes, exploratory correlational analyses ($\alpha = 0.05$) were conducted between the score on the dual-task, and the TBWs and PSSs obtained before and after each intervention. Although a significant relation was found between the cognitive task score and the TBW obtained from the SJ task after resting for 20 minutes ($r(11) = 0.624$, $p = 0.040$; $BF_{10} = 2.41$), this relation was deemed non-significant once the Bonferroni correction was applied ($\alpha = 0.05/24 = 0.0021$), as was the case with the correlational analyses conducted above.

3.6 Discussion

The aim of this pilot study was to determine whether a single bout of aerobic exercise could improve multisensory processing and to help guide future researchers in their endeavour to better understand the malleability of the multisensory processing system. Older adults were asked to attend the lab at three different times to partake in three intervention conditions which included resting, completing a cognitively-demanding task, and exercising for 20 minutes. We found a near-significant interaction between task, intervention, and time (completing the tasks pre- versus post-intervention) for the TBW obtained from the TOJ task, indicating that our interventions may play a role in modifying the TBW. Indeed, we found that the largest Bayes factor was one that included time, intervention, and task, providing further evidence that both the SJ and TOJ tasks are affected by exposure to the interventions utilized in our study. Further, figure 3.8 depicts the difference scores obtained by subtracting the pre-intervention TBW values from post-intervention values, and indicates that the TBW is malleable and changes after each intervention condition for both the SJ and TOJ tasks. Interestingly, the TBW consistently became narrower post-exercise while consistently increasing in width post-rest, suggesting that exercise may improve temporal perception on a wider scale rather than targeting the specific networks that subserve either of the SJ and TOJ tasks individually. Further, consistent with previous results, our findings showed a significant main effect of task with wider TBWs found for SJ compared to the TOJ task.

Although our results did not reveal a main effect of time or intervention for the analyses conducted with PSS, we did find that pre-exercise, participants required sound to be presented before the flash to perceive simultaneity and this shifted after exercising, where participants required the flash to be presented before sound to perceive simultaneity for the TOJ task. Although participants were not aware of the order in which they would be completing each intervention, we suspect that some may have used deductive reasoning to determine when they would be exercising, and this could have impacted their performance on the task. However, it is unlikely that knowledge of engagement in exercise is the only explanation, as performance would have also been affected on the SJ task, however, we did not see such an effect. It may be possible that this shift in PSS may have contributed to the large Bayes factor obtained for the main effect of task. Future research is recommended to more fully assess this beyond this initial pilot study.

The RT task revealed promising results, where Gondan's permutation [178] was violated for all the intervention conditions, potentially providing evidence for co-activation models. Although only a main effect of modality was found for the RT task, the lack of a main effect for time and intervention may be related to the lack of power with the current sample. As mentioned above, a power analysis was conducted to determine the sample that would be necessary to obtain small to moderate effects sizes and the analysis revealed that we would need to collect data from 27-161 participants. However, given the COVID-19 pandemic, we were able to utilize data from only 11 participants, which although comparable to the sample size utilized by previous studies (6 – 19 participants) for measuring the direct effects of exercise on MSI, is a major limitation of this study. An additional limitation of this study is the lack of a control group consisting of young adults, which could not be tested in this study due to the COVID-19 pandemic restrictions. Regardless of these limitations, the Bayes factors provided 'extreme evidence' in favour of the hypothesis that intervention, time, and modality ($BF_{10} = 1.585 \text{ x } 10^{34}$) interact with one another in a meaningful way. To further investigate this finding using Bayes factors, it was found that both intervention and modality ($BF_{10} = 1.933$ x 10^{34}) and modality and time ($BF_{10} = 9.885$ x 10^{32}) provided extreme or decisive evidence against the null hypothesis, while intervention and time ($BF_{10} = 0.151$) provided evidence for the null hypothesis, suggesting that modality may be central to change in performance and may be impacted by time and intervention to affect the underlying networks associated with multisensory processing.

As this pilot study is the first of its kind with well-controlled exercise parameters and various control conditions, there were additional exploratory analyses that were conducted in order to better understand the underlying mechanisms associated with exercise and perception. As multiple correlations were conducted, it was important for the research team to apply the Bonferroni correction in order to reduce the likelihood of Type I error. However, when the Bonferroni correction was applied, none of the correlations remained significant. One correlational analysis that is of interest, however, is the correlation found between the GAQ score and the TBW from the TOJ task before participating in the exercise intervention ($r(11) = 0.685$, $p = 0.020$; $BF_{10} = 4.08$). Although the relation between GAQ and the TBW was deemed non-significant once the Bonferroni correction was applied ($\alpha = 0.05/32 = 0.0016$), the Bayes factor does provide substantial evidence that this relation may be meaningful. This correlation suggests that those who were more physically active at baseline also tended to have wider temporal binding windows at baseline. This somewhat counter-intuitive finding parallels the work of Mahoney and colleagues [294], who found, using the RT task, that those who were more physically active tended to benefit less from multimodal cues. Given that our previous work has revealed a significant correlation between the violations of the race model (as obtained from the RT task) and the TOJ task, albeit the PSS and not the TBW, our results may be providing further evidence for a potentially similar mechanism that is affected by physical activity.

The original hypotheses aimed to determine the difference before and after each intervention condition, and although the Bayes factors did reveal that the interventions the participants were exposed to in our study did impact multisensory processing, the results from frequentist analyses did not reveal significant differences for any of the analyses investigating a main effect of intervention. Taken together, these results suggests that this study is under-powered. Regardless of the limited sample, we are not limited from comparing our results to previous literature; especially relevant are studies with similar sample sizes. Our comparison revealed that in studies of perception where vision was the focus, as was the case for studies utilizing the critical flicker fusion (CFF; the frequency at which an intermittent light stimulus appears to be completely steady) task, relatively small sample sizes (n = 6, 7, 16, 19 in [171, 114, 113, 250] respectively) led to significant changes in sensory processing post-exercise as compared to baseline performance.

Below we will discuss the specifics of the exercise conditions that may have significantly influenced the changes reported in sensory processing. In a study conducted by Godefroy and colleagues [171], 6 trained male triathletes completed the CFF over six sessions including: before exercise, immediately after, 5-, 20-, 60- minutes after, and one day after exercise. The exercise condition consisted of an incremental test of maximal volume uptake (VO_{2max}) with the test leading to exhaustion. CFF was measured over a range of 20 to 44 Hz where a rise in CFF was classified as “an indicator of CNS activation" and a fall in CFF was associated with CNS fatigue [171]. The means of ascending and descending values were used to calculate the total mean (M_{tot}) as well as the difference between the means (M_{di}). Although they did not find any significant effect of exercise fatigue on M_{tot}, they did find a significant fall in M_{di} following exercise indicating that exhausting physical exercise could lead to decrements in perceptual responses. Similarly, Davranche and colleagues [114] also examined the effect of exhausting exercise on sensory sensitivity. Seven male participants performed an incremental cycling test to exhaustion and CFF measurements were carried out before and immediately after exercise. CFF was measured over 0 to 100 Hz and either increased from 0 to 100 Hz until the subject perceived fusion or decreased from 100 to 0 Hz until a flicker was detected. Similar to Goodfroy and colleagues [171], Davranche and colleagues [114] also calculated the M_{tot} (defined as the sensory sensitivity criterion) as well as the M_{di} (defined as "the subjective judgment criterion"). However, contrary to Goodfroy and colleagues [171], Davranche and colleagues [114] found that exercise increased the M_{tot} CFF threshold and failed to find a significant effect of exercise on M_{di}. Thus, the negative effects of exhausting exercise were not observed on perceptual responses and instead the results found suggested an increase in cortical arousal and sensory sensitivity. The authors further posited that a lack of effect for the M_{di} CFF thresholds suggests that the changes observed for M_{tot} were not linked to a more liberal response criterion utilized by the subjects. They also attributed the differences in their findings to the methods utilized for determining CFF thresholds (e.g., 20-44 Hz versus 0-100 HZ).

In another study conducted by Davranche and colleagues [113], 16 athletes (7 females and 9 males) were asked to complete two tasks, a choice RT task and the CFF. The choice RT task was completed at rest and at two intensities of exercise (20% and 50% of their maximal aerobic power). Participants were asked to complete the CFF before and after each block of the choice RT task. They found that exercise at 50% of maximal aerobic power reduced the RT compared to rest but did not find any significant difference between rest and 20% of maximal aerobic power. Further, they found that CFF threshold values were greater (indicative of greater CNS activation [171]) at 50% of maximal aerobic power compared to rest and 20% of maximal aerobic power condition. At rest, the CFF was found to decreases after the choice-reaction time task. No differences in CFF were observed during the 20% of maximal aerobic power condition. These results indicate that submaximal exercise (50% of maximal aerobic power) improves performance on both a choice RT task and for CFF. In a more recent study conducted by Lambourne and colleagues [250], the effects of immediate and delayed aerobic exercise on CFF thresholds (measured at 0 to 100 Hz frequency) were assessed in 19 young adults (11 females and 8 males). Participants were asked to exercise at a 90% ventilatory threshold and either completed the CFF before, at 8-, 14-, 22-, 28-, and 34-minutes during the 40 minute exercise session, and 1-, 15-, and 30-minutes post-exercise. Unlike many of the studies described above, participants also partook in a rest condition where the same protocol was followed as the exercise condition except they were not exposed to exercise. They found an increase in CFF thresholds during a moderate bout of aerobic exercise which increased from baseline and dropped immediately after the cessation of exercise. Of interest, they found that performance on the CFF improved after 15-20 minutes of exercise.

Although they did not use the CFF to investigate the effects of exercise on sensory processes, similar results regarding the cessation of effects post-exercise were found in a study conducted by Audiffren and colleagues [19]. In their study 17 participants (8 females and 9 males) performed an auditory choice RT at 10 points including: 5 minutes before the start of the exercise, 8-, 14-, 22-, 28-, 34-, and 40-minutes during exercise, and 1-, 15-, and 30-minutes following termination of exercise. The researchers found that at a 90% ventilatory threshold, there was a significant reduction in the participants' RT by approximately 17 ms, however, the facilitating effects of exercise decreased immediately after cessation of physical activity. The studies described above indicate that the methods utilized to measure the effects of exercise largely impact whether or not an effect is observed by researchers and require well-controlled environments. Some of these results suggest that perhaps a higher intensity of exercise is required to observe the effects of exercise on sensory processes [114, 171] and given that some of the researchers found the effects of exercise facilitation decreased immediately after cessation of physical activity [19, 250], this suggests that the lack of effect observed in our study may be related to timing of test administration (we administered the MSI tasks immediately after exercise rather than during exercise as found in much of the literature presented above), and intensity utilized (we had participants exercise at a moderate intensity rather than the vigorous intensity that led to exhaustion, a process that could be subserved via different underlying mechanisms) of exercise.

As with the studies mentioned above, studies utilizing audiovisual cues can also yield mixed results. In a recent study conducted by O'Brien and colleagues [352], physical activity and multisensory processing was evaluated in young children (6-8 years old), who, similar to older adults, typically tend to integrate multisensory cues over a wider window of time (extended TBWs; [1, 72]). Fifty-one children (23 females and 28 males) were divided into three groups including open-skill exercise ($n = 16$), closed-skill exercise ($n = 16$), and classroom activity ($n = 19$) and they were asked to complete the SIFI before and after their assigned activity, which lasted approximately 30 minutes. They found that both open- and closed-skill exercise improved perceptual sensitivity to the SIFI. On the contrary, an earlier study conducted by the same research group [351] in older adults (60 - 81 years old) found that only open-skill exercise led to improvements in susceptibility to the SIFI. Although these studies pertain to different age groups, they provides insights into the malleability of the multisensory integration processes in response to exercise and indicate that physical activity affects audiovisual multisensory integration processes. Note however that the wide age range in the older group in both O'Brien and colleagues' [351] work and our pilot study may also provide an additional source of limitation, given that a small number of participants were utilized in both studies, and both failed to find significant improvements in multisensory processing from closed-skill exercise using frequentist analyses. Perhaps a narrow age range should be utilized in the future to determine if age range is significantly affecting the findings. Overall, these results are however consistent with Sander's cognitive-energetic model [403] where an increase in arousal, such as that induced through exercise, may benefit cognitive and perceptual processes by priming an individual to respond to incoming stimuli

The lack of a significant effect of exercise found in our pilot study may be indicative of the fact that either a relation between exercise and multisensory integration processes does not exist or that our analyses are underpowered and require additional data to make reliable conclusions. In addition to having a small sample, another limitation of our study is the fact that our perceptual tasks took approximately 15-30 minutes to complete both pre- and post-intervention, which when compared to some of the literature described above is significantly longer. For instance, Davranche and Pichon [114] presented their participants with 3 ascending and 3 descending trials, before and after exercise, that lasted approximately 3 to 4 minutes. Lambourne and colleagues [250] presented participants with 40 practice trials consisting of 20 ascending and 20 descending sequences during the first session, and participants performed 9 blocks consisting of 3 ascending and 3 descending trials during the experimental and rest sessions. Although 9 blocks were performed during the exercise and rest sessions, participants only completed 54 experimental trials per session, which is significantly less than the number of trials our participants completed. Such differences in the number of trials and therefore the duration of the task may explain why an effect was not observed in our study, especially given that a meta-analysis conducted by Chang and colleagues [84] suggested that optimal timing for administration of post-exercise tests is between 11-20 minutes. However, similar to our duration, Davranche and Audiffren [113], presented their participants with 128 trials, which took approximately 17 minutes to complete. Similarly, Auddiffren, Tomporowski, and Zagrodnik [19] presented their participants with three to ten blocks of 40 practice trials during the practice and evaluation session and nine blocks of 104 trials during the exercise and rest sessions; each block of practice trials lasted approximately 3 minutes, whereas each block of experimental trials was approximately 5 minutes. In their study, although each block was shorter in length, the total number of trials performed during the exercise session was indeed higher than ours. Regardless, and in spite of the fact that the studies mentioned above present some limitations (e.g., some studies had long test times, some failed to include a control condition, and many consisted of small sample sizes), they indicate that there is an effect of exercise on perceptual processing.

While higher order cognitive function has traditionally been investigated using exercise paradigms, growing evidence, as discussed above, suggests that perceptual processes can also be modified through exercise. Indeed, the results of our pilot study contribute to the limited evidence for the modifiability of the temporal binding window as well as race model violations with exercise. Our results are especially relevant for the aging population as the efficiency of perceptual processes, especially as they relate to multisensory integration, have been found to be associated with global cognition [122], thus testing and understanding the effects of exercise on multisensory processes provides researchers with an opportunity to design interventions that can help improve the overall health of the CNS.

3.7 Conclusion

In this pilot study, we found evidence indicating that aerobic exercise may target the underlying mechanisms that subserve the general integration process rather than specific mechanisms that subserve each of the tasks utilized in this study, as we found consistent reductions in the TBW for both the SJ and TOJ tasks as well as an increase in race model violations (i.e., increased integration) only after the exercise condition. One potential mechanism through which exercise may differ from the other conditions tested in our study is that it may be increasing arousal and potentially offsetting the effects of boredom that may be affecting the rest and cognitive task conditions. Based on the results of this pilot study, we recommend that further research is conducted to understand the relation between exercise and sensory integration where controls such as the dual-task and reading are appropriately utilized to best distinguish the underlying relation. The results from this pilot study also suggest that either one or two tasks, or tasks with fewer trials are utilized to test for changes in multisensory processing pre- and post-exercise, as timing of test administration plays a crucial role in obtaining the effects of interest. Further, the results suggest that future researchers may want to consider utilizing exhaustion rather than fatigue, as elicited by an intense versus a moderate bout of aerobic exercise respectively, for better comparisons with previous literature.

Chapter 4

The effects of virtual exergaming on the SJ, TOJ, RT, and SIFI tasks in community-dwelling older adults

In preparation: Basharat A, Muñoz JE, Mehrabi S, Cao S, Boger J, Middleton L, and Barnett-Cowan M. The effects of virtual exergaming on the SJ, TOJ, RT, and SIFI tasks in community-dwelling older adults. To be submitted to the Journal of Vision. [35]).

4.1 Abstract

Chronic and acute aerobic exercise has been associated with positive changes in higher-order cognitive function as well as multisensory processing. Here, we investigate the effects of exergaming on community-dwelling older adults to determine how chronic (6 weeks) and acute bouts of exergaming within virtual environments, as compared to reading, impact multisensory processing. Here, multisensory processing was measured using commonly utilized tasks including the audiovisual: response time (RT), simultaneity judgments (SJ), sound-induced flash illusion (SIFI), and temporal order judgments (TOJ) tasks. We believe this is the first effort to remotely investigate acute and long-term effects of exergmaing on multisensory processing using not only an experimental, but also a control condition. This non-randomized control trial recruited 13 community dwelling older adults who were sent virtual-reality headsets pre-loaded with custom-designed exergames called 'Seas the Day' and 14 community-dwelling older adults that were recruited to read for 6 weeks. Baseline (week 1) and post-intervention (week 8) measures were collected before the start and at the end of the intervention-period. Our results revealed that both exergaming and reading interventions impact multisensory processing, however, those who participated in the exergaming intervention were found to achieve higher accuracy scores on the audiovisual trials of the SIFI throughout the intervention. They additionally exhibited faster response times on the audiovisual RT task throughout and post-intervention. Although promising, these results must be interpreted with caution as baseline differences between

the two groups may have contributed to the observed differences. Our results indicate that those in the reading group were not only older, but also exhibited a greater potential for improvement during baseline testing as they performed worse on both the SIFI and the RT tasks as compared to those in the exergaming group. Our results highlight the importance of inclusion of a control group, however, given the unexpected improvement in the reading group, our results suggest that reading may not necessarily be the best control condition for future research.

4.2 Introduction

Previous research (including the previous chapter) suggests that physical exercise impacts not just cognitive but also perceptual processes. However, much of the research exploring the impact of physical activity (PA) in older adults came to a halt due to the COVID-19 pandemic from 2020 to 2022. During this time, many older adults were unable to continue to partake in PA due to closures of exercise programs and fitness facilities. Staying physically active during the COVID-19 pandemic, however, was particularly important for older adults as PA has been found to be a protective factor against viral infections that can improve the immune response [336, 511]. However, as exercise opportunities were restricted and because of disruptions to group exercise programs and other community-based activities, there was an increased risk of social isolation and loneliness in older adults during the pandemic. These factors were thought to lead to and exacerbate health-related consequences such as increased risk of falling, cognitive decline, and dementia in older adults [362, 109, 63, 18, 174].

Given the limited access to PA, adopting strategies that facilitated participation in PA in the safety of one's home was prioritized in this study. Given that lack of motivation is one of the primary barriers to PA participation in older adults (with and without cognitive impairment), interactive video games that combine gaming and physical activity, referred to as exergames, have been thought of as a useful strategy to encourage PA [227]. In particular, virtual reality (VR) exergames provide a multisensorial environment that offer unique exercise options and require minimal guidance and supervision from researchers and/or medical professionals [234]. The immersive experience of VR can provide access to enjoyable virtual environments that are not otherwise readily available (e.g., beaches or forests) especially during the COVID-19 pandemic, while targeting desired physical activity outcomes through gameplay [234]. In addition to encouraging participation in PA, VR is an innovative technology that has been employed as a therapeutic tool to support rehabilitation and to promote the health and wellness of older adults [227, 328, 507]. Further, research suggests that when paired with exercise, VR is associated with motor learning, neural plasticity, improved cognitive function (including executive function and processing speed), increased energy, reduction in tiredness, and improvement in overall quality of life [296, 507, 368, 9, 427, 116, 263]. In addition, VR exergaming has been found to be a complementary addition to conventional PA [479, 12, 189]. However, because the literature related to the implementation and utilization of VR to promote exercise through exergaming is quite limited, the larger research team associated with this project, previously developed and tested an early VR exergame prototype. Here, older adults living in long term care facilities, along with their therapists, were recruited to assess acceptability and feasibility of exergaming in this population. They found that VR exergaming was indeed feasible and acceptable and that it provoked similar movements to conventional exercise sessions [138, 139, 140]. Additionally, through the use of participatory design, the research team was able to identify certain factors that should be incorporated in head mounted display (HMD)-VR design to maintain the interest of, and to keep participants engaged, while maintaining their safety [138, 139, 140]. These factors included the following: providing clear verbal instructions to participants in the form of story-telling, avoiding the use of buttons for ease of movement, using high contrast tasks that are intuitive, signalling how to interact with objects within the game, allowing exploration, clearly indicating when a task was successfully accomplished, and finally consulting specialists and stakeholders to obtain feedback from end-users [139].

Given preliminary results related to the potential benefits of VR exergames to promote PA among older adults and given that the sensory integration processes changes with age and may benefit from exercise, we have designed one of the first HMD-VR exergames for community dwelling older adults to help assess the relation between these factors. Using HMD-VR exergames allowed the research team to work within the constraints of the COVID-19 pandemic to provide creative solutions to not only further understand how these mechanisms are affected by the aging process and with exercise, but also to potentially help improve the quality of life of this population. Based on the previous findings obtained by the larger research-team [139], this project used participatory design to engage with, and obtain feedback from, end-users (older adults living with MCI or dementia) and exercise professionals (e.g., therapists) to design and develop a set of exergames with VR Vision, the industry partner for the development of exergames, that were specifically tailored to the unique needs and preferences of older adults. Note that although the initial design was more focused on older adults living with cognitive impairment, the exergames that were designed through our collaboration with this population can also be utilized for cognitively intact older adults. Although the larger project seeks to evaluate the feasibility, usability, acceptability, and potential health benefits of our co-designed VR exergames in community-dwelling older adults with and without cognitive impairment, these will not be the focus of this chapter. For the purpose of this thesis, I will focus on the potential impact of exergaming on the multisensory integration process.

Unlike commercially produced products that are built for general populations, the VR exergames used for this project were built in close collaboration with end-users (i.e. older adults living with cognitive impairment, kinesiologists, exercise therapists, etc.) while carefully considering their needs and preferences. Using this strategy made it possible for all of our participants, including those living with mild cognitive impairment, to safely participate in PA while also enjoying the unique virtual environments that were specifically designed with feedback from end-users. We anticipated that our co-designed games would make it possible to engage in exercise activities within an enriched, secure, and enjoyable virtual environment and would provide an engaging strategy to promote physical activity participation, which was especially pertinent during the COVID-19 pandemic where access to other forms of physical activity were limited.

Furthermore, engagement in this 6-week intervention program (further details in the methods below) was anticipated to increase access to tailored PA programs that align with the World Health Organization's (WHO) and the Canadian Society for Exercise Physiology's (CSEP) physical activity recommendations for older adults as well as with the Canadian dementia research priorities to improve access to health care. We also anticipated that these VR exergames would potentially enhance sensory integration in older adults with and without cognitive impairment. Limited evidence for the effect of exergaming on sensory integration processes is provided through a study conducted by Merriman and colleagues [314]. In their study, Merriman and colleagues [314] pseudo-randomly assigned 76 healthy and fall-prone older adults to either a 5-week VR exergame training condition ($n = 38$; 17 fall-prone) that required them to shift their balance on a Wii board twice a week for 30 minutes, or to a control condition ($n = 38$; 17 fall-prone) where they were asked to record any physical activity (in a diary) according to intensity of the activity (i.e., light, moderate, intense). Susceptibility to the sound induced flash illusion (SIFI; see methods for more information) was measured prior to the start of, as well as at the end of the intervention. They found that while balance and postural control improved for all the participants assigned to the intervention condition, no difference in susceptibility to the illusion was found between the control and the intervention group at the post-assessment stage. Further, they failed to find an overall group difference in susceptibility to the illusion between fall-prone and healthy older adults. Although the researchers failed to find a main effect of intervention training on susceptibility to the illusion, they did observe a trend for better performance for fall-prone older adults in the intervention group as their accuracy improved from 36.79% to 52.21% post-intervention. Upon further investigation of the fall-prone participant category, a difference in mean SIFI accuracy was observed whereby fall-prone older adults living in sheltered accommodations were less accurate than community-dwelling older adults. Interestingly, they additionally found that fall-prone older adults living independently were also less accurate than healthy older adults living in sheltered accommodations, indicating that health-status (fall prone or not) impacts multisensory integration. To further understand the differences between these groups, correlational analyses were conducted between the Berg Balance Scale scores and susceptibility to the illusion pre- and post-intervention for control and target groups which revealed that susceptibility was correlated with improved balance in fall-prone older adults who were in the training group only. Such a correlation suggests that as the Berg scores improved for fall-prone older adults following the VR exergame training intervention, so too did their susceptibility to the illusion. In other words, a link between balance control and efficient sensory integration is thought to exist and although the focus of our VR exergames is not to improve balance, we hope to see changes in sensory perception due to an increase in the amount of physical activity that our participants engaged in, as assessed via the Physical Activity Scale for the Elderly (PASE).

Given that recent studies have shown that changes in perceptual processing, as observed in the aging population, may be associated with increased risk of falling, increased fear of falling, poor decision making, and an inability to dissociate from distracting or unrelated cues [135, 415, 314], VR exergaming interventions such as the one being investigated in this project may help to decrease the likelihood of incorrect or dangerous outcomes for community-dwelling older adults. Of importance, the VR exergames that were utilized in our project were designed to be completed while seated as aging is associated with loss of balance control [239] and although loss of balance control can arise from multiple factors, one of the major factors, as alluded to above, is inefficient processing and coordination of sensorimotor modalities. Balance control is dependent on continuous integration of information from relevant senses including the vestibular, proprioceptive, auditory, and visual modalities [28, 83, 15, 274], and because increased physical activity is associated with better balance control [199, 315], this project aims to determine whether exergaming can help improve sensory integration, one of the underlying processes of balance. This is an exploratory study, as we have designed one of the first studies to determine whether long-term engagement with exergaming impacts perceptual processes related to integration of multisensory stimuli as measured through the audiovisual response time (RT), simultaneity judgment (SJ), temporal order judgment (TOJ), and the sound-induced flash illusion (SIFI) tasks. The following hypotheses, based on limited research, were proposed. We hypothesized that 6-weeks of participation in our co-designed exergame intervention, as compared to a reading control, would: 1. reduce susceptibility to the SIFI, 2. reduce the width of the TBW for both the SJ and TOJ tasks, and 3. reduce response time and increase race model violations. We additionally conducted exploratory analyses to investigate the acute effects of exergaming and reading on multisensory processing as assessed via the RT and SIFI tasks.

4.3 Materials and Methods

4.3.1 Experimental Setup

The data obtained for this chapter stems from a larger non-randomized controlled trial where the intervention (exergaming) and control (reading) groups were recruited consecutively to capture and evaluate the effects of using a VR exergame program on physical activity, cognition, perception, mental well-being, and game experience in a group of community-dwelling older adults. Both groups were recruited using the same inclusion and exclusion parameters and followed the same timeline, with the exception that those in the control group read instead of engaging with exergames. The study consisted of two stages (1) pre- post-assessments and (2) focus group/semi-structured interviews that were carried out over a period of 8 weeks. The perceptual tasks utilized in these studies were created using PsychoPy builder, exported into PsychoJS (Javascript), and hosted on Pavlovia, allowing us to run the experiments in a browser. PsychoPy was used to design the tasks and Pavlovia was utilized as a host as previous literature indicates that when used in conjunction, these had the lowest latencies across OS/browser combinations, achieving a precision of under 3.5 ms [58]. All participants completed the perceptual tasks on their computing device of choice (either laptop or desktop computer) using Firefox as their browser to limit variability across the participants. Prior to the start of each task, participants were provided with instructions embedded in each task. They were asked to sit in a quiet room, to turn off their lights, and to ensure that the brightness as well as the sound on their device were maximally bright and loud respectively to increase ensure that they perceived the stimuli as supra-threshold. Participants were asked not to use headphones to ensure that the auditory stimuli appeared to stem from the same location as the visual stimuli.

When completing any of the four perceptual tasks, participants were asked to directly face their personal computing device and to place their personal computing device at arm's length, equating to an approximate distance of 57 cm. The visual stimuli were presented in the form of white circles, subtending 2° of visual angle and they appeared approximately 8° below the fixation cross (visual angle = 1.5 °), which appeared at the center of the screen and remained on display throughout the trial for approximately 16 ms. Auditory stimuli were presented in the form of a beep (approximately 3500 Hz, 16 ms, 68 dBA) through speakers either connected to the participant's device or through external speakers placed besides the screen. In order to reduce temporal predictability, each trial began with the stimulus being presented after a delay of 1000-3000 ms. A computer keyboard either attached to, or external to the computing device was utilized by participants to input their responses for each trial. Participants completed the SIFI, SJ, TOJ, and RT tasks in a randomized order during the baseline and post-intervention sessions. A response from the participant initiated the next trial for each task except the RT task, where a lack of response for over 3 seconds triggered a message reminding the participant to respond as soon as they detected any of the stimuli. Participants were presented with practice trials prior to the commencement of each of the experimental tasks.

4.3.2 Participants

Community dwelling older adults ($n = 13$, experimental/exergame group and $n = 14$, control/reading group) with or without cognitive impairment were recruited to partake in a larger study entitled 'VR-At-Home: Feasibility of using virtual reality (VR) exergames to promote physical and mental well-being in community-dwelling older adults (contactless remote testing). Community-dwelling older adults were identified through the Waterloo Research in Aging Pool (WRAP), the Centre for Community, Clinical and Applied Research Excellence (CCCARE) mailing list, as well as professional networks (e.g., AGE-WELL, Canadian Frailty Network, etc.). Personal Twitter and LinkedIn were also utilized for advertisement and recruitment purposes.

The following inclusion criteria was used: participants were 60 years of age or older, able to provide their own consent, able to complete the Montreal Cognitive Assessment (MoCA) and achieve a score of 18 or higher, able to communicate verbally in English (consent form was read to participants if they experienced any difficulties), able to participate in light-to-moderate unsupervised activity without requiring doctoral approval (as assessed through the 'Get Active Questionnaire'), had access to either a laptop or desktop PC to perform the task, and had access to internet in their place of residence. Participants were excluded if: a diagnosis of moderate to severe dementia was obtained (assessed through the MoCA; MoCA score < 18), they had hearing impairment which may have interfered with their ability to understand verbal cues as well as their ability to hear the auditory cues in the perceptual and cognitive tasks, they had an ear infection in the past 12 months, they had a diagnosis of a disease of the middle ear such as Meniere's disease, they had uncorrected visual impairment (e.g., cataracts, glaucoma, macular degeneration, etc.) which may have interfered with their ability to see and interact with the exergames and with their ability to perform the perceptual and cognitive tasks, they were prone to severe motion sickness, they commonly experienced motion sickness or nausea when riding a car, train, or bus (self-reported), they had any pre-existing conditions that would preclude them from doing the exercise activity (as advised by a physician or a healthcare professional or self-reported in GAQ), and if they had a heart pacemaker. Demographic information from the exergaming and reading groups are provided below.

Of the 13 participants in the exergame group, 7 were males (all Caucasian except for 1 individual who identified as 'mixed'). The mean age for this group was 68.46 (s.e. = 1.34). Education level was broadly distributed with 1 individual with a high school degree or equivalent, 1 with some post-secondary certificate, diploma, or degree, 6 with post-secondary certificate, diploma, or degree, and 4 with post-graduate degrees. The results revealed that most individuals in this group were educated past high school and held post-secondary diploma or above. Further, cognitive function, as assessed using the MoCA, revealed a mean score of 26.69 (s.e = 0.75) for this group. Participants also reported on their habitual exercise habits using the PASE both at baseline (mean = 120.71, s.e. = 15.72) and at post-intervention (mean = 120.55, s.e. = 16.84). Of the 14 participants in the reading control group, 2 were males (all Caucasian). The mean age for this group was 74.83 (s.e. = 1.48). Education level was broadly distributed with 4 individuals with high school degrees or equivalent, 7 with post-secondary certificate, diploma, or degree, and 3 with post-graduate degrees. Those in the reading group obtained a mean score of 25.93 (s.e = 0.77) on the MoCA. Participants reported a mean PASE score of 129.59 (s.e. = 12.98) at baseline and a mean score of 126.59 (s.e. = 9.67) at post-intervention.

4.3.3 Procedure

As mentioned above, in this dissertation, data is utilized specifically from the four perceptual tasks described below to determine the effects of partaking in a 6 week VR exergaming intervention as compared to 6-weeks of reading on multisensory integration processes. We will however begin this section by describing the design of the larger study and end this section with a detailed description of the four perceptual tasks.

Prior to the start of the intervention, participants were contacted via email or by telephone by a member of the research team to provide them with information regarding the study, answer any questions, and ensure that they met the inclusion criteria. To confirm eligibility, a screening questionnaire and the Get Active Questionnaire (GAQ) were used to ensure that participants met the inclusion criteria and that it was safe for them to exercise at home without a referral from a doctor or medical professional. After their eligibility was confirmed, verbal consent was obtained and participants were asked to complete a demographic questionnaire (history of falls was obtained during this stage). All of these questionnaires (Screening, GAQ, and demographic questionnaire) were completed either via the telephone or online using Qualtrics and with the assistance of a trained researcher, if necessary. All participants who provided verbal consent and met the inclusion criteria were then sent a VR headset with controllers, a booklet containing instructions, description of the tasks, a weekly checklist, and a series of links to complete the questionnaires, perceptual, and cognitive tasks if they were in the exergame group. If they were in the reading group, participants were sent a binder containing the description of all the tasks, a weekly checklist, and the links to complete the questionnaires, perceptual, and cognitive tasks.

The following tests were completed prior to the intervention, in the span of three days by both the experimental and control groups **(week 1)**:

Day 1 (approximately 60 minutes total) consisted of completing a remote MoCA (10-15 minutes to complete), PASE (5-10 minutes to complete), the short form of the Geriatric Depression Scale (GDS-15; 5 minutes to complete), Physical Activity Affect Scale (PAAS; 2-3 minutes to complete), and an exercise self-efficacy scale (5 minutes to complete). MoCA was completed using an audio-video conferencing platform (i.e., Zoom) with the guidance of a trained researcher. The rest of the questionnaires were completed online using Qualtrics. Participants also spent some time with the student research team (30 minutes) to get to know the team and the research questions that each member of the team was interested in. This was implemented after receiving feedback from the pre-pilot co-design process where the participants indicated how much they appreciated the social aspect of participation in a research study and expressed desire for further interactions.

Day 2 (approximately 20-40 minutes total) consisted of completing four perceptual tasks including the audiovisual RT task, the SIFI, the SJ task, and the TOJ task; these tasks took approximately 5-10 minutes each to complete (see below for detailed descriptions of these tasks). These tasks were distributed online wherein participants were provided with URLs for each of the tasks that they accessed using their personal computers. All instructions were embedded within the tasks and did not require the presence of a researcher to be completed. However, a researcher joined the participants for the entire duration of the first session of these tasks in order to ensure that all inquiries and technical difficulties were resolved as soon as they arose. Further, researchers met with all the participants on a bi-weekly basis to ensure that they were not experiencing any issues, and to answer any questions that they may have had regarding the tasks.

Day 3 (approximately 30 minutes total) consisted of completing the flanker test (10-15 minutes to complete), the oral trail making test (OTMT; 5 minutes to complete), and the verbal fluency test (VF animal naming; 2-3 min to complete). OTMT and VF were administrated in an oral format via phone or via an audio-video conferencing platform (i.e., Zoom). Similar to the perceptual tasks, the Flanker task was distributed online wherein participants were provided with the URL for the task so that they could access it using their personal computing device. All instructions were embedded within the task and did not require the presence of a researcher to be completed. However, a researcher joined the participants for the entire duration of the first session of the flanker task in order to ensure that all inquiries and technical difficulties were resolved as soon as they arose.

These clinical assessments as well as all the perceptual and cognitive tasks (e.g., OTMT, and Flanker tasks) provide characteristics about each participant that will be utilized in data comprehension and analysis for the larger study. In total, the pre-assessments took between 1 hour and 40 minutes to 2 hours and 10 minutes to complete.

Once all the assessments and tasks were completed in week 1, participants then started either the exergame or reading intervention remotely, from their home. The intervention was **6 weeks in total**. Each participant in the exergame group was provided with an Oculus Quest 2 VR headset, VR controllers, a booklet containing instructions, a weekly checklist (to easily track their progress), the VR system care guide, various questionnaires including the rate of perceived exertion (OMNI RPE), perceived enjoyment, and PAAS, and blank pieces of paper to jot down comments and concerns. The headset along with the sanitizing protocol, booklet of instructions, and questionnaires were all delivered to the participants' homes via mail or by a member of the research team who followed the public health guidelines regarding social and physical distancing protocol during the pandemic. As mentioned above, participants in the reading group were provided with the same items as those in the exergame group, except for the Oculus Quest 2 VR headset and VR controllers, as well as questionnaires related to engagement with the exergames (RPE and perceived enjoyment).

The VR headset contained a set of custom-made VR exergames called 'Seas the Day', that were specifically co-designed with and for older adults. Our participants were asked to engage with these exergames three times a week for 6 weeks. Participants were encouraged to play in the mornings and to try to play on the same days every week. Participants engaged with the exergames for approximately 15-20 minutes and they were encouraged to exert a light to moderate amount of energy such that the exergame achieved a light to moderate intensity. Participants in the reading group were asked to read a book for 15-20 minutes and as with the exergaming group, those in the reading group were also asked to read in the mornings and on the same days every week. In order to assess the acute effects of exergaming and reading on cognition, perception, and mood, participants were asked to complete specific questionnaires and tasks before and/or after each session of play or reading. The specific tasks and questionnaires that participants in the exergame group were asked to complete are outlined below:

Complete after each session (one page):

1. Perceived enjoyment (1 minute)
2. Perceived rate of exertion (pictorial OMNI scale; 1 minute)

Completed only at specific time points:

1. PAAS (Completed once per week before and after any one session; 2-3 minutes)
2. RT test (Completed before and after any one session during weeks 1, 3, and 5; 5-10 minutes)
3. OTMT (Completed before and after any one session during weeks 1, 3, and 5; 5 minutes)

4. SIFI (Completed before and after any one session during weeks 2, 4, and 6; 5-10 minutes)
5. Flanker Task (Completed before and after any one session during weeks 1, 3, and 5; 10-15 minutes)
6. Exercise Self-efficacy questionnaire (Completed before and after any one session during weeks 1, 3, and 5; 5 minutes)
7. Verbal Fluency (To be completed before and after any one session during weeks 1, 3, and 5; 2-3 minutes)

Completed at-will:

Free form comments – participants were invited to share any thoughts or feelings they wished to at any time by jotting them down in a blank journal; there were no minimum or maximum requirements and this component was optional for all participants.

Participants in the reading group were asked to follow the same timeline as outlined above for the exergame group, however, they did not complete the perceived enjoyment and perceived rate of exertion questionnaires.

Once the participants completed 6 weeks of reading or exergaming interventions, post-intervention assessments took place during **week 8**, which, like the pre-assessments, were divided into three days and were completed in the same order as described above.

Detailed Procedure of the Perceptual Tasks

The procedures used for this chapter are slightly modified from our previous work, as the tasks were originally designed to be completed in a lab setting and are now being completed online. As such, the auditory stimuli were presented for a longer period of time and also had a higher frequency (3500 Hz, 16 ms, 68 dBA) in order to help participants perceive the stimuli at a supra-threshold level. Further the fixation cross was not only larger in size, but was also chosen to minimize involuntary eye movements [462] and thus, it looked like the combination of a bulls eye and a cross hair (visual angle = approximately 1.5 °). Participants were instructed to fixate on this cross throughout the experimental procedure, as is the case in our previous in-lab studies. Further, the SOAs utilized in this study were also modified from those used in the lab to ensure that participants were able to complete each task in a shorter period of time without losing interest or abandoning the task or the study. In order to maintain consistency across the four perceptual tasks of interest for this project, the same stimuli and stimulus duration were used (see the experimental setup section above for details).

Sound Induced Flash Illusion

The SIFI task consisted of three conditions (vision-only, auditory-only, and audiovisual). In the vision-only block, two flashes were presented, and the participants' task was to indicate the number of flashes they saw. In the auditory-only block, two beeps were presented, and the participants were asked to indicate the number of beeps they heard. The following stimulus onset asynchrony (SOAs) werre used in these conditions: 70 ms, 150 ms, and 230 ms for both 2 beep and 2 flashes conditions (see Figure 4.1 and Table 4.1 for further details). There were 30 trials in each of the unimodal conditions, where each SOA was presented 10 times. Participants were explicitly told to respond as accurately as possible as opposed to responding quickly. Note that the unimodal visual condition trials were randomly interleaved with the multimodal audiovisual trials and the auditory block was completed separately, as instructions and modality of interest differed between auditory and audiovisual conditions.

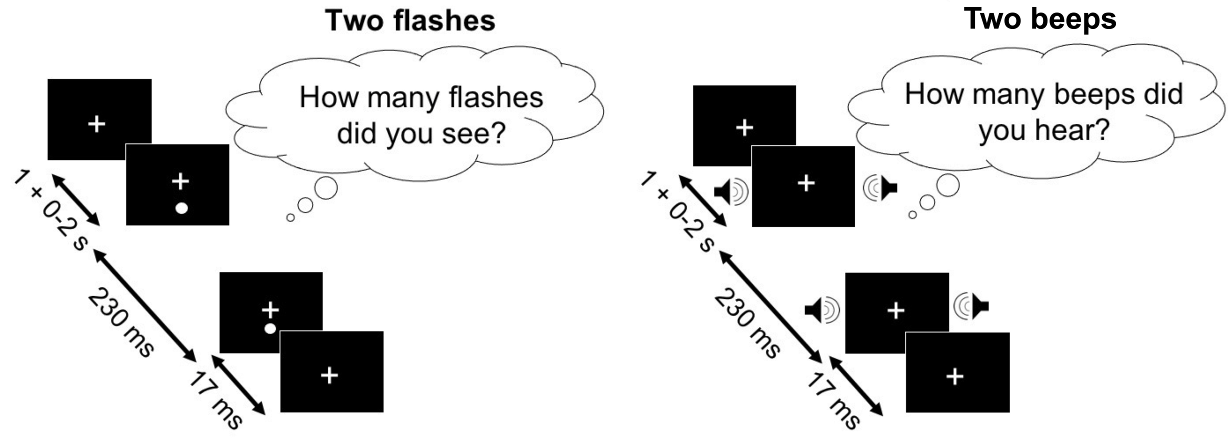


Figure 4.1: Visual-only (left) and the audio-only (left) trials were presented to participants with the SOAs of 70, 150, 230 ms. In both tasks, the first stimulus of the pair can appear 1-3 sec following the fixation cross and the second stimulus appears between 70 – 230 ms after the first stimulus.

The audiovisual trials consisted of two control conditions (1 beep/1 flash and 2 beeps/2 flashes) as well as the illusory condition (2 beeps/1 flash). In the audiovisual control conditions, the auditory and visual stimuli were presented simultaneously. In the 2 beeps/1 flash (illusory condition) auditory-lead trials, the auditory stimulus was presented first, after which the auditory and visual stimuli were presented simultaneously following a variable SOA. In the 2 beeps/1 flash vision-lead trials, the first auditory stimulus was accompanied by a visual stimulus and the second auditory beep was presented following a variable SOA. The following SOAs were utilized for the multimodal condition: 0 ms, ±70 ms, ±150 ms, and ±230 ms; here '+' indicates vision-lead trials while '-' indicates auditory lead trials. The three audiovisual conditions were randomly presented within the testing block to avoid response bias. Participants were asked to fixate on the fixation bulls-eye for the duration of the task and to report the number of flashes seen, while ignoring the auditory stimuli. All conditions were repeated 10 times for a total of 100 trials (including 10 repetitions for 0 SOA where a single beep and flash were presented simultaneously; see Figure 4.2 and Table 4.1 for further details). In total, 166 trials were presented for all three conditions (vision-only, auditory-only, and audiovisual) including 6 practice trials, which were presented in order to help familiarize the participants with the task. This task took approximately 10 minutes to complete. Previous literature indicates [399] that participants have reported having seen or heard three or more stimuli, thus responses will not be limited to '1' or '2', as participants can perceive more than the presented number of stimuli (audio or visual). Participants were explicitly told to respond as accurately as possible as opposed to responding quickly. Participants completed this task not only at the beginning and end of the intervention but also six times during the intervention (pre- and post-gameplay or reading during weeks 2, 4, and 6 for a total of 8 times).

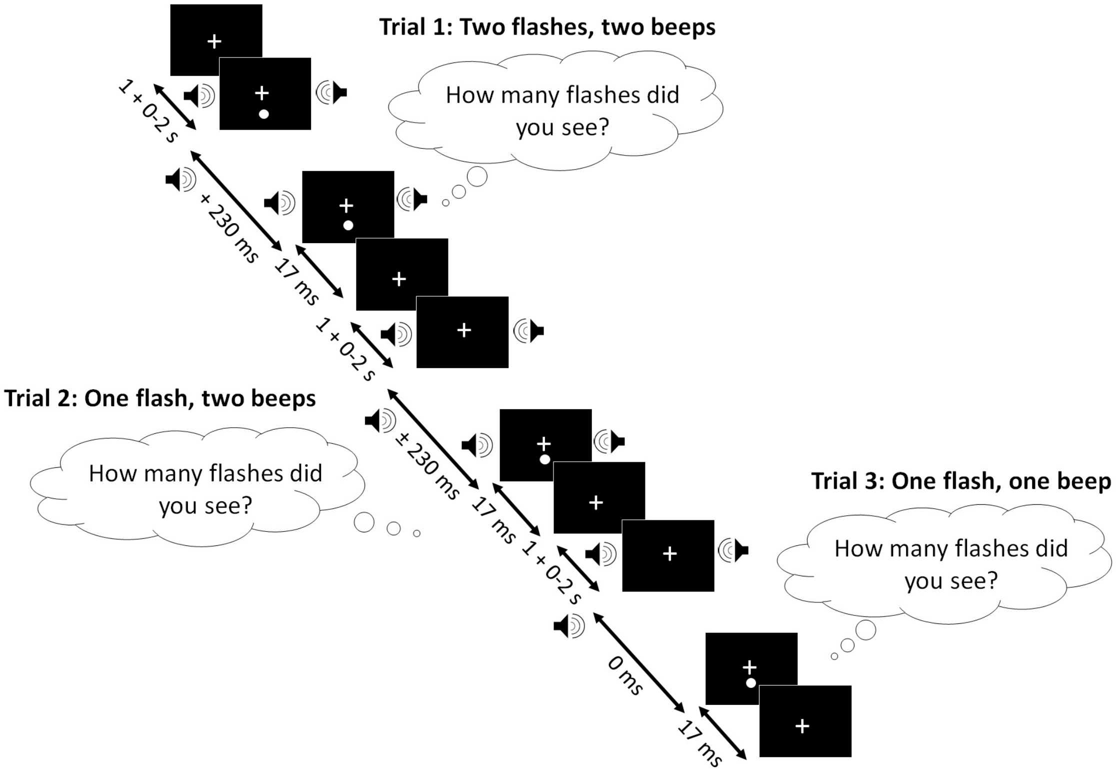


Figure 4.2: The control conditions consisted of the presentation of 2 flashes/2 beeps (trial 1) and 1 beep/1 flash (trial 3), while the illusory condition consisted of the presentation of 2 beeps/1 flash (trial 2). In the 1 beep/1 flash control condition, the auditory and visual stimuli were presented simultaneously. In the 2 beeps/2 flashes condition, the following SOA was used 70, 150, 230 ms. In the illusory condition, the auditory stimulus was either presented prior to the presentation of the auditory and visual stimuli (auditory-lead) following a variable SOA 70, 150, 230 ms or a visual stimulus was presented alongside the auditory stimulus followed by the second auditory stimulus (vision-lead) at a variable SOA of 70, 150, 230 ms. For all the conditions, the first stimulus could appear 1-3 sec following the fixation cross and the second stimulus appeared between 0 – 230 ms after the first stimulus.

Condition	**# Beeps**	**# Flashes**	**SOAs (ms)**
Multisensory - illusory condition (2B1F)	2	1	-230, -150, -70, 70, 150, 230
Multisensory - control condition (2B1F)	2	2	70, 150, 230
Multisensory - control condition (1B1F)	1	1	0
Unimodal visual (0B2F)	0	2	70, 150, 230
Unimodal auditory (2B0F)	2	0	70, 150, 230

Table 4.1: This table provides details regarding the parameters utilized for each condition included in the Sound-induced flash illusion (SIFI). SOA = Stimulus Onset Asynchrony, where negative values indicate that a beep preceded the flash-beep pair.

Simultaneity Judgment

For the SJ task, participants were instructed to report, using the number '1' and '2' keys on their keyboard, to indicate whether they perceived the auditory and visual stimuli as occurring simultaneously (number '1' key) or not (number '2' key; see Figure 4.3). Participants were explicitly told to respond as accurately as possible as opposed to responding quickly. The following SOAs were utilized: 0 ms, ±70 ms, ±150 ms, and ±230 ms; here '+' indicates vision-lead trials while '-' indicates auditory lead trials. 10 trials were presented in a randomized order for each SOA and 6 practice trials were also presented for a total of 76 trials. This task took approximately 5-10 minutes to complete. Participants completed this task twice; before and after the intervention (exergame or reading).

Temporal Order Judgment

The experimental design of the TOJ task was identical to the SJ task with the exception of the task instructions. Here, participants were asked to report, using the number '1' and '2' keys on their keyboard, whether they perceived the visual (number '1' key) or auditory (number '2' key) stimulus as appearing first, 'synchronous' or 'I don't know' options were not provided for this task (see Figure 4.3). Here again, participants were explicitly told to respond as accurately as possible as opposed to responding quickly. This task took approximately 5-10 minutes to complete. Participants completed this task twice; before and after the intervention (exergame or reading).

Response Time Task

For the response time (RT) task, participants were told that they would either see a flash of light, hear a beep, or a combination of the two. Participants were instructed to press the response button (space bar key) as soon as they detected any one of the three experimental conditions: unisensory Visual (V), unisensory Auditory (A) or multisensory audiovisual (AV; audio and visual stimuli were presented simultaneously for each trial; see Figure 4.4). Each stimulus was presented 50 times in random order with 6 practice trials [289, 179, 319]). Note however, that if a participant responded too quickly (< 100 ms) or

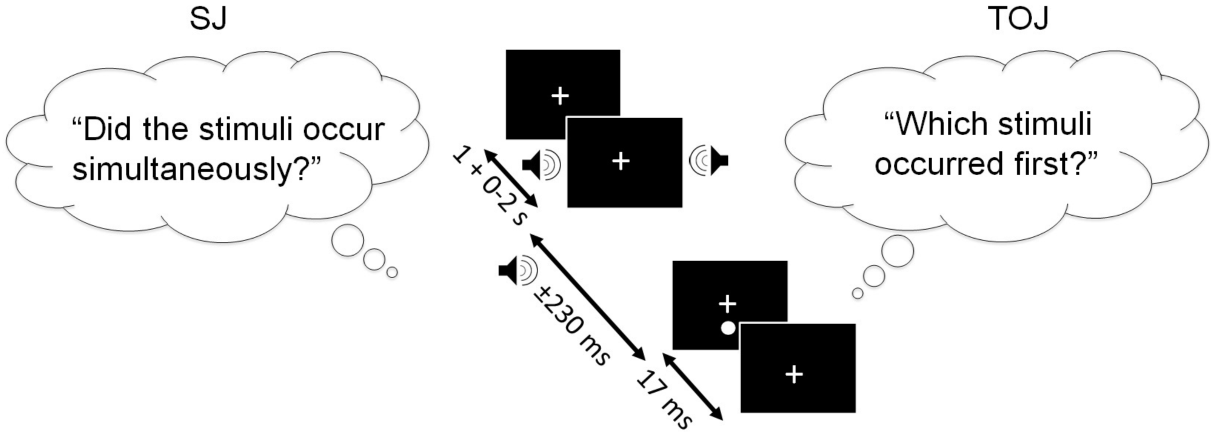


Figure 4.3: SJ task (left) and the TOJ task (right), presented with the SOAs of ±0, ±70, ±150, ±230 ms (-ve = sound appeared before light). In both tasks, the first stimulus of the audiovisual pair appeared 1-3 sec following the fixation cross and the second stimulus appeared between 0 − 300 ms after the first stimulus. The figure depicts the auditory stimulus (i.e., beep) as presented before the visual stimulus (i.e., flash). Note, that the experimental design for the SJ and TOJ is identical, however the instructions vary by task.

took longer than 3 seconds to respond to a trial where stimuli were presented, that trial was repeated. This task took approximately 5-10 minutes to complete. Participants completed this task not only at the beginning and end of the intervention but also six times during the intervention (pre- and post-gameplay or reading during weeks 1, 3, and 5 for a total of 8 times).

4.4 Statistical Analysis

4.4.1 Exergaming and Reading group comparison

Independent t-tests were utilized to assess any differences between age, MoCA scores, and Physical Activity Scale for the Elderly (PASE) scores from baseline and post-intervention and the results revealed that those in the reading group (mean age = 74.83, s.e. = 1.48) were significantly older as compared to those in the exergaming group ($p < 0.001$; mean age = 68.46, s.e. = 1.34), even after the Bonferroni correction was applied (0.05/3 = 0.0165).

4.4.2 Brief Description of Analyses

Note, that similar analysis procedures were utilized in this chapter as the chapters before for the SJ, TOJ, and RT tasks. The primary difference arose from assessing the impact of long-term engagement with VR exergame and reading interventions on the parameters obtained from the SIFI, SJ, TOJ, and RT task (a pre- and post-exergame and reading

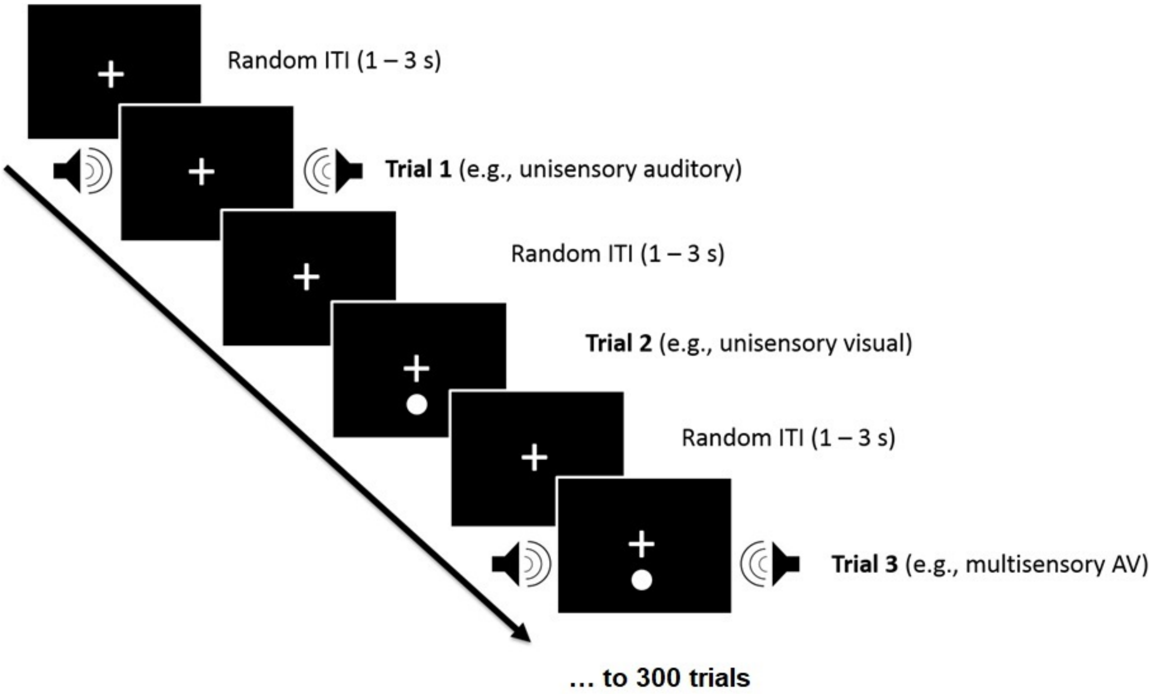


Figure 4.4: Participants were presented with unimodal [auditory (A) or visual (V)] or bimodal [audiovisual (AV)] stimuli and were asked to make speeded responses to all stimuli, regardless of sensory modality, by pressing the spacebar, which triggered the next trial. A, V, and AV stimuli were randomly presented with random inter-trial-intervals (ITIs) of 1 – 3 s.

engagement comparison). Further, acute changes to multisensory processing were also investigated for the RT and SIFI tasks using pre- and post-session scores obtained during the intervention. We will begin with a description of the statistical analyses for the task that hasn't been utilized in this dissertation and by the Multisensory Brain and Cognition lab in the past, the SIFI, after which we will describe the analyses for the SJ, TOJ, and RT tasks.

4.4.3 Sound Induced Flash Illusion

Repeated measures ANOVAs were conducted in order to determine whether there are sensory differences between those who participated in the exergame intervention and those who did not; analyses were conducted separately on the proportion correct for unimodal and multimodal conditions and on acute versus long-term data. To investigate the effects of long-term exposure to unimodal and multisensory perception between community-dwelling older adults who participated in the exergame intervention and those who read, a 2 [group: experimental (exposed to exergame intervention) or control (exposed only to perceptual tasks without engagement in exercise: reading group)] x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted for both auditory and visual cues. In order to assess whether participation in the exergame intervention as compared to a reading control would reduce susceptibility to the SIFI (hypothesis 1), a 2 (group) x 2 (time) x 4 (accuracy per condition: overall, 1-flash/1-beep or 2-flash/2-beep or 1-flash/2-beeps) mixed-design ANOVA was conducted for the multisensory cues. Exploratory analyses were further conducted to examine potential acute changes to unimodal and multisensory perception where a 2 (group) x 6 (time: pre-, post-week 2; pre-, post-week 4; pre-, post-week 6) mixed-design ANOVA was conducted for both auditory and visual cues, while a x 2 (group) x 6 (time) x 4 (accuracy per condition: overall, 1-flash/1-beep or 2-flash/2-beep or 1-flash/2-beeps) mixed-design ANOVA was conducted for the multisensory cues. Mauchly's test of sphericity was conducted and Greenhouse-Geisser adjustments were used to correct for lack of homogeneity of variance for all analyses if needed. Pairwise comparisons were also made to further assess the differences between group, condition, and time.

To further investigate the data, difference scores were computed by subtracting baseline accuracy and post-intervention accuracy to asses long-term changes and by subtracting the pre-session accuracy from post-session accuracy for sessions 1, 2, and 3 to assess acute changes. The data was analysed using mixed-design ANOVAs. A 2 (group) x 1 (time: baseline - post-intervention) x 4 (condition) mixed-design ANOVA investigating the effects of chronic exergaming versus reading was conducted and a 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, post-session 3 - pre-session 3) x 4 (condition) mixed-design ANOVA was conducted to investigate acute changes on the multisensory trials. While a 2 (group) x 3 (time) mixed-design ANOVA was conducted for the unisensory conditions to investigate acute changes. Mauchly's test of sphericity was conducted and Greenhouse-Geisser adjustments were used to correct for lack of homogeneity of variance for all analyses if needed. Pairwise comparisons were also made to further assess the differences between group, condition, and time. Further, independent t-tests were computed to investigate long-term changes for the unisensory conditions.

4.4.4 Simultaneity and Temporal Order Judgement Tasks

To estimate the accuracy (PSS values) and the precision (TBW) with which participants made their judgments for SJ and TOJ tasks, psychometric functions were fitted to each participant's responses as a function of SOA using SigmaPlot version 12.5. Each task was analyzed individually for each participant, with participant data fit to both Gaussian (for the SJ task; Eq. 1) and logistic (for the TOJ task; Eq. 2) functions:

$$Eq.1 : y = a \cdot e^{(-0.5((x-x\emptyset)/b)^2)} \tag{4.1}$$

Where a is the amplitude, xø is the PSS and b is the standard deviation.

$$Eq.2 : y = 100/(1 + e^{(-(x-x\emptyset)/b)})\% \tag{4.2}$$

Where a is fixed to 1, xø is the PSS and b is the standard deviation.

The best fit parameters corresponding with the PSS and TBW were identified for each participant separately, and those participants whose data was poorly estimated were excluded from further statistical analyses ($r^2 \leq 0.2$; $n = 1$ in the exergame group, $n = 3$ in the reading group).

As we were interested in the relationships between TBWs obtained from the two tasks and not their absolute size, we have chosen to analyze the b values (i.e., standard deviation) of these psychometric functions as a proxy for the size of the TBW to avoid discrepancies in the literature that differ when defining the absolute size of the TBW.

To assess whether participation in the exergame intervention, as compared to the reading intervention, would reduce the width of the TBW (hypothesis 2), a 2 (group: exergaming or reading) x 2 (task: SJ or TOJ) x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted for the TBW to determine the impact of task, time, and participation in the intervention (or lack thereof). The same analysis was conducted with PSS values. For both the SJ and TOJ tasks, difference scores were also computed by subtracting baseline values from post-intervention values for the TBW and PSS, and exploratory 2 (group) x 2 (task) mixed-design ANOVAs were conducted with said difference scores to further investigate and understand the data. Additionally, difference scores were computed for the 'a' values and an exploratory independent t-test was conducted with said values. Mauchley's test of sphericity was conducted, and if the dependent variables were not proportional to the identity matrix, the Greenhouse-Geisser adjustment was used for the mixed-design ANOVA. The Shapiro-Wilk test was used to determine normality for the independent t-test tests. Pairwise comparisons were also made to assess differences between the tasks, intervention, and group for the mixed-design ANOVA.

4.4.5 Response Time Task

Error analysis and outlier removal

As previously mentioned, participants responded to 150 trials in total (50 per condition). Data trimming procedures were not applied (see [178, 179, 288, 295, 289, 37]; however responses faster than 100 ms and slower than 1500 ms were set to infinity rather than excluded (see [289] for a race model inequality (RMI) tutorial and [37] where this method of data trimming was recently used). Here, we found that $< 1\%$ of trials for both exergaming (average accuracy = 99.78%) and reading (average accuracy = 99.4%) groups were outliers that were set to infinity.

Mean RT Analysis

In order to assess whether participation in the exergame intervention would reduce response time more so than participation in the reading intervention (hypothesis 3), a 2 (group) x 2 (time: baseline and post-intervention) x 3 (modality: auditory, visual, or audiovisual) mixed design ANOVA was conducted to determine the long-term impact of time, modality, and participation in the exergame versus reading interventions. Further, an exploratory mixed-design 2 (group) x 6 (time: pre-, post-week 1; pre-, post-week 3; pre-, post-week 5) x 3 (modality) ANOVA was conducted to determine the acute impact of time, modality, and participation in the exergame versus reading interventions. To further investigate the data, difference scores were computed by subtracting baseline response time from post-intervention response time to asses long-term changes, and by subtracting the pre-session response time from post-sessions response time for sessions 1, 2, and 3 to assess acute changes, which were compared using exploratory mixed-design ANOVAs. A 2 (group) x 1 (time: baseline - post-intervention) x 3 (modality) mixed-design ANOVA was conducted to assess long-term effects of intervention on multisensory processing. A 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, post-session 3 - pre-session 3) x 3 (modality) mixed-design ANOVA was conducted to assess acute effects of intervention on multisensory processing. Mauchly's test of sphericity was conducted and the Greenhouse-Geisser were used if necessary. Pairwise comparisons were utilized to further assess the differences between time, modality, and experimental group.

Test of the Race Model

The race model asserts that the response to redundant signals is produced by the modality that processes its respective signal the fastest and thus is the "winner" of the race [379]. Race model violations are typically tested using cumulative distribution function (CDF) models which compare the *observed* CDF distribution to the *predicted* CDF distribution [318].

To compute CDFs, each participant's data was sorted in ascending order for all three conditions (A, V, AV). Each participant's RTs were then be quantized into 5th percentile bins until the 100th percentile was reached, which yielded 21 bins in total.

Observed CDF distributions were formed using the following equation (Eq. 3):

$$Eq.3 : CDF_{observed} = P(RT_{AV} \leq t) \tag{4.3}$$

Where RT_{AV} represents the RT *observed* for the multisensory condition for any latency, t [97, 291]. *Predicted* CDF models were formed using the following equation (Eq. 4):

$$Eq.4 : CDF_{predicted} = Min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{4.4}$$

Where RT_A and RT_V represent the RTs *observed* for unisensory condition 'A' (i.e., auditory) and 'V' (i.e., vision), for any time, t [97, 291].

Differences between the *observed* CDF distribution and the *predicted* CDF distribution were calculated for every participant across all percentile bins as follows (Eq. 5):

$$Eq.5 : RT_{AV} = P(RT_{AV} \leq t) - min[P(RT_A \leq t) + P(RT_V \leq t), 1] \tag{4.5}$$

When the *observed* CDF is less than or equal to the *predicted* CDF, the race model is accepted. However, the race model is violated when the *observed* CDF is greater than the *predicted* CDF. Thus, a negative value (or zero) indicates acceptance of the race model while values greater than zero provide evidence for multisensory integration as they are indicative of race model violations [97, 293].

To investigate if the race model inequality was violated, Gondan's permutations were computed over the fastest quartile (0 - 25%) of responses [178, 179, 289] for all the sessions for both the exergame and reading groups (see Tables 4.2 and 4.3 below for outcomes of Gondan's permutations for the exergaming and reading groups). Further, in addition to performing Gondan's permutation test of race model, [179], we also calculated the area under the curve (AUC; which served as our independent variable) in an effort to further quantify the magnitude of RMI violation over the first quartile of responses. As described in [289], the AUC was calculated for each time bin over the 0-25th percentile, where the difference value obtained from the observed CDF and the predicted CDF from the first time bin (i.e., 0%) was summed with the difference value obtained from the second time bin (5%) and divided by two. This was repeated for the subsequent time bins until the 25th percentile was reached. All the values obtained were summed to generate a total AUC of the CDF difference wave during the 25th percentile.

Time	t_{max}	t_{crit}	**p-value**
Baseline	4.503	2.281	$p \leq 0.001$
Session 1 pre-exergaming	3.064	2.337	$p \leq 0.05$
Session 1 post-exergaming	3.605	2.260	$p \leq 0.05$
Session 2 pre-exergaming	5.807	2.208	$p \leq 0.001$
Session 2 post-exergaming	4.965	2.095	$p \leq 0.001$
Session 3 pre-exergaming	5.866	2.336	$p \leq 0.001$
Session 3 post-exergaming	4.879	2.205	$p \leq 0.001$
Session 2 post-exergaming	6.185	2.164	$p \leq 0.001$

Table 4.2: This table provides details regarding the outcome of Gondan's permutation for 8 of the sessions over which data was collected for the exergaming group. Note that the statistically significant outcome of Gondan's permutations indicate that race model inequality was violated for all the sessions.

In order to assess whether participation in the exergame intervention would increase race model violations more so than participation in the reading intervention (hypothesis 3), a mixed-design 2 (group: exergame or reading) x 2 (time: baseline and post-intervention) ANOVA was conducted with AUC values in order to compare the long-term effects of exergaming and reading interventions on the AUC. Further, an exploratory mixed-design 2 (group: exergame or reading) x 6 (time: pre-, post-week 1; pre-, post-week 3; pre-, post-week 5) ANOVA was conducted with AUC values in order to compare the acute effects of exergaming and reading interventions on the AUC.

To further investigate the data, difference scores were computed for the AUC by subtracting baseline AUC and post-intervention AUC to asses long-term changes, and by subtracting the pre-session AUC from post-sessions AUC for sessions 1, 2, and 3 to assess

Time	t_{max}	t_{crit}	**p-value**
Baseline	5.991	2.227	$p \leq 0.001$
Session 1 pre-exergaming	7.207	2.26	$p \leq 0.01$
Session 1 post-exergaming	9.201	2.146	$p \leq 0.001$
Session 2 pre-exergaming	3.620	2.179	$p \leq 0.01$
Session 2 post-exergaming	4.773	2.094	$p \leq 0.001$
Session 3 pre-exergaming	5.909	2.153	$p \leq 0.0001$
Session 3 post-exergaming	6.394	2.339	$p \leq 0.0001$
Session 2 post-exergaming	7.094	2.291	$p \leq 0.001$

Table 4.3: This table provides details regarding the outcome of Gondan's permutation for 8 of the sessions over which data was collected for the reading group. Note that the statistically significant outcome of Gondan's permutations indicate that race model inequality was violated for all the sessions.

acute changes, which were compared using mixed-design ANOVAs. Exploratory independent t-tests were computed to compare the difference score obtained from post-intervention and baseline sessions between participants who engaged in the exergame versus reading interventions. Further, an exploratory 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, post-session 3 - pre-session 3) mixed-design ANOVA was conducted to assess acute effects of intervention on multisensory processing. Mauchly's test of sphericity was conducted and the Greenhouse-Geisser were used if necessary. Pairwise comparisons were also made to assess the differences between time and experimental group.

Median RT Analysis

The same analyses as those conducted with mean RT data were conducted for the median RT data.

4.5 Results

4.5.1 SIFI

SIFI: Audiovisual Conditions

A 2 (group) x 2 (time) x 4 (conditions) mixed-design ANOVA was conducted to investigate the effects of long-term exposure to exergaming and reading on the SIFI. The analysis revealed a significant interaction between time and condition ($F(3, 69) = 9.004$, $p < 0.001$; $\eta_p^2 = 0.281$). Planned pairwise comparisons revealed that compared to accuracy on the illusory trials at baseline, the accuracy was higher for all conditions at both baseline and at post-intervention, including the accuracy to the illusory condition at time of post-intervention

($p < 0.001$). Further, the results revealed that compared to overall accuracy achieved at baseline, the accuracy was higher for all other conditions (i.e., 1-flash/1-beep, 2-flashes/2-beeps, 1-flash/2-beeps) at both baseline and at post-intervention ($p < 0.05$), except for the accuracy achieved for the illusory condition from the post-intervention session (see Table 4.4 for more information). Note that Levene's test for Equality of Variance was violated for time and condition, as such non-parametric, Friedman tests were conducted, which revealed a main effect of time (χ^2 (1) = 6.570, p = 0.010) and a main effect of condition (χ^2 (3) = 70.024, $p < 0.001$). Conover's post-hoc pairwise comparisons investigating the main effect of condition revealed that the main effect was driven by a significantly higher accuracy to the 1 flash-1 beep condition as compared to the illusory (p = 0.002) and the overall accuracy conditions (p = 0.019). The pairwise comparison investigating the main effect of time failed to reveal a significant difference between accuracy obtained at baseline and post-intervention (p = 0.254), suggesting a lack of power to differentiate where the effect arose from. Finally, the analysis failed to find a significant effect of group (F(1, 23) = 2.711, p = 0.113; η_p^2 = 0.105). See Figures 4.5 and 4.7 for long-term accuracy scores obtained from the exergaming and reading groups. This concludes the results that were used to assess hypothesis 1, what follows are exploratory analyses that investigate potential acute changes, difference scores, and any changes in unimodal perception.

A 2 (group) x 6 (time) x 4 (conditions) mixed-design ANOVA investigating the acute effects of exergaming and reading revealed a significant main effect of group (F(1, 18) = 5.051, p = 0.037; η_p^2 = 0.219); pairwise comparisons found that those in the exergame (mean accuracy = 85.6%) intervention were significantly more accurate as compared to those in the reading group (mean accuracy = 78.2%; p = 0.037). Further, a significant interaction between time and condition (F(15, 270) = 1.753, p = 0.041; η_p^2 = 0.089) was found. Pairwise comparisons investigating the interaction between time and condition revealed multiple significant outcomes (refer to Table 4.5 for details), however, of primary interest, the results revealed that compared to pre-intervention accuracy to the illusion of session 1, accuracy to the illusion was higher for both pre- (p = 0.001) and post-sessions (p = 0.047) of session 3. Further, the results showed that participants achieved higher accuracy on the 1 flash-1 beep trials at all times that SIFI was administered as compared to overall accuracy ($p < 0.01$) and the accuracy achieved for the illusory condition ($p < 0.05$). Additionally, accuracy to the 1 flash-1 beep condition was also higher than the 2 flash-2 beeps condition but primarily during sessions 2 and 3. Note that Levene's test for Equality of Variance was violated for time and condition, as such non-parametric, Friedman tests were conducted, which revealed a main effect of condition (χ^2 (3) = 138.972, $p < 0.001$), but no main effect of time (χ^2 (5) = 3.282, p = 0.657). Pairwise comparisons investigating the main effect of condition found that accuracy to the 1 flash-1 beep condition was significantly higher than all the other conditions including accuracy to the overall condition (p = 0.003), illusory condition (p = 0.003), and 2 flashes-2 beeps condition (p = 0.014). See Figures 4.6 and 4.8 for acute accuracy scores obtained during the 6-week intervention from the exergaming and reading groups.

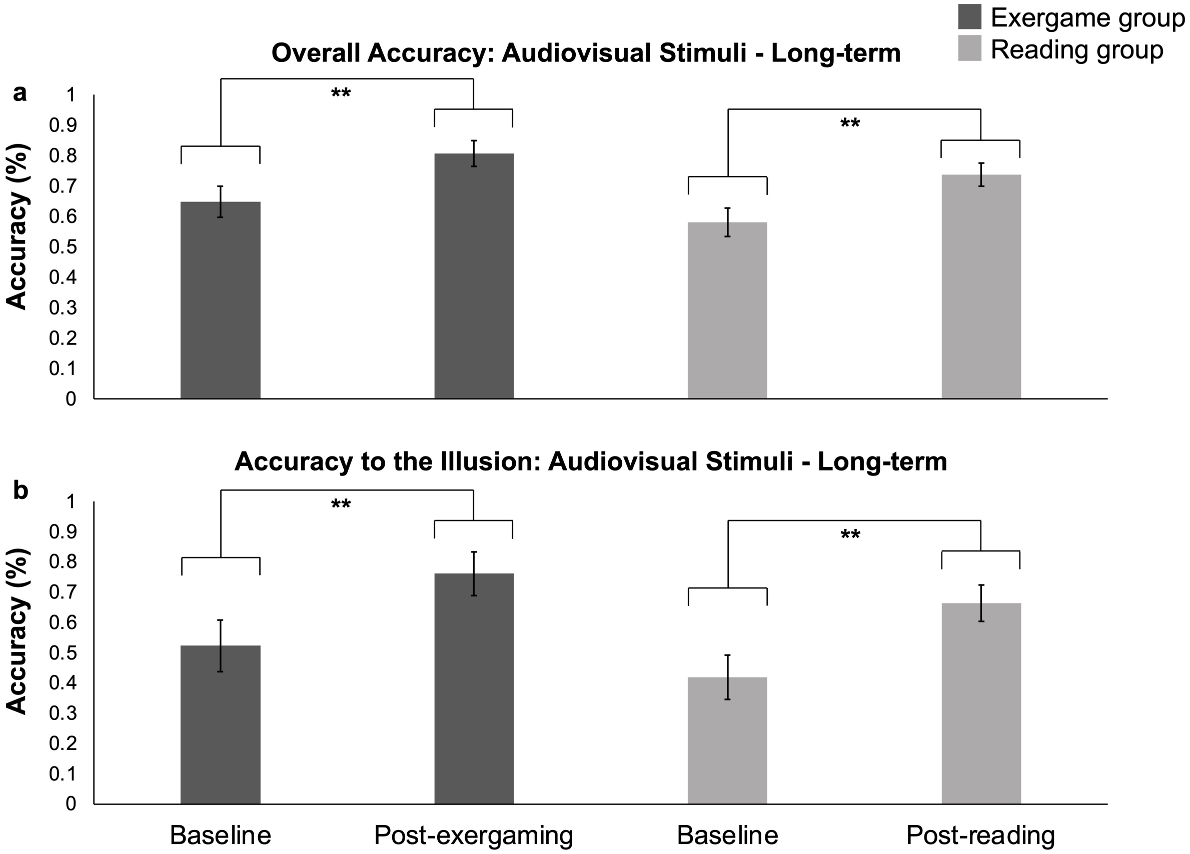


Figure 4.5: This figure depicts the accuracy achieved from baseline and post-intervention sessions for all the conditions combined (overall; panel a) as well as the accuracy achieved on the illusory condition (panel b) from both the exergaming group (dark grey) and reading (light grey) groups. Compared to overall accuracy (panel a) achieved at baseline, the overall accuracy was higher during post-intervention ($p = 0.005$). Further, compared to accuracy achieved on the illusory conditions (panel b) at baseline, accuracy was also higher during post-intervention ($p < 0.001$). Note here that although a main effect of time ($p = 0.010$) was found, pairwise comparison investigating this effect failed to reveal a significant difference between accuracy obtained at baseline and post-intervention ($p = 0.254$). The error bars indicate the standard error of mean (SEM).

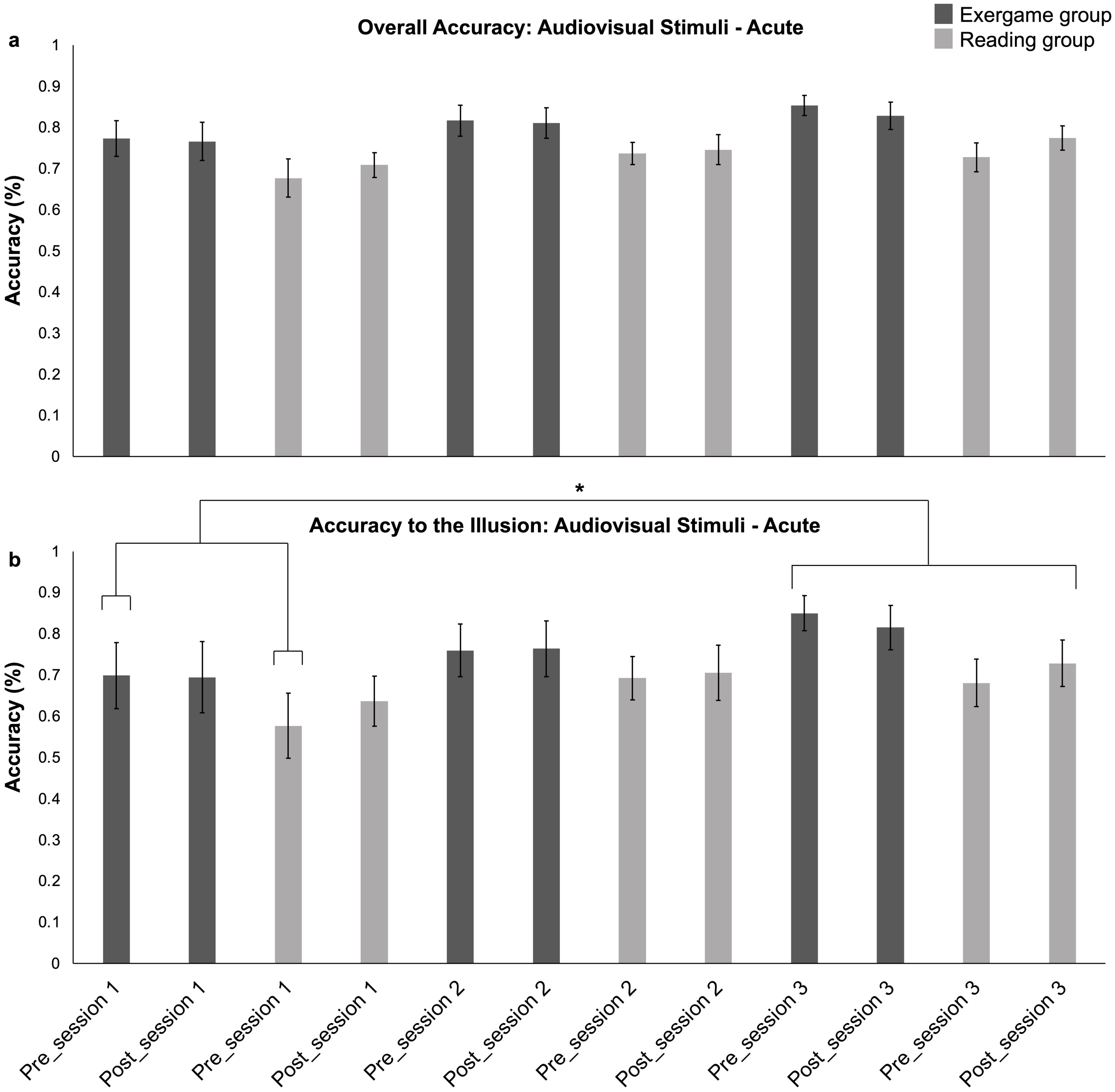


Figure 4.6: This figure depicts the acute accuracy achieved for all the conditions combined (overall; panel a) as well as the accuracy achieved on the illusory condition (panel b) from both the exergaming (dark grey) and reading (light grey) groups over sessions 1, 2, and 3. Note that those in the exergaming group were found to have significantly higher accuracy than those in the reading group ($p = 0.037$). Panel b depicts that compared to pre-intervention accuracy to the illusion of session 1, accuracy to the illusion was higher for both pre- ($p = 0.001$) and post-sessions ($p = 0.047$) of session 3. Note, 'pre' = baseline and 'post' = post-intervention. The error bars indicate the SEM.

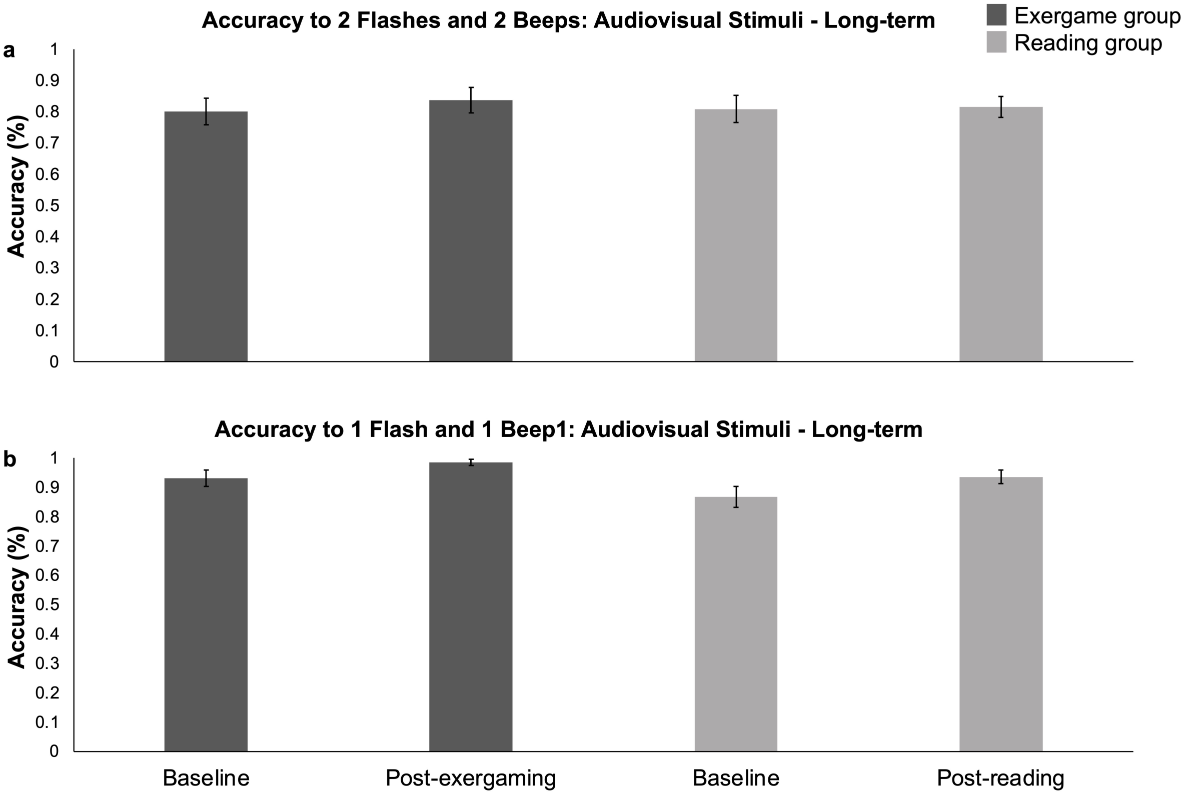


Figure 4.7: This figure depicts the accuracy achieved from baseline and post-intervention sessions for the 2 flashes-2 beeps (panel a) and 1 flash-1 beep (panel b) condition from both the exergaming (dark grey) and reading (light grey) groups. Note that significantly higher accuracy to the 1 flash-1 beep condition was found as compared to the illusory ($p = 0.002$) and the overall accuracy conditions ($p = 0.019$). The error bars indicate the SEM.

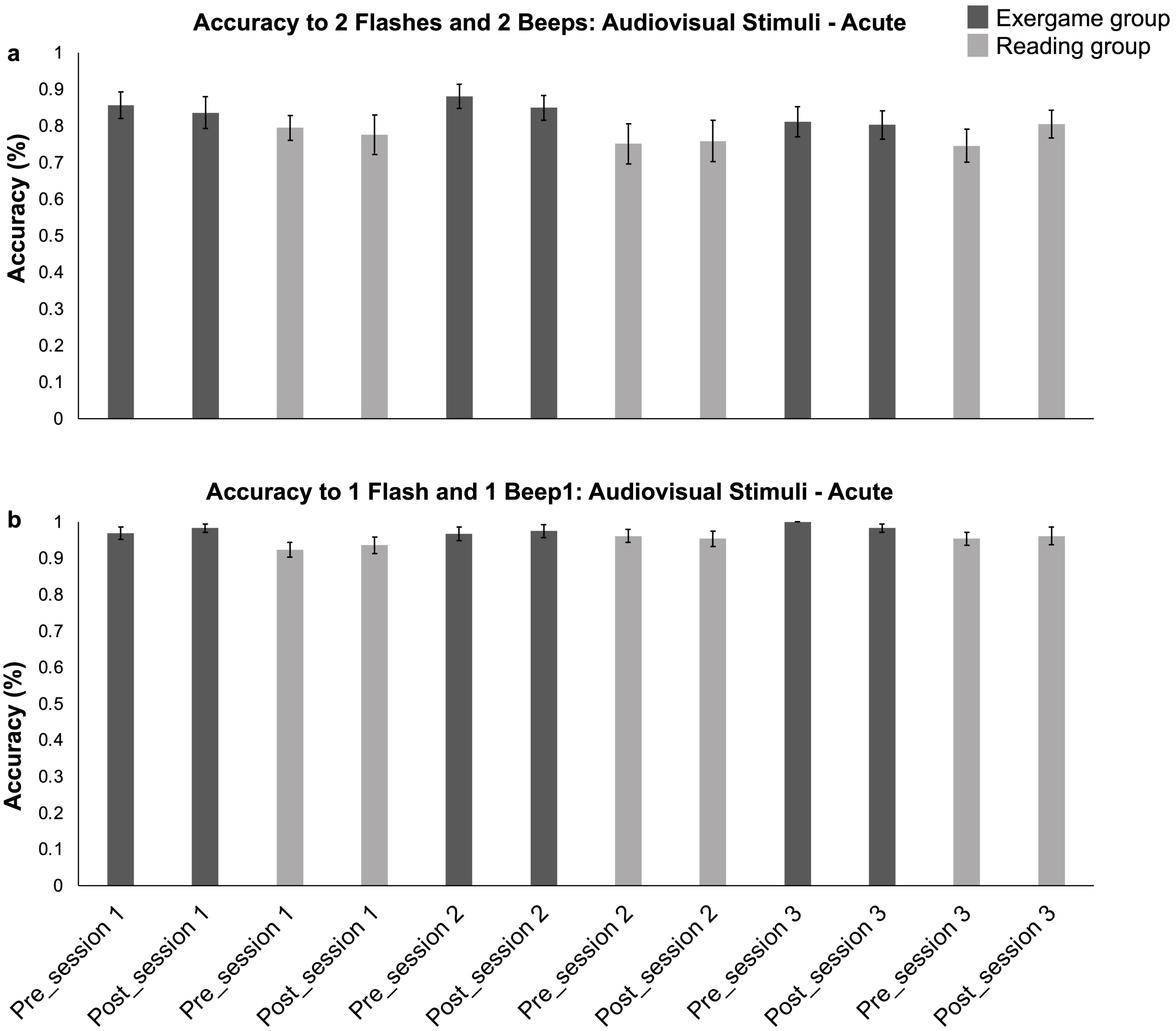


Figure 4.8: This figure depicts the accuracy achieved on the 2 flashes-2 beeps (panel a) condition and the 1 flash-1 beep (panel b) condition by those in the exergame (dark grey) and reading (light grey) groups. Accuracy to the 1 flash-1 beep condition was significantly higher than all the other conditions including accuracy to the overall condition ($p = 0.003$), illusory condition ($p = 0.003$), and 2 flashes-2 beeps condition ($p = 0.014$). Note, 'pre' = baseline and 'post' = post-intervention. The error bars indicate the SEM.

Time*Condition	Time*Condition	Mean Difference	SE	t	Cohen's d	p_{bonf}
B, Overall	PI, Overall	−0.147	0.037	−3.966	−0.833	0.005
	B, Illusion	0.143	0.043	3.347	0.812	0.031
	B, 2 flash	−0.191	0.043	−4.467	−1.083	< .001
	PI, 2 flash	−0.203	0.047	−4.329	−1.154	< .001
	B, 1 flash	−0.285	0.043	−6.682	−1.620	< .001
	PI, 1 flash	−0.350	0.047	−7.454	−1.986	< .001
PI, Overall	B, Illusion	0.290	0.047	6.173	1.645	< .001
	PI, 1 flash	−0.203	0.043	−4.754	−1.153	< .001
B, Illusion	PI, Illusion	−0.228	0.037	−6.152	−1.293	< .001
	B, 2 flash	−0.334	0.043	−7.814	−1.895	< .001
	PI, 2 flash	−0.346	0.047	−7.375	−1.965	< .001
	B, 1 flash	−0.428	0.043	−10.029	−2.432	< .001
	PI, 1 flash	−0.493	0.047	−10.499	−2.798	< .001
PI, Illusion	B, 1 flash	−0.201	0.047	−4.276	−1.139	0.001
	PI, 1 flash	−0.265	0.043	−6.207	−1.505	< .001
B, 2 flash	PI, 1 flash	−0.159	0.047	−3.389	−0.903	0.027
PI, 2 flash	PI, 1 flash	−0.147	0.043	−3.433	−0.833	0.023

Table 4.4: Details regarding the post-hoc comparisons found for the audiovisual condition of the SIFI for baseline (B) and Post-intervention (PI) sessions. Of note, the results indicate that compared to accuracy on the illusory trials at baseline, the accuracy was higher for all conditions at both baseline and post-intervention, including the accuracy to the illusory condition at time of post-intervention ($p < 0.001$). Further, the results revealed that compared to overall accuracy achieved at baseline, the accuracy was higher for all conditions at both baseline and post-intervention ($p < 0.05$), expect for the accuracy achieved for the illusory condition from the post-intervention session. Note that only the significant results are presented here.

Time*Condition	Time*Condition	Mean Difference	SE	t	Cohen's d	p_{bonf}
T 1-pre, Overall	T 1-pre, 1 flash	−0.217	0.043	−5.002	−1.479	< .001
	T 1-post, 1 flash	−0.227	0.044	−5.199	−1.548	< .001
	T 2-pre, 1 flash	−0.232	0.044	−5.314	−1.582	< .001
	T 2-post, 1 flash	−0.232	0.044	−5.314	−1.582	< .001
	T 3-pre, 1 flash	−0.252	0.044	−5.772	−1.718	< .001
	T 3-post, 1 flash	−0.252	0.044	−5.772	−1.718	< .001
T 1-post, Overall	T 1-pre, 1 flash	−0.203	0.044	−4.649	−1.384	0.002
	T 1-post, 1 flash	−0.213	0.043	−4.910	−1.452	< .001
	T 2-pre, 1 flash	−0.218	0.044	−4.993	−1.486	< .001
	T 2-post, 1 flash	−0.218	0.044	−4.993	−1.486	< .001
	T 3-pre, 1 flash	−0.238	0.044	−5.451	−1.623	< .001
	T 3-post, 1 flash	−0.238	0.044	−5.451	−1.623	< .001
T 2-pre, Overall	T 1-pre, 1 flash	−0.168	0.044	−3.859	−1.149	0.049
	T 1-post, 1 flash	−0.179	0.044	−4.088	−1.217	0.021
	T 2-pre, 1 flash	−0.183	0.043	−4.230	−1.251	0.012
	T 2-post, 1 flash	−0.184	0.044	−4.203	−1.251	0.013
	T 3-pre, 1 flash	−0.203	0.044	−4.661	−1.387	0.002
	T 3-post, 1 flash	−0.203	0.044	−4.661	−1.387	0.002
T 2-post, Overall	T 1-post, 1 flash	−0.171	0.044	−3.917	−1.166	0.040
	T 2-pre, 1 flash	−0.176	0.044	−4.031	−1.200	0.026
	T 2-post, 1 flash	−0.176	0.043	−4.057	−1.200	0.024
	T 3-pre, 1 flash	−0.196	0.044	−4.489	−1.336	0.004
	T 3-post, 1 flash	−0.196	0.044	−4.489	−1.336	0.004
T 3-pre, Overall	T 3-pre, 1 flash	−0.178	0.043	−4.103	−1.213	0.020
	T 3-post, 1 flash	−0.178	0.044	−4.077	−1.213	0.022
T 3-post, Overall	T 2-pre, 1 flash	−0.168	0.044	−3.859	−1.149	0.049
	T 2-post, 1 flash	−0.169	0.044	−3.859	−1.149	0.049
	T 3-pre, 1 flash	−0.189	0.044	−4.317	−1.285	0.008
	T 3-post, 1 flash	−0.188	0.043	−4.345	−1.285	0.008
T 1-pre, Illusion	T 3-pre, Illusion	−0.137	0.029	−4.653	−0.932	0.001
	T 3-post, Illusion	−0.112	0.029	−3.802	−0.761	0.047
	T 1-pre, 2 flash	−0.169	0.043	−3.900	−1.153	0.043
	T 1-pre, 1 flash	−0.297	0.043	−6.858	−2.028	< .001
	T 1-post, 1 flash	−0.307	0.044	−7.043	−2.096	< .001
	T 2-pre, 1 flash	−0.312	0.044	−7.157	−2.130	< .001
	T 2-post, 1 flash	−0.312	0.044	−7.157	−2.130	< .001
	T 3-pre, 1 flash	−0.332	0.044	−7.615	−2.267	< .001
	T 3-post, 1 flash	−0.332	0.044	−7.615	−2.267	< .001
T 1-post, Illusion	T 1-pre, 1 flash	−0.267	0.044	−6.108	−1.818	< .001
	T 1-post, 1 flash	−0.277	0.043	−6.378	−1.886	< .001
	T 2-pre, 1 flash	−0.282	0.044	−6.451	−1.920	< .001
	T 2-post, 1 flash	−0.282	0.044	−6.451	−1.920	< .001

	T 3-pre, 1 flash	−0.302	0.044	−6.909	−2.057	< .001
	T 3-post, 1 flash	−0.302	0.044	−6.909	−2.057	< .001
T 2-pre, Illusion	T 1-post, 1 flash	−0.220	0.044	−5.039	−1.500	< .001
	T 2-pre, 1 flash	−0.225	0.043	−5.187	−1.534	< .001
	T 2-post, 1 flash	−0.225	0.044	−5.153	−1.534	< .001
	T 3-pre, 1 flash	−0.245	0.044	−5.611	−1.670	< .001
	T 3-post, 1 flash	−0.245	0.044	−5.611	−1.670	< .001
T 2-post, Illusion	T 3-pre, 1 flash	−0.229	0.044	−5.249	−1.562	< .001
	T 3-post, 1 flash	−0.229	0.044	−5.249	−1.562	< .001
T 3-pre, Illusion	T 1-post, 1 flash	−0.171	0.044	−3.913	−1.165	0.040
	T 2-pre, 1 flash	−0.176	0.044	−4.027	−1.199	0.026
	T 2-post, 1 flash	−0.176	0.044	−4.027	−1.199	0.026
	T 3-pre, 1 flash	−0.196	0.043	−4.514	−1.335	0.004
	T 3-post, 1 flash	−0.196	0.044	−4.485	−1.335	0.004
T 3-post, Illusion	T 1-pre, 1 flash	−0.186	0.044	−4.256	−1.267	0.011
	T 1-post, 1 flash	−0.196	0.044	−4.485	−1.335	0.004
	T 2-pre, 1 flash	−0.201	0.044	−4.600	−1.369	0.003
	T 2-post, 1 flash	−0.201	0.044	−4.600	−1.369	0.003
	T 3-pre, 1 flash	−0.221	0.044	−5.058	−1.505	< .001
	T 3-post, 1 flash	−0.221	0.043	−5.091	−1.505	< .001
T 1-post, 2 flash	T 3-pre, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
	T 3-post, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
T 2-pre, 2 flash	T 3-pre, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
	T 3-post, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
T 2-post, 2 flash	T 2-pre, 1 flash	−0.168	0.044	−3.855	−1.148	0.050
	T 2-post, 1 flash	−0.168	0.043	−3.880	−1.148	0.046
	T 3-pre, 1 flash	−0.188	0.044	−4.314	−1.284	0.009
	T 3-post, 1 flash	−0.188	0.044	−4.314	−1.284	0.009
T 3-pre, 2 flash	T 1-post, 1 flash	−0.177	0.044	−4.046	−1.204	0.024
	T 2-pre, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
	T 2-post, 1 flash	−0.182	0.044	−4.161	−1.238	0.016
	T 3-pre, 1 flash	−0.202	0.043	−4.649	−1.375	0.002
	T 3-post, 1 flash	−0.202	0.044	−4.619	−1.375	0.002
T 3-post, 2 flash	T 3-pre, 1 flash	−0.187	0.044	−4.275	−1.273	0.010
	T 3-post, 1 flash	−0.187	0.043	−4.303	−1.273	0.009

Table 4.5: Details regarding the post-hoc comparisons found for the audiovisual condition of the SIFI for sessions 1, 2, and 3. Of note, the results indicate that compared to pre-intervention accuracy to the illusion of session 1, accuracy to the illusion was higher for both pre- ($p = 0.001$) and post-sessions ($p = 0.047$) of session 3. Further, participants achieved higher accuracy on the 1 flash-1 beep trials at all times that SIFI was administered as compared to overall accuracy ($p < 0.01$) and the accuracy achieved for the illusory condition ($p < 0.05$). The table outlines the 6 times data was obtained for this task where T1 = session 1 (week 2), T2 = session 2 (week 4), and T3 = session 3 (week 6). Note that only the significant results are presented here.

To further investigate the data, difference scores were computed by subtracting baseline accuracy from post-intervention accuracy to asses long-term changes and by subtracting the pre-session accuracy from post-session accuracy for sessions 1, 2, and 3 to assess acute changes. A 2 (group) x 1 (time: post-intervention - baseline) x 4 (condition) mixed-design ANOVA investigating the effects of long-term exposure to exergaming and reading revealed a main effect of condition ($F(3, 72) = 8.070$, $p < 0.001$; $\eta_p^2 = 0.252$). Pairwise comparisons were conducted to investigate the main effect of condition, which revealed that the difference in accuracy to the illusory condition was significantly higher than that for the 2 flash-2 beep ($p < 0.001$) and 1 flash-1 beep condition ($p = 0.005$), indicating that susceptibility to the illusion not only decreased after 6 weeks of both exergaming and reading interventions, but also showed higher improvement as compared to the control conditions. Further, the pairwise comparisons revealed that the difference in overall accuracy was significantly higher than that for the 2 flash-2 beep condition ($p = 0.035$). The ANOVA failed to find a main effect of group ($F(1, 24) = 0.225$, $p = 0.639$; $\eta_p^2 = 0.009$) or a significant interaction between condition and group ($F(3, 72) = 0.223$, $p = 0.880$; $\eta_p^2 = 0.009$). See Figure 4.9 and 4.10 for a comparison of difference scores obtained from subtracting baseline accuracy from post-intervention accuracy scores from the exergaming and reading group.

A 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, post-session 3 - pre-session 3) x 4 (condition) was conducted to investigate acute effects of time, condition, and intervention. The analysis failed to reveal a significant effect of group (($F(1, 20) = 1.606$, $p = 0.220$; $\eta_p^2 = 0.074$), time (($F(2, 40) = 0.433$, $p = 0.652$; $\eta_p^2 = 0.021$), and condition (($F(3, 60) = 0.017$, $p = 0.997$; $\eta_p^2 < 0.001$). Further, no significant interactions were found for group and time ($p = 0.837$), group and condition ($p = 0.818$), and time, condition, and group ($p = 0.996$). See Figures 4.11 and 4.12 for a comparison of the acute difference scores from the exergaming and reading group.

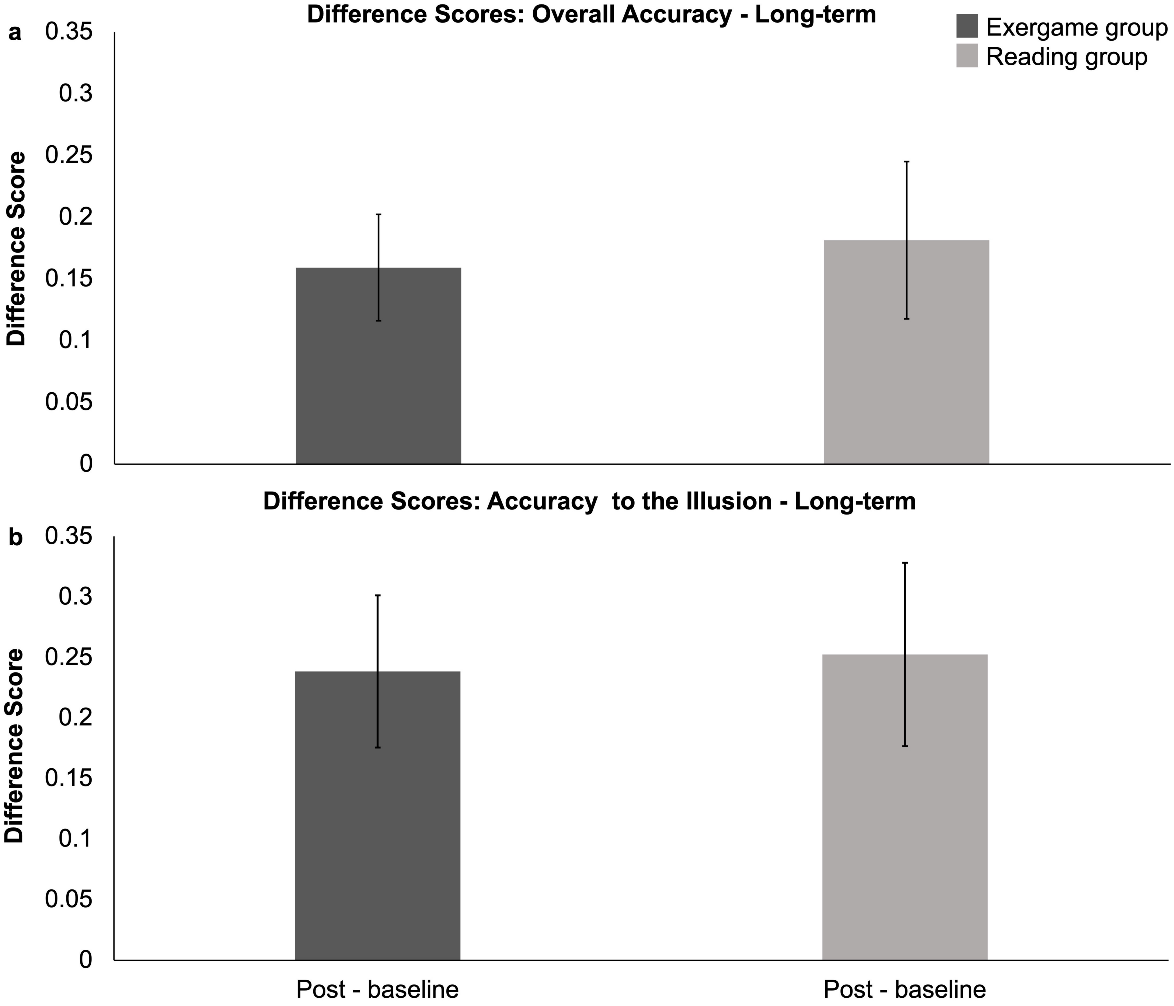


Figure 4.9: This figure depicts the difference scores calculated by subtracting baseline accuracy from post-intervention accuracy for the overall accuracy (panel a) and illusory (panel b) conditions. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. The difference in accuracy to the illusory condition was significantly higher than that for the 2 flash-2 beep ($p < 0.001$) and 1 flash-1 beep condition ($p = 0.005$), indicating that susceptibility to the illusion not only decreased after 6 weeks of both exergaming and reading interventions, but also showed higher improvement than the control conditions. Further, the pairwise comparisons revealed that the difference in overall accuracy was significantly higher than that for the 2 flash-2 beep condition ($p = 0.035$). The error bars indicate the SEM.

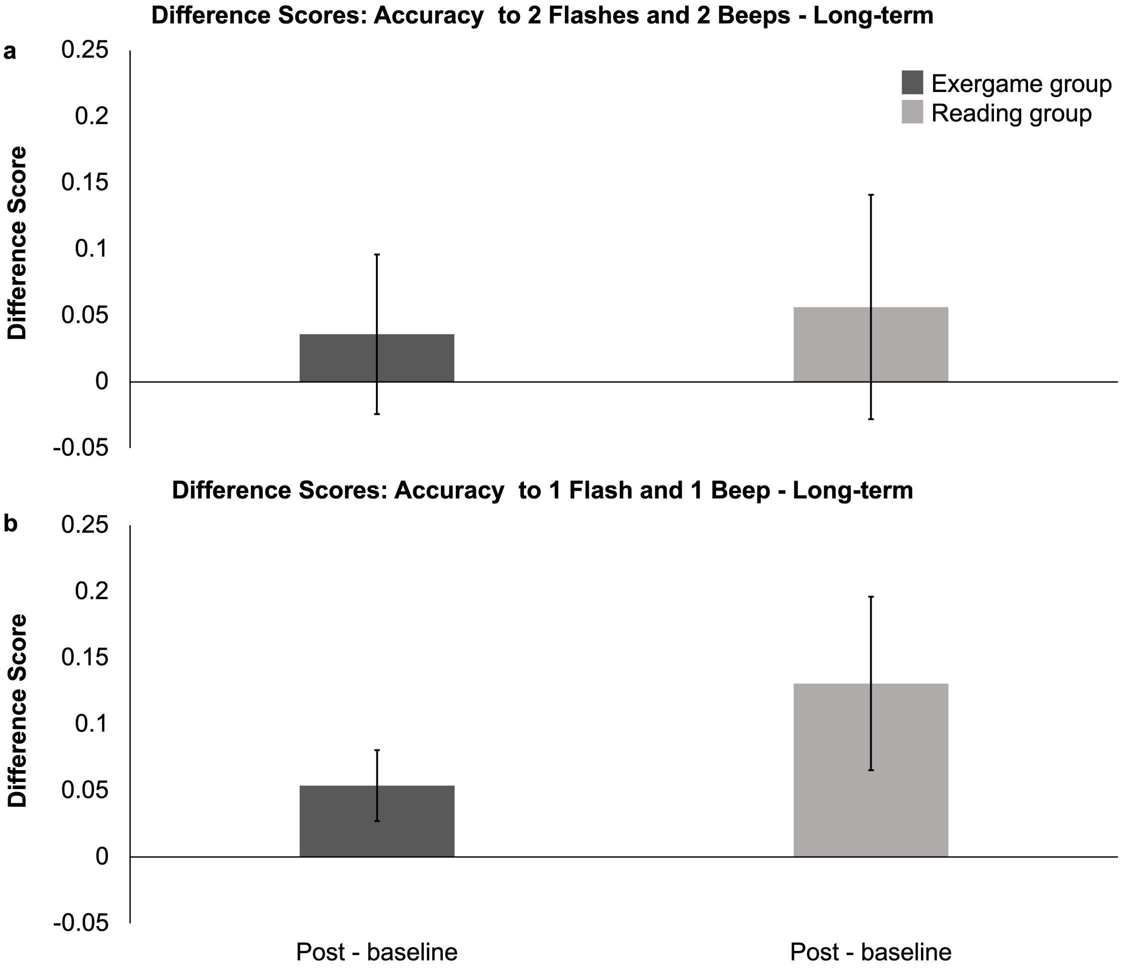


Figure 4.10: This figure depicts the difference scores calculated by subtracting baseline accuracy from post-intervention accuracy for the 2 flashes-2 beeps (panel a) and 1 flash-1 beep (panel b) condition. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. No significant differences were found between the sessions. The difference in accuracy to the illusory condition was significantly higher than that for the 2 flash-2 beep ($p < 0.001$) and 1 flash-1 beep condition ($p = 0.005$), indicating that susceptibility to the illusion not only decreased after 6 weeks of both exergaming and reading interventions, but also showed higher improvement than the control conditions. Further, the pairwise comparisons revealed that the difference in overall accuracy was significantly higher than that for the 2 flash-2 beep condition ($p = 0.035$). The error bars indicate the SEM.

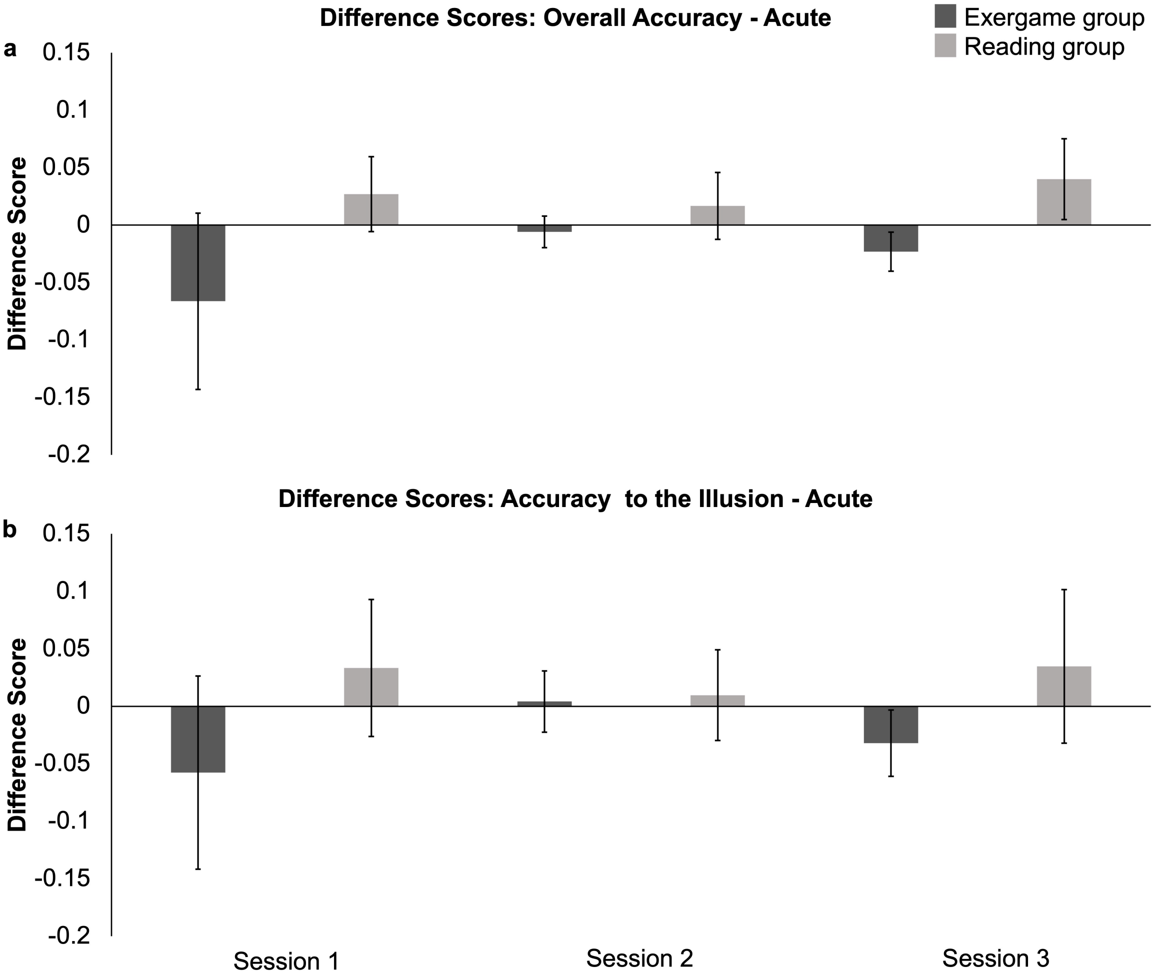


Figure 4.11: This figure depicts the difference scores calculated by subtracting pre-session accuracy from post-session accuracy from sessions 1, 2, and 3 for overall accuracy (panel a) and accuracy to the illusory (panel b) conditions. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. No significant differences were found between the sessions. The error bars indicate the SEM.

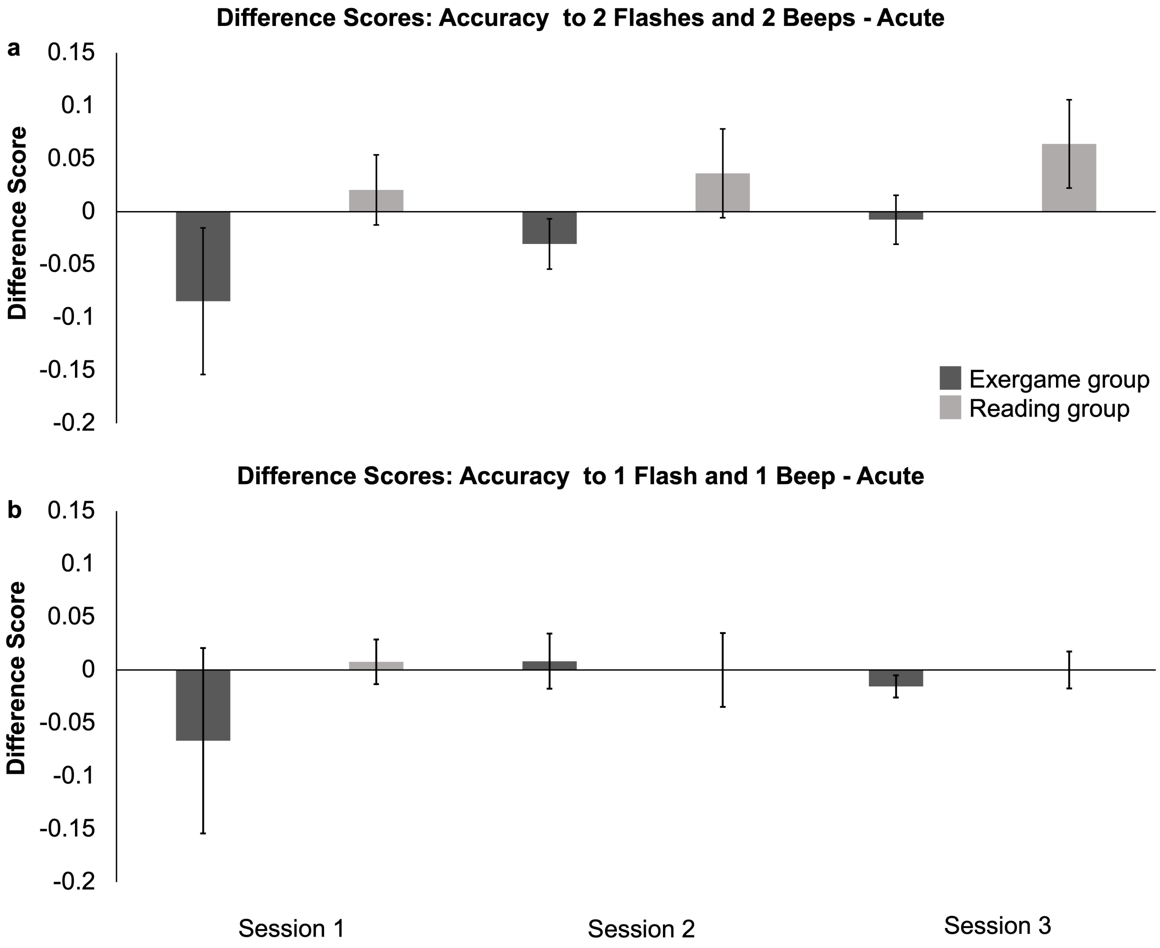


Figure 4.12: This figure depicts the difference scores calculated by subtracting pre-session accuracy from post-session accuracy from sessions 1, 2, and 3 for the 2 flashes-2 beeps (panel a) and 1 flash-1 beep (panel b) conditions. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. No significant differences were found between the sessions. The error bars indicate the SEM.

SIFI: Unimodal Control Conditions

A 2 (group) x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted to assess long-term effects of intervention on the auditory condition which revealed a violation for Levene's test for Equality of Variance for time, thus a Friedman test was conducted, and it revealed a significant main effect (χ^2 (1) = 7.118, p = 0.008), Conover's post-hoc pairwise comparisons investigating the main effect of time revealed that accuracy obtained for auditory cues during the post-intervention session was significantly higher than at baseline (p = 0.011). A main effect of group (F(1, 25) 0.803, p = 0.379; η_p^2 = 0.031) or an interaction between group and time (F(1, 25) 0.738, p = 0.398; η_p^2 = 0.029) were not found. A 2 (group) x 6 (time) mixed-design ANOVA was conducted to assess acute changes for the auditory condition which did not reveal a significant main effect of group (F(1, 18) < 0.01, p = 0.987; η_p^2 < 0.01) or time (F(2.338, 42.081) = 1.203, p = 0.315; η_p^2 = 0.063). Further, no significant interaction between group and time was found (F(2.338, 42.081) = 1.941, p = 0.150; η_p^2 = 0.097). See Figure 4.13 for a graphical representation of both the long-term and acute auditory accuracy obtained from those in the reading and exergaming group.

To further investigate the data, difference scores were used to assess long-term and acute effects. An independent t-test was conducted to investigate the long-term effects of exergmaing and reading on the auditory condition and results failed to find a significant difference between the two groups (t(25) = -0.859, p = 0.398; *Cohen's d*= - 0.331). Further, a 2 (group) x 3 (time) mixed-design ANOVA was conducted for the auditory cues to investigate any acute changes. The analysis did not reveal a significant effect of group (F(1, 21) = 0.930, p = 0.346; η_p^2 = 0.042) nor a significant interaction between group and time (F(1.394, 29.271) = 1.806, p = 0.189; η_p^2 = 0.079). Levene's test for Equality of Variance was violated, thus a Friedman test was conducted, which failed to reveal a main effect of time (χ^2 (2) = 0.552, p = 0.759). See Figures 4.14 and 4.15 for a graphical representation for both the long-term and acute difference scores, respectively obtained from both the auditory and visual modalities.

A 2 (group) x 2 (time) mixed-design ANOVA was conducted to assess long-term effects of intervention for the visual condition which did not reveal a significant main effect of group (F(1, 23) = 0.099, p = 0.756; η_p^2 = 0.004) or time (F(1, 23) = 0.057, p = 0.813; η_p^2 = 0.002). Further, no significant interaction between group and time was found (F(1, 23) = 1.280, p = 0.270; η_p^2 = 0.053). Additionally, a 2 (group) x 6 (time) mixed-design ANOVA was conducted to assess acute effects of intervention for the visual condition, which did not reveal a significant main effect of group (F(1, 18) = 0.048, p = 0.829; η_p^2 = 0.003) or time (F(5, 90) = 0.467, p = 0.800; η_p^2 = 0.025). Further, no significant interaction between group and time was found (F(5, 90) = 0.686, p = 0.636; η_p^2 = 0.037). See Figure 4.16 for accuracy scores obtained by those in the exergame and reading group.

To further investigate the data, difference scores were used to assess long-term and acute effects. An independent t-test was conducted to investigate the long-term effects of exergmaing and reading on the visual condition and the results revealed a near-significant difference between the two groups (t(25) = -1.837, p = 0.078; *Cohen's d*= - 0.707), with those in the reading group achieving a larger difference in accuracy as compared to those in the exergaming group. Further, a 2 (group) x 3 (time) mixed-design ANOVA was conducted for the visual cues to investigate acute changes. The analysis did not reveal a significant effect of group ($F(1,\ 20) < 0.01$, $p = 0.983$; $\eta_p^2 < 0.001$) or time ($F(2,\ 40) = 2.286$, $p = 0.115$; $\eta_p^2 = 0.103$) nor a significant interaction between group and time ($F(2,\ 40) = 1.934$, $p = 0.158$; $\eta_p^2 = 0.088$). Finally, see Figures 4.14 and 4.15 for a graphical representation of both the long-term and acute difference scores, respectively obtained from both the auditory and visual modalities.

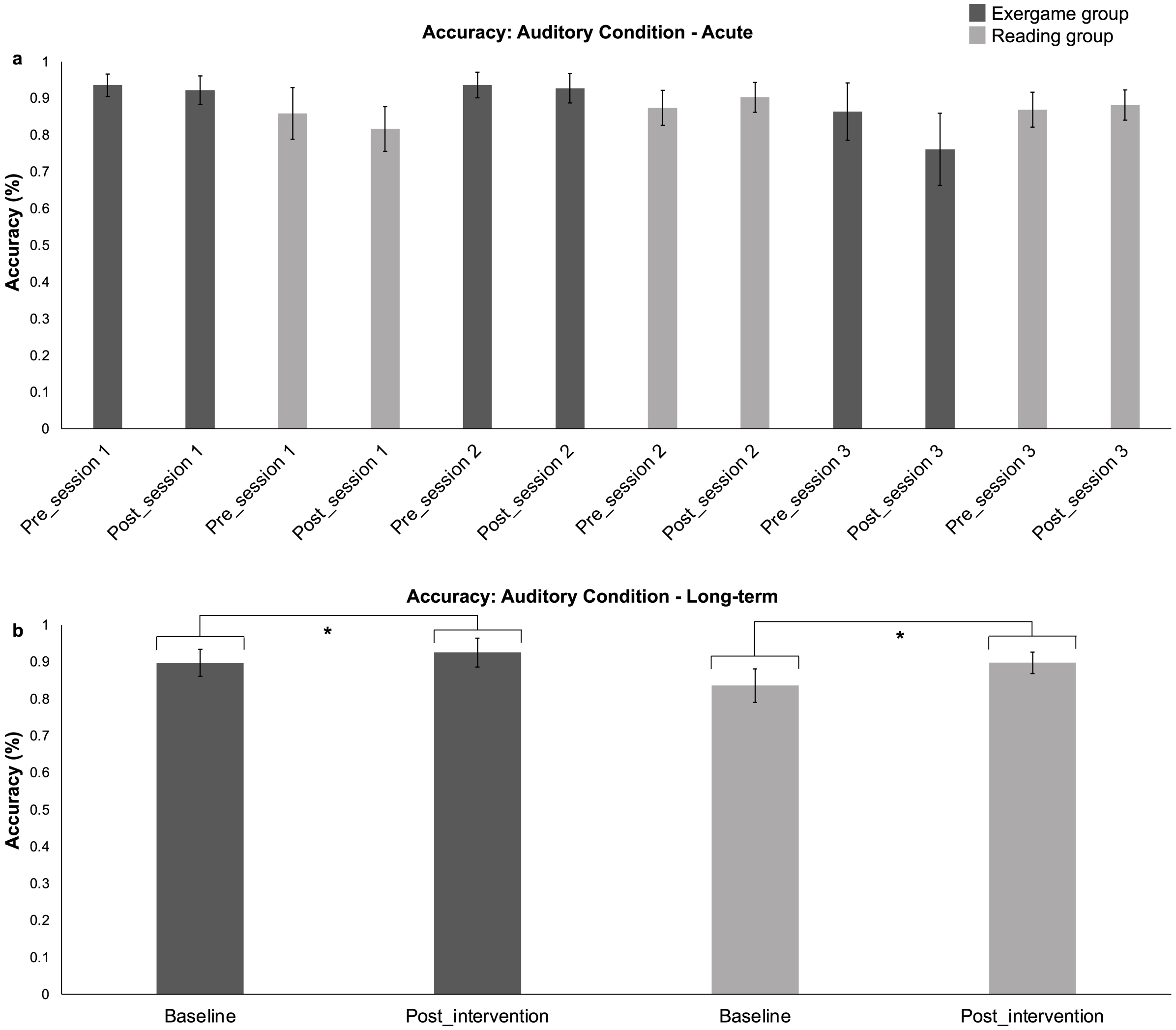


Figure 4.13: This figure depicts acute (panel a) and long-term (panel b) accuracy achieved for the unimodal auditory condition by those in the exergaming (dark grey) and reading (light grey) groups. Analyses revealed that accuracy was higher post-intervention as compared to baseline ($p = 0.011$; panel b). The error bars indicate the SEM.

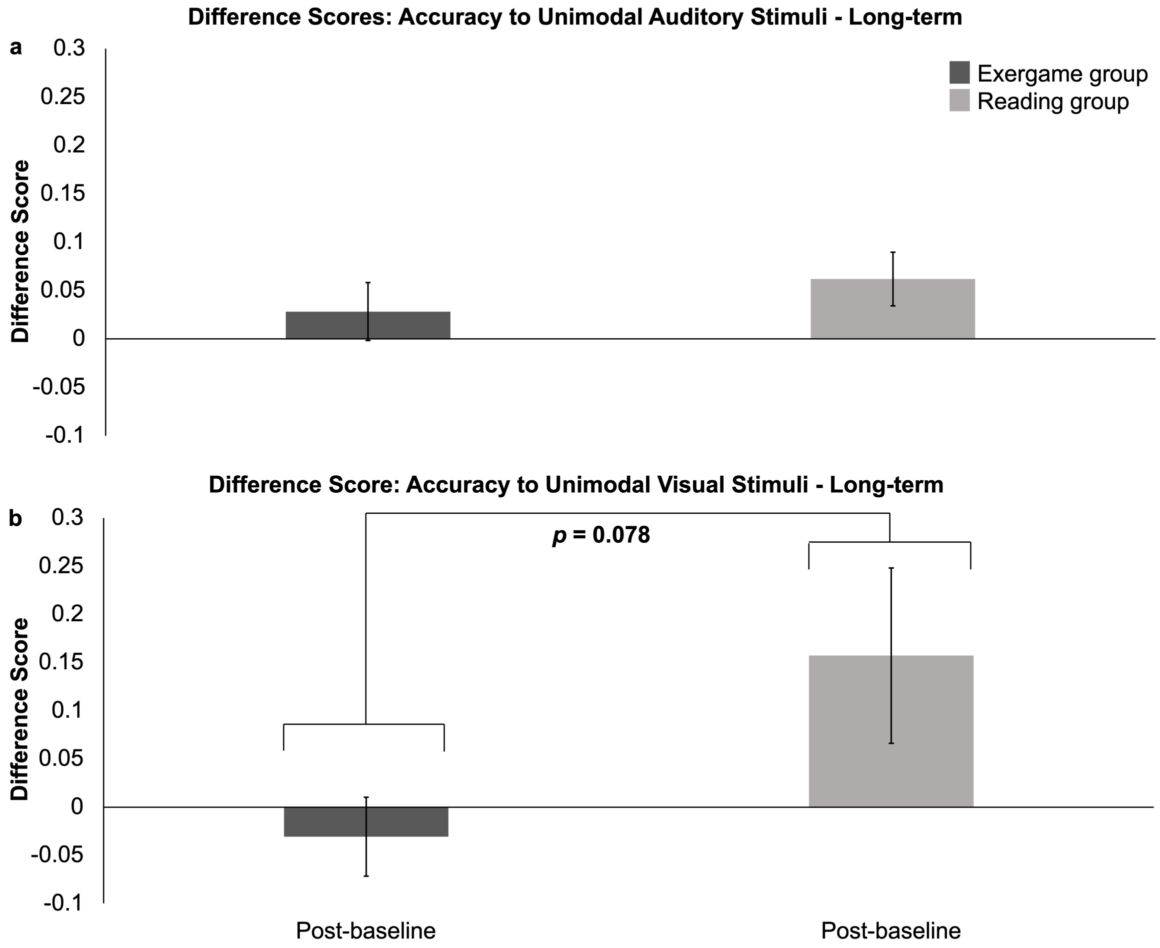


Figure 4.14: This figure depicts the difference scores calculated by subtracting baseline accuracy from post-intervention accuracy for the auditory (panel a) and visual (panel b) conditions. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. An independent t-test with the long-term difference score (panel b) revealed that those in the reading group achieved a larger accuracy difference as compared to those in the exergaming group ($p = 0.078$). No significant differences were found for the auditory condition. The error bars indicate the SEM.

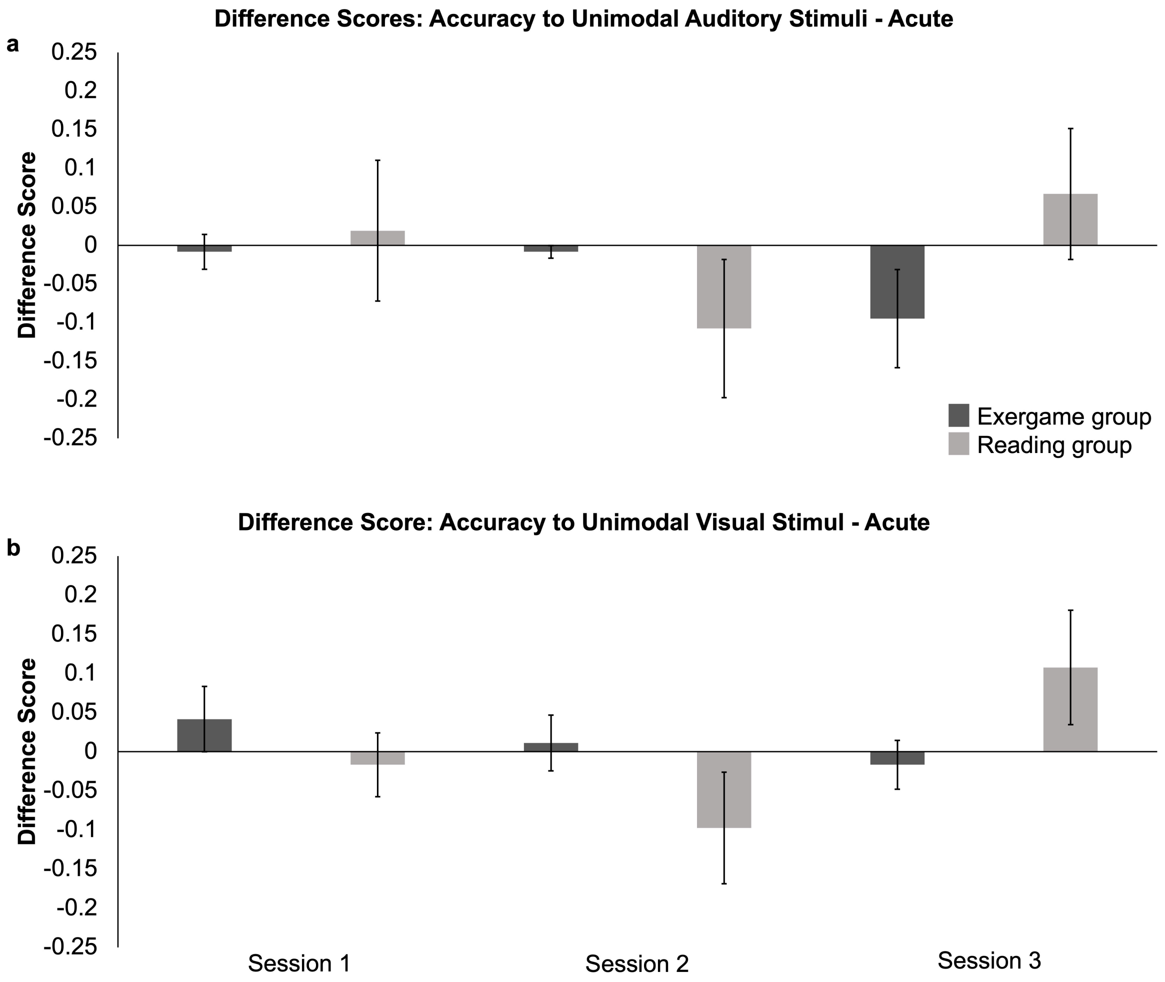


Figure 4.15: This figure depicts the difference scores calculated by subtracting pre-session accuracy from post-session accuracy for sessions 1, 2, and 3 for auditory (panel a) and visual (panel b) conditions. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. No significant differences were found for auditory and visual conditions. The error bars indicate the SEM.

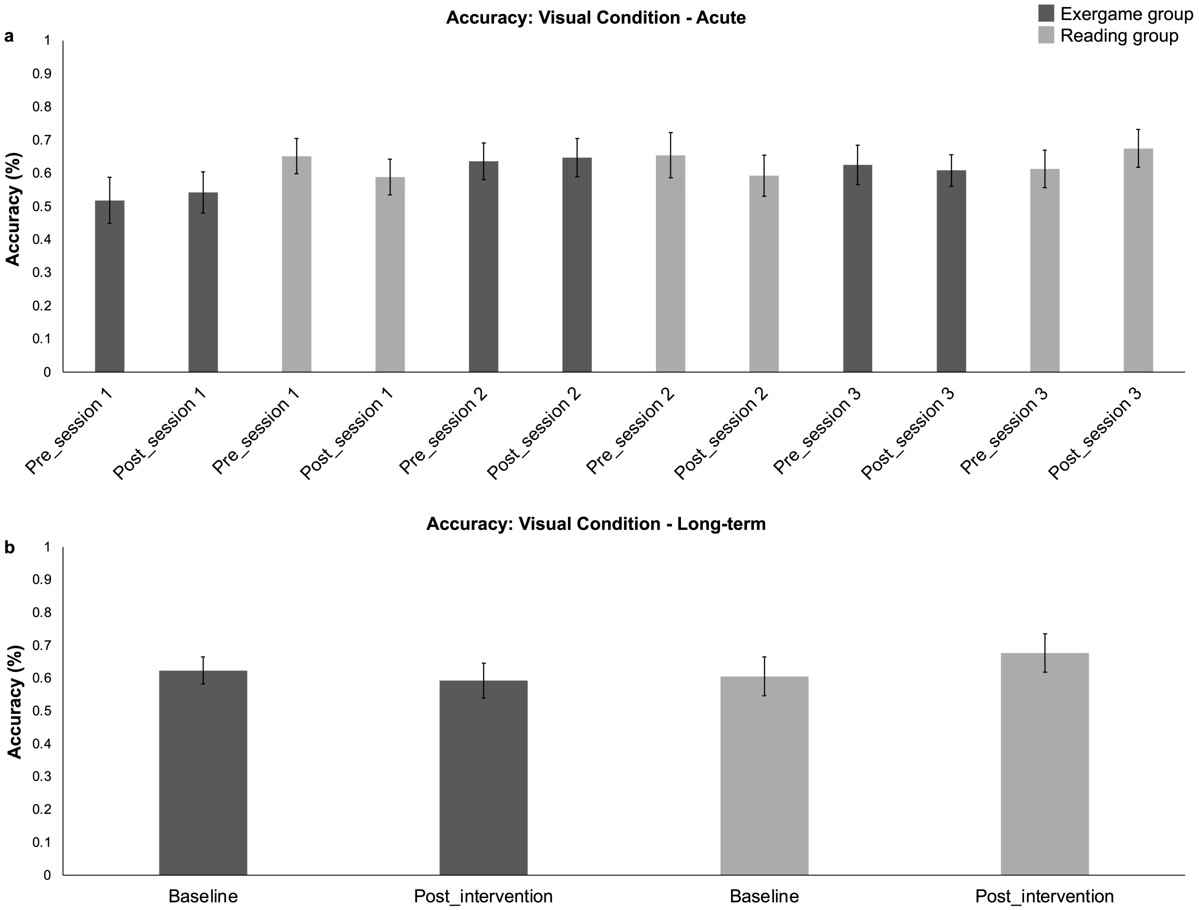


Figure 4.16: This figure depicts acute (panel a) and long-term (panel b) accuracy achieved for the unimodal visual condition by those in the exergaming (dark grey) and reading (light grey) groups. No significant differences were found for both the acute as well as the long-term analyses. The error bars indicate the SEM.

4.5.2 Simultaneity and Temporal Order Judgement Tasks

Initially, a 2 (group: exergaming or reading) x 2 (task: SJ or TOJ) x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted for the TBW. As Levene's test for Equality of Variance was violated, Friedman tests were conducted, which revealed only a significant main effect of task (χ^2 (1) = 13.365, $p < 0.001$), while failing to find a significant effect of time (χ^2 (1) = 2.504, $p = 0.114$). Pairwise comparisons investigating the effect of task found that participants exhibited wider TBWs for the SJ task ($p = 0.021$) and that they had wider TBWs at baseline versus post-intervention. The analysis did not reveal a significant effect of group ($F(1, 21) = 0.055$, $p = 0.816$; $\eta_p^2 = 0.003$) or a significant interaction between group, time, and task ($F(1, 21) = 0.054$ $p = 0.818$; $\eta_p^2 = 0.003$). See Figure 4.17 for the average Gaussian (SJ) function and Figure 4.18 for the average Logistic (TOJ) function. This concludes the analyses that were conducted to assess hypothesis 2, what follows are exploratory analyses investigating the effects of long-term exposure to the interventions on the PSS and amplitude. Further, difference score analyses were also conducted to investigate the effects of chronic exergaming and reading on outcomes of interest from the SJ and TOJ tasks.

A 2 (group: exergaming or reading) x 2 (task: SJ or TOJ) x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted for the PSS which failed to reveal a main effect of task ($F(1, 21) = 2.967$, $p = 0.100$; $\eta_p^2 = 0.124$), a main effect of group ($F(1, 21) = 0.884$, $p = 0.358$; $\eta_p^2 = 0.040$), and time ($F(1, 21) = 0.196$, $p = 0.662$; $\eta_p^2 = 0.009$). Further no significant interaction was found between group, time, and task ($F(1, 21) = 1.208$, $p = 0.284$; $\eta_p^2 = 0.054$). See Figure 4.17 for the average Gaussian (SJ) function and Figure 4.18 for the average Logistic (TOJ) function.

A 2 (group: exergaming or reading) x 2 (time: baseline and post-intervention) mixed-design ANOVA was conducted for the 'a' values obtained from the SJ task. The analysis failed to reveal a main effect of group ($F(1, 21) = 0.135$, $p = 0.717$; $\eta_p^2 = 0.006$), time ($F(1, 21) = 0.079$, $p = 0.781$; $\eta_p^2 = 0.004$), or a significant interaction between group and time ($F(1, 21) = 0.349$, $p = 0.561$; $\eta_p^2 = 0.016$). See Figure 4.17 for the average Gaussian (SJ) function.

To further investigate the data, difference scores were used to assess long-term effects of exergaming and reading on the SJ and TOJ tasks. A 2 (group) x 2 (task) mixed-design ANOVA was conducted with said difference scores for both the TBW and PSS which revealed no significant effect of group ($F(1, 21) = 1.285$, $p = 0.270$; $\eta_p^2 = 0.058$) or task ($F(1, 21) = 1.692$, $p = 0.207$; $\eta_p^2 = 0.075$) for the TBW and the same was true for the PSS [group ($F(1, 22) = 0.979$, $p = 0.333$; $\eta_p^2 = 0.043$) and task ($F(1, 22) = 0.013$, $p = 0.910$; $\eta_p^2 < 0.001$)]. Further, no significant interactions between group and task were found for the TBW ($F(1, 21) = 0.054$, $p = 0.818$; $\eta_p^2 = 0.003$) and the PSS ($F(1, 22) = 1.463$, $p = 0.239$; $\eta_p^2 = 0.062$) difference values. An independent t-test was conducted to investigate any differences in amplitude between those in the reading and exergaming group. The results failed to find a significant difference between the two groups ($t(21) =$ -0.591, $p = 0.561$; *Cohen's d* = - 0.247; reading ($mean_{baseline} = 0.905$; $mean_{post-intervention} = 0.921$) and exergaming ($mean_{baseline} = 0.931$; $mean_{post-intervention} = 0.925$). See Figure 4.19 for a graphical representation of the difference scores obtained for the SJ and TOJ tasks for both the exergame and reading groups. See Figure 4.20 for the amplitude difference scores.

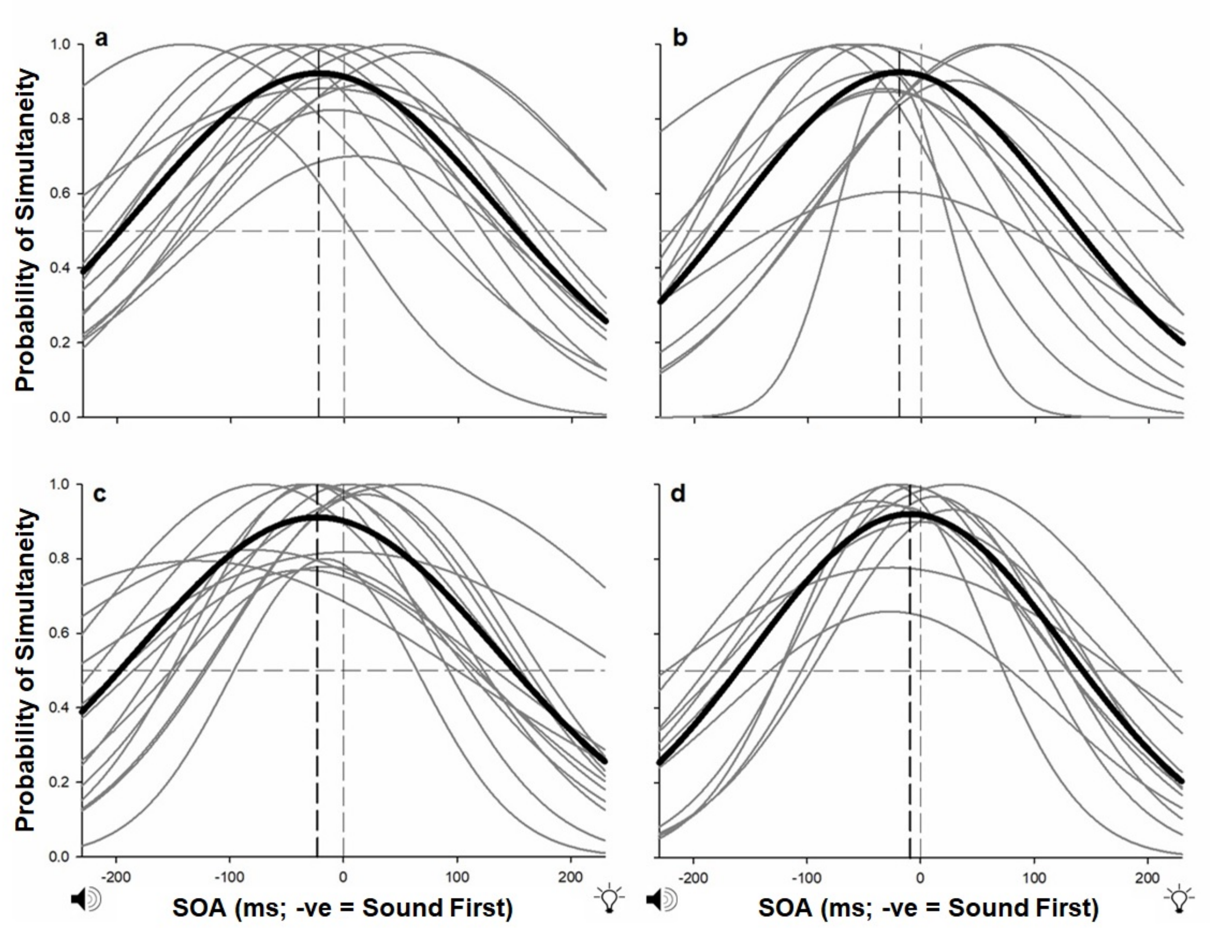


Figure 4.17: SJ: here the Gaussian function is fit to the average (thick lines) and individual (thin lines) data from the exergaming (a and c) and reading (b and d) groups. A and B represent data obtained from pre-intervention (exergamging and reading respectively) while C and D represent data from post-intervention. Those in the exergaming group required sound to be presented 22 ms before light in order to perceive simultaneity at baseline and their point of subjective simultaneity (PSS) shifted slightly closer to true simultaneity post-intervention, with participants requiring sound to be presented approximately 19 ms before light to perceive simultaneity. Further, those in the exergaming group had wider temporal binding windows (TBWs) at baseline (mean = 158.13) as compared to post-intervention (mean = 142.24). Those in the reading group, required sound to be presented 23 ms before light in order to perceive simultaneity at baseline and their PSS also shifted slightly closer to true simultaneity post-intervention, with participants requiring sound to be presented approximately 9 ms before light to perceive the two stimuli as simultaneous. Similar to the exergaming group, those in the reading group had wider TBWs at baseline (mean = 158.73) as compared to post-intervention (mean = 137.83). No significant differences in amplitude were found.

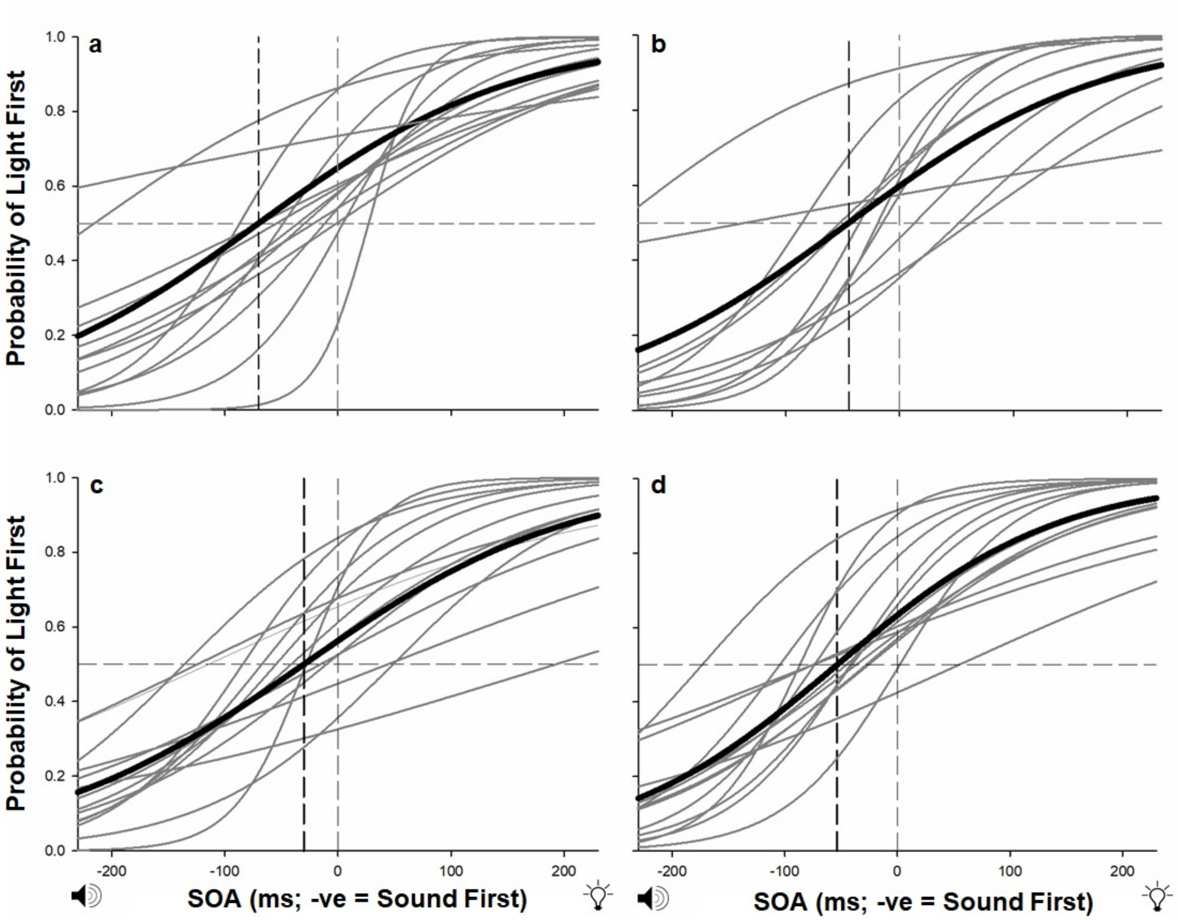


Figure 4.18: TOJ: the sigmoidal function is fit to average (thick lines) and individual (thin lines) data. A and B represent data obtained from pre-intervention (exergamging and reading respectively) while C and D represent data from post-intervention. Those in the exergaming group required sound to be presented approximately 70 ms before light in order to perceive simultaneity at baseline and their point of subjective simultaneity (PSS) shifted slightly closer to true simultaneity post-intervention, with participants requiring sound to be presented approximately 45 ms before light to perceive simultaneity. Further, those in the exergaming group had slightly wider temporal binding windows (TBWs) at baseline (mean = 114.06) as compared to post-intervention (mean = 112.17). Those in the reading group, required sound to be presented approximately 30 ms before light in order to perceive simultaneity at baseline and their PSS also shifted further from true simultaneity post-intervention, with participants requiring sound to be presented approximately 54 ms before light to perceive the two stimuli as simultaneous. Those in the reading group also had wider TBWs at baseline (mean = 118.92) as compared to post-intervention (mean = 97.82).

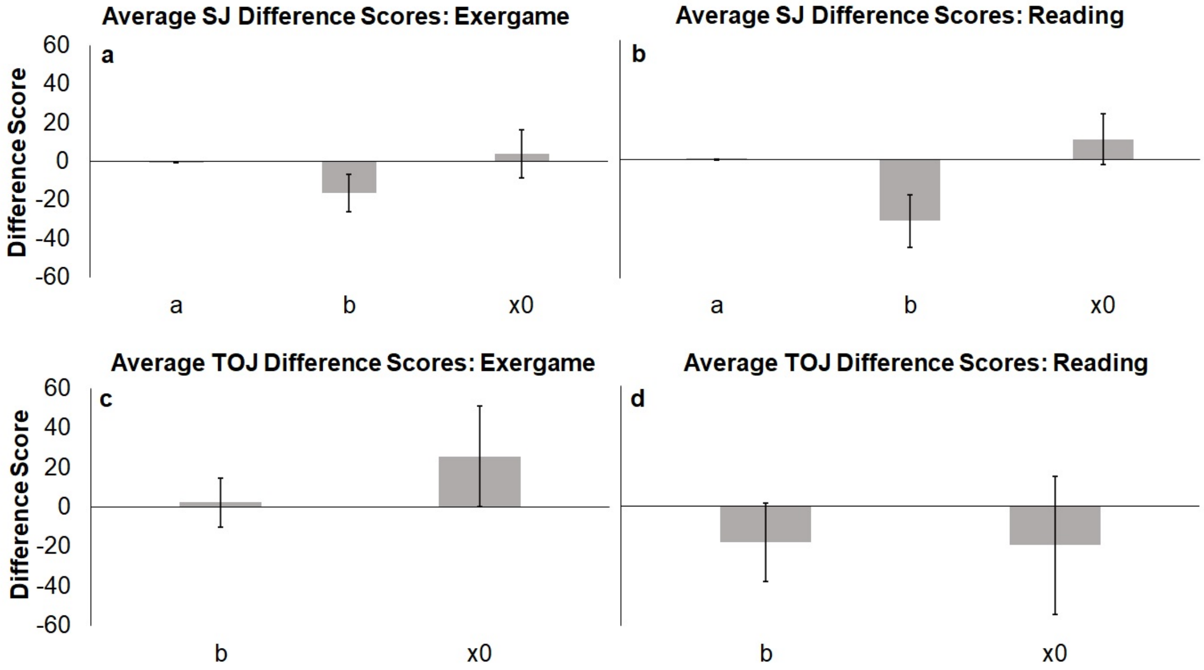


Figure 4.19: This figure depicts the difference scores calculated by subtracting baseline TBW (b) and PSS (x0) values from post-intervention TBW and PSS values for both the SJ and TOJ tasks. Scores obtained from the SJ task for the exergame and reading groups are represented in panels a and b respectively, while difference scores obtained for the TOJ task are represented in panels c and d for the exergame and reading groups respectively. No significant effects of group or task, neither an interaction between group and task were found for TBW and PSS. Additionally, no significant difference was found between the reading and exergaming group on the 'a' values as well; note that the difference between amplitudes is very small for both the reading (mean = 0.016; s.e. = 0.029) and exergaming (mean = -0.006; s.e. = 0.022) groups, especially relative to the TBW and PSS, which is why it is not visible in this figure. See Figure 4.20 below for a graphical representation of the difference score obtained from the two groups. The error bars indicate the SEM.

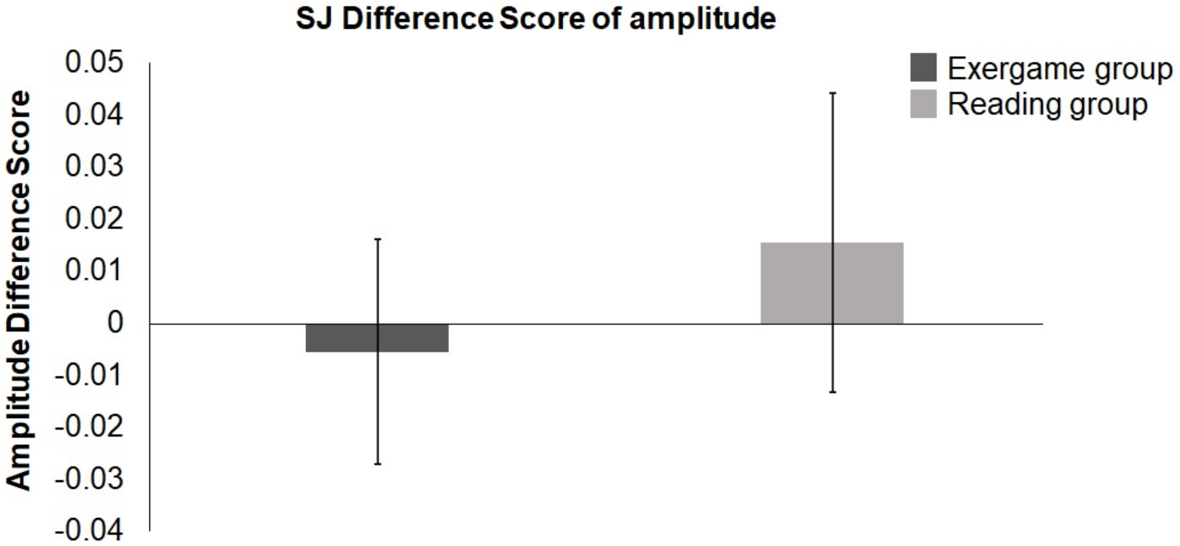


Figure 4.20: This figure depicts the difference scores calculated by subtracting the amplitude obtained from baseline from the amplitude obtained at post-intervention for the SJ task. Scores obtained from the SJ task for the exergame group are in dark grey, while scores obtained from the reading group are represented in light grey. No significant effect of group was found. The error bars indicate the SEM.

4.5.3 Response Time

Mean Response Time

A 2 (group) x 2 (time: baseline and post-intervention) x 3 (modality: auditory, visual, or audiovisual) mixed design ANOVA was conducted to determine the long-term effects of participation in the exergame versus reading intervention. The analysis revealed a main effect of group ($F(1,\ 24) = 7.318$, $p = 0.012$; $\eta_p^2 = 0.234$) and modality ($F(1.445,$ $34.673) = 67.898$, $p < 0.001$; $\eta_p^2 = 0.739$). Pairwise comparisons investigating the main effect of group revealed that those in the reading group displayed longer response times as compared to those in the exergame group ($p = 0.012$). Pairwise comparisons investigating the main effect of modality revealed that both auditory ($p < 0.001$) and visual ($p < 0.001$) stimuli had significantly longer response times as compared to audiovisual stimuli. The analysis failed to find a significant main effect of time ($F(1,\ 24) = 0.907$, $p = 0.350$; $\eta_p^2 =$ 0.036) or a significant interaction between group, time, and modality $F(1.684,\ 40.417) =$ 0.593, $p = 0.556$; $\eta_p^2 = 0.024$). See Figure 4.21 for a graphical representation of the mean response time data for the baseline and post-intervention sessions for both the exergaming and the reading group. This section concludes that analyses that were used to assess the effects of intervention on mean response time (hypothesis 3), what follows are exploratory analyses that investigate potential acute changes as well as difference scores obtained from longitudinal and acute sessions.

A 2 (group: experimental or control) x 6 (time: pre-, post-week 1; pre-, post-week 3;

pre-, post-week 5) x 3 (modality: auditory, visual, or audiovisual) mixed-design ANOVA was conducted to determine the acute impact of exergaming versus reading interventions. The analysis revealed a main effect of group ($F(1,\ 23) = 9.127$, $p = 0.006$; $\eta_p^2 = 0.284$); pairwise comparisons revealed that those in the reading group displayed longer response times as compared to those in the exergame group ($p = 0.006$). As Levene's test for Equality of Variance was violated, Friedman test was conducted, which revealed a main effect of modality (χ^2 (2) = 134.776, p < 0.001). Pairwise comparisons revealed that both auditory ($p < 0.001$) and visual ($p < 0.001$) stimuli had significantly longer response times as compared to audiovisual stimuli. The analysis failed to find a significant main effect of time (χ^2 (5) = 8.246, p = 0.143) or a significant interaction between group, time, and modality $F(4.692, 107.914) = 1.052$, $p = 0.389$; $\eta_p^2 = 0.044$). See Figure 4.22 for a graphical representation of the mean response time data for the acute conditions.

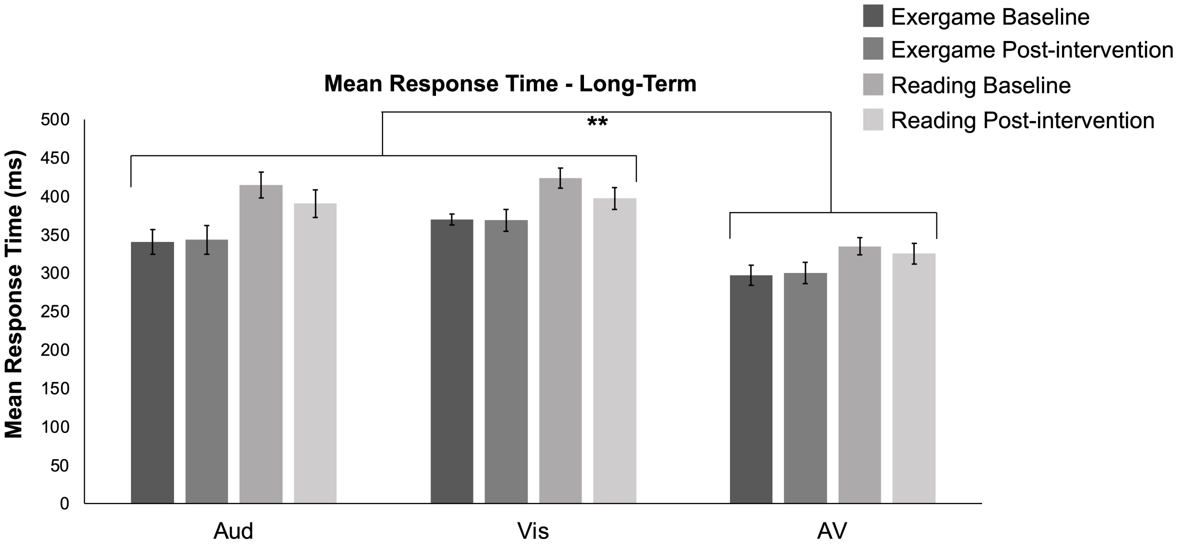


Figure 4.21: This figure depicts the mean response time obtained from baseline (darker shade) and post-intervention (lighter shade) session, both from those in the exergaming (dark grey) and reading (light grey) interventions for audiovisual, auditory, and visual trials. Those in the reading group displayed longer RTs (mean = 381.305, s.e. = 16.832) as compared to those in the exergaming group (mean = 336.9172, s.e. = 12.954, $p = 0.012$). Further, response times to the audiovisual stimuli (mean = 314.792, s.e. = 9.275) were significantly faster as compared to the auditory (mean = 372.524, s.e. = 18.195; $p < 0.001$) and visual (mean = 390.0177, s.e. = 13.047; $p < 0.001$) modalities. Note, Aud = auditory stimuli, Vis = visual stimuli, AV = audiovisual stimuli, pre = baseline, and post = post-intervention. The error bars indicate the SEM.

To further investigate the data, difference scores were used to assess long-term and acute effects. To further investigate the data, a 2 (group) x 3 (modality) mixed-design ANOVA was conducted to assess long-term effects of intervention on multisensory processing on said difference scores. The analysis failed to reveal a main effect of group ($F(1,\ 24) = 1.356$, $p = 0.256$; $\eta_p^2 = 0.053$), or modality ($F(2,\ 48) = 1.086$, $p = 0.346$; $\eta_p^2 = 0.043$),

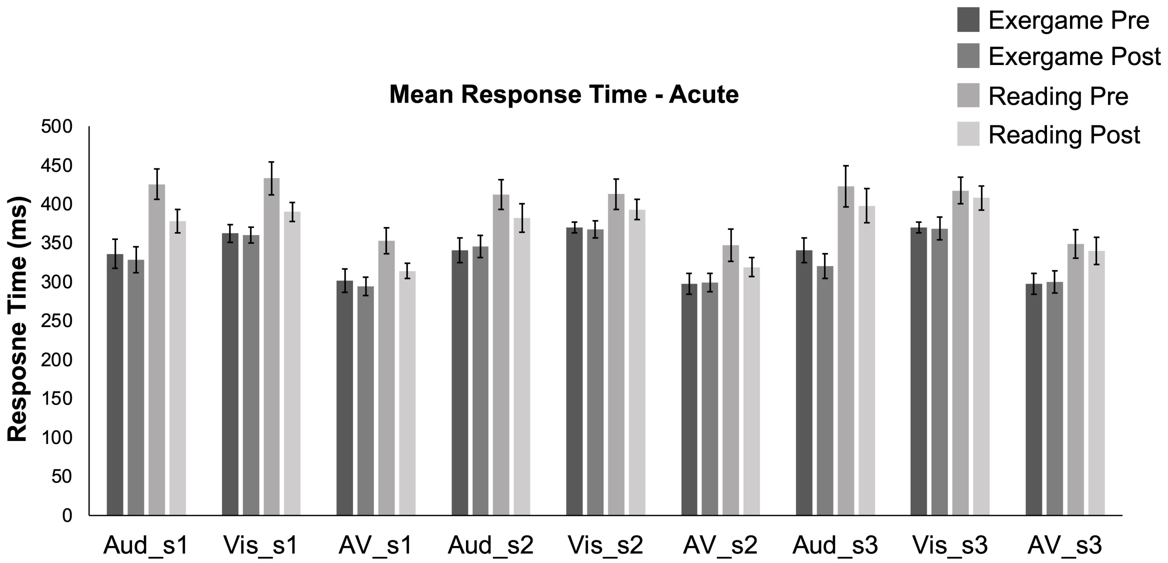


Figure 4.22: This figure depicts the mean response time obtained from sessions 1, 2, and 3 (dark shades represent pre-session and light shades represent post-session response times), both from those in the exergaming (dark grey) and reading (light grey) interventions for audiovisual, auditory, and visual trials. Those in the reading group displayed longer RTs (mean = 383.088, s.e. = 8.841) as compared to those in the exergaming group (mean = 333.376, s.e. = 6.880, $p = 0.006$). Further, response times to the audiovisual stimuli (mean = 317.061, s.e. = 5.842) were significantly faster as compared to the auditory (mean = 368.933, s.e. = 9.781; $p < 0.001$) and visual (mean = 387.108, s.e. = 6.6335; $p < 0.001$) modalities. Note, 'S' = session, 'E' = exergaming group, and 'R' = reading group. The error bars indicate the SEM.

or an interaction between group and modality ($F(2, 48) = 0.593$, $p = 0.556$;$\eta_p^2 = 0.024$). Further, a 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, post-session 3 - pre-session 3) x 3 (modality) mixed-design ANOVA was conducted to assess acute effects of intervention on multisensory processing. This analysis did not reveal a main effect of group ($F(1, 23) = 3.445$, $p = 0.076$; $\eta_p^2 = 0.130$), or modality ($F(2, 46) = 2.206$, $p = 0.122$; $\eta_p^2 = 0.088$), or time ($F(2, 46) = 1.726$, $p = 0.189$;$\eta_p^2 = 0.070$), however, a significant interaction between time and modality ($F(2.957, 68.002) = 3.157$, $p = 0.018$; $\eta_p^2 = 0.121$) was found. Pairwise comparisons investigating the interaction between time and modality revealed that the interaction was driven by the auditory modality exhibiting a larger difference when the pre-session 3 scores were subtracted from post-session 3 scores (i.e., greater improvement; mean = -27.54, s.e. = 19.86) as compared to the session 3 difference scores obtained for the audiovisual modality ($p = 0.027$; mean = -1.768, s.e. = 4.363). Note, that although not significant, the main effect of group neared-significance and post-hoc pairwise comparisons revealed that those in the reading condition showed a larger difference in performance (mean = -27.25, s.e. = 4.84) as compared to those in the exergaming intervention (mean = -3.63, s.e. = 2.55). See Figure 4.23 for both the acute (panel a) and long-term (panel b) difference scores.

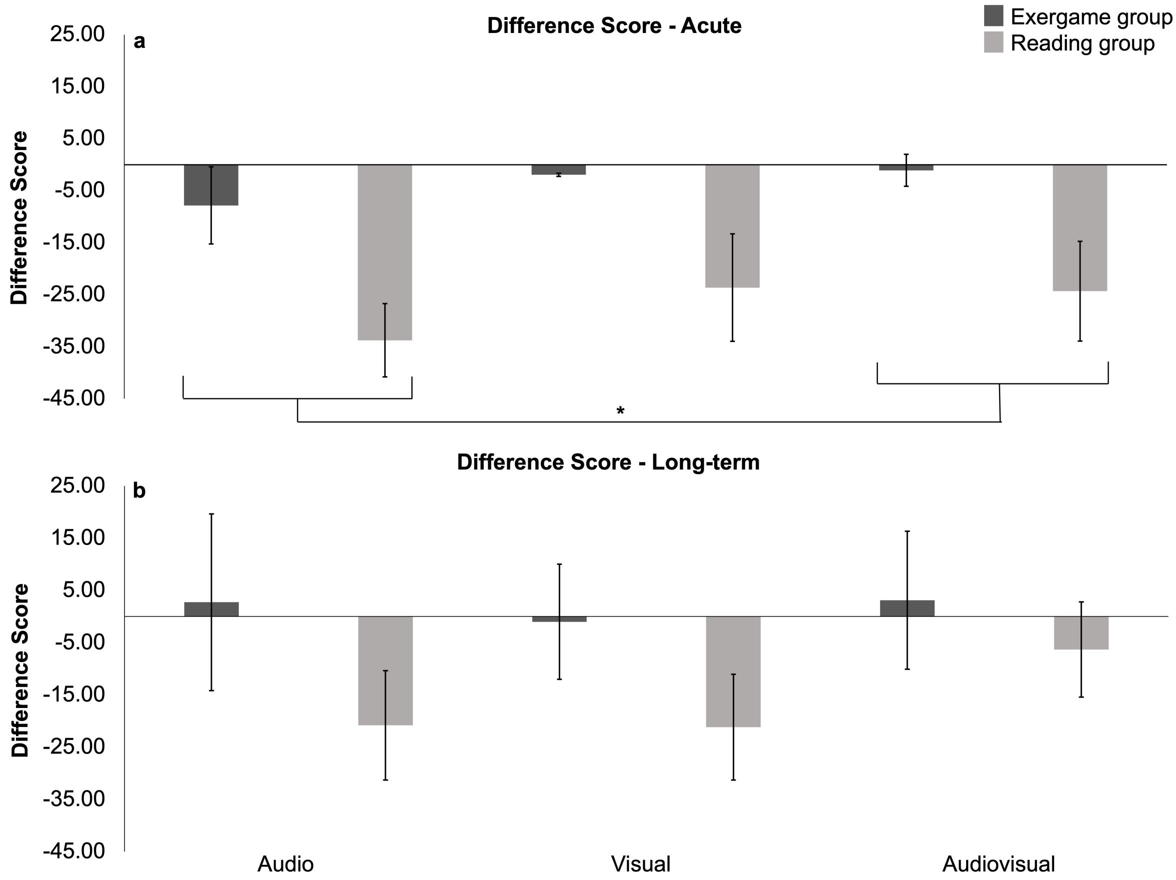


Figure 4.23: This figure depicts the difference scores calculated by subtracting pre-session response time for the auditory, visual, and audiovisual stimuli from post-session response time. The response times represented are collapsed across 3 times (session 1 post - pre session 1 , session 2 post - pre session 2, and session 3 post - pre session 3) in panel 'a' and 1 time (post - baseline) in panel 'b'. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. For the acute sessions, a significant interaction between time and modality was found which may have been driven by a larger difference for the auditory modality as compared to the audiovisual modality over session 3 (p = 0.027). Although not significant, those in the reading group showed a larger difference in performance (i.e., greater improvement) as compared to those in the exergame group. No other significant effects or interactions were found. The error bars indicate the SEM.

AUC

To investigate the long-term effects of the interventions, a 2 (group) x 2 (time) mixed-design ANOVA was conducted which revealed a near-significant effect of time ($F(1, 25) = 3.526$, $p = 0.072$; $\eta_p^2 = 0.124$), but failed to reveal a main effect of group ($F(1, 25) = 0.859$, $p = 0.363$; $\eta_p^2 = 0.033$) or a significant interaction between group and time ($F(1, 25) = 0.10$, $p = 0.923$; $\eta_p^2 < 0.001$). Pairwise comparisons investigating the near significant effect of time revealed that the area under the curve increased post-intervention as compared to baseline, indicating that violations increased post-intervention. This section concludes that analyses that were used to assess the effects of intervention on race model violations (hypothesis 3), what follows are exploratory analyses that investigate potential acute changes as well as difference scores obtained from longitudinal and acute sessions. A 2 (group) x 6 (time) mixed-design ANOVA investigating the acute effects of intervention on AUC revealed no significant effect of group ($F(1,\ 23) = 1.332$, $p = 0.260$; $\eta_p^2 = 0.055$) or time ($F(3.531,\ 81.209) = 1.913$, $p = 0.124$; $\eta_p^2 = 0.077$). Further, no significant interaction between group and time was revealed ($F(3.531,\ 81.209) = 0.931$, $p = 0.442$; $\eta_p^2 = 0.039$). See Figure 4.24 and 4.25 for the graphical representation of the acute and long-term area under the curve for the exergaming and reading groups respectively.

To further investigate the long-term effects of intervention on AUC through the use of difference scores, an independent t-test was conducted, which failed to reveal a significant difference between the two groups ($t(25) = 0.098$, $p = 0.923$; *Cohen's d*= 0.038). Difference scores were also used to assess acute effects, where a 2 (group) x 3 (time: post-session 1 - pre-session 1, post-session 2 - pre-session 2, and post-session 3 - pre-session 3) mixed-design ANOVA investigating acute effects which failed to reveal a significant main effect of group group ($F(1,\ 24) = 0.039$, $p = 0.846$; $\eta_p^2 = 0.002$) or time ($F(2,\ 48) = 1.829$, $p = 0.172$; $\eta_p^2 = 0.071$). Further, no significant interaction between group and time was revealed ($F(2,\ 48) < 0.01$, $p = 0.999$; $\eta_p^2 < 0.001$). See Figure 4.26 for both the acute (panel a) and long-term (panel b) difference scores from those in the exergaming and reading group.

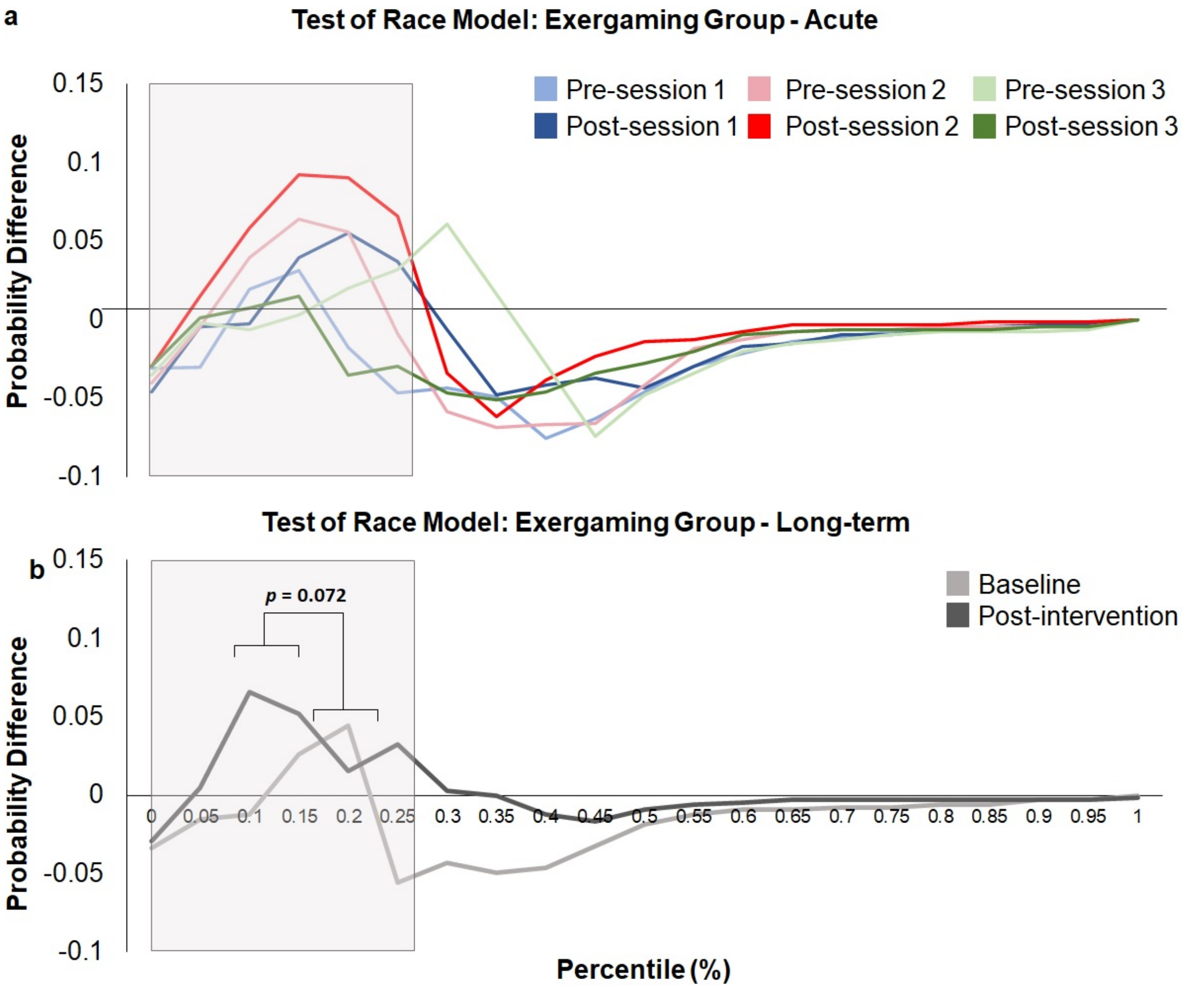


Figure 4.24: This figure represents the test of the race model for those in the exergaming group. The graph represents the probability difference wave where the *predicted* CDF is subtracted from the *observed* CDF for (a) acute changes (sessions 1, 2, and 3) and (b) long-term differences (i.e., baseline and post-intervention). The grey box indicates the area over which the analyses were conducted. A near significant effect of time from the acute analysis revealed that area under the curve increased after both interventions ($p = 0.072$). No further significant effects or interactions were found.

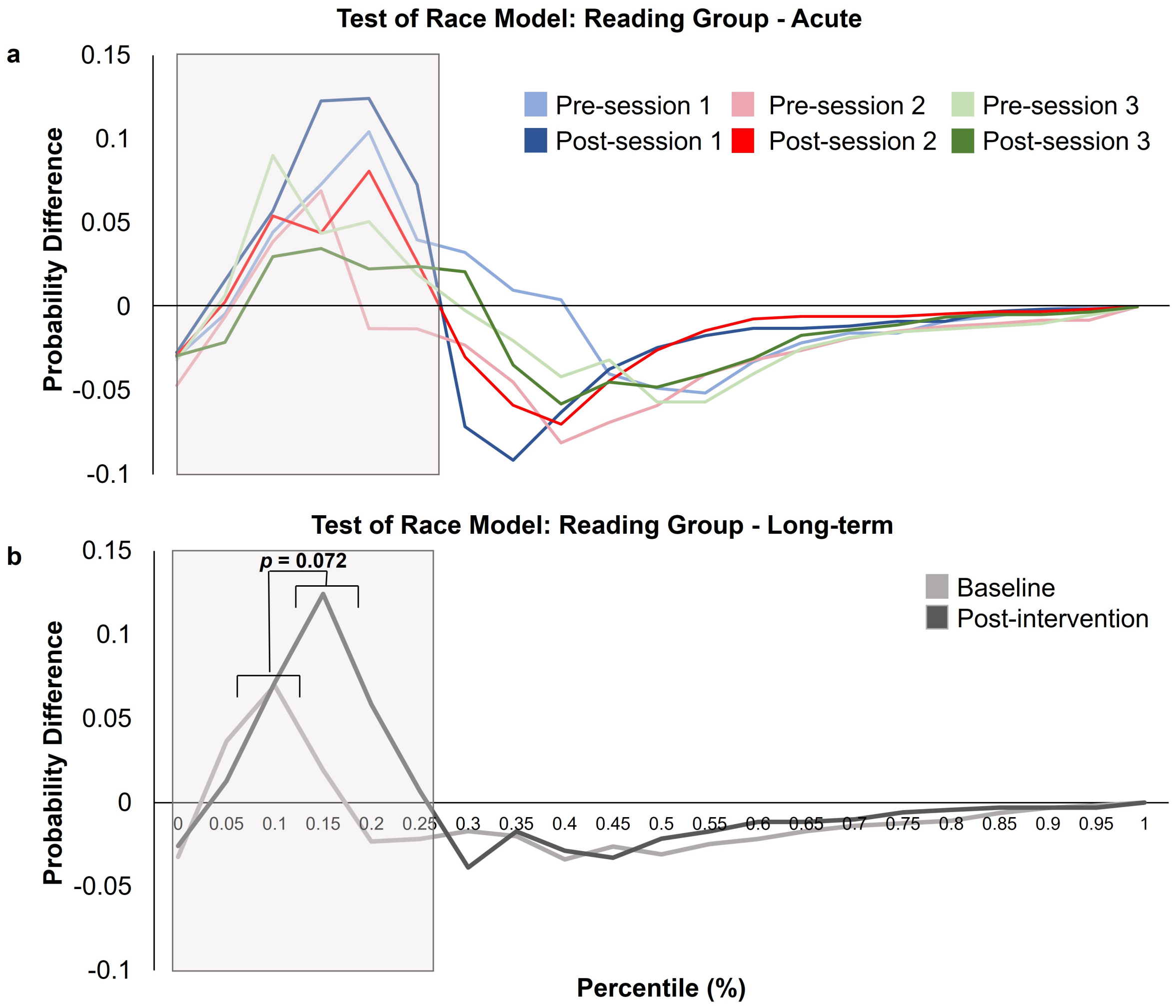


Figure 4.25: This figure represents the test of the race model for those in the reading group. The graph represents the probability difference wave where the *predicted* CDF is subtracted from the *observed* CDF for (a) acute changes (sessions 1, 2, and 3) and (b) long-term differences (i.e., baseline and post-intervention). The grey box indicates the area over which the analyses were conducted. A near significant effect of time from the acute analysis revealed that area under the curve increased after both interventions ($p = 0.072$). No further significant effects or interactions were found.

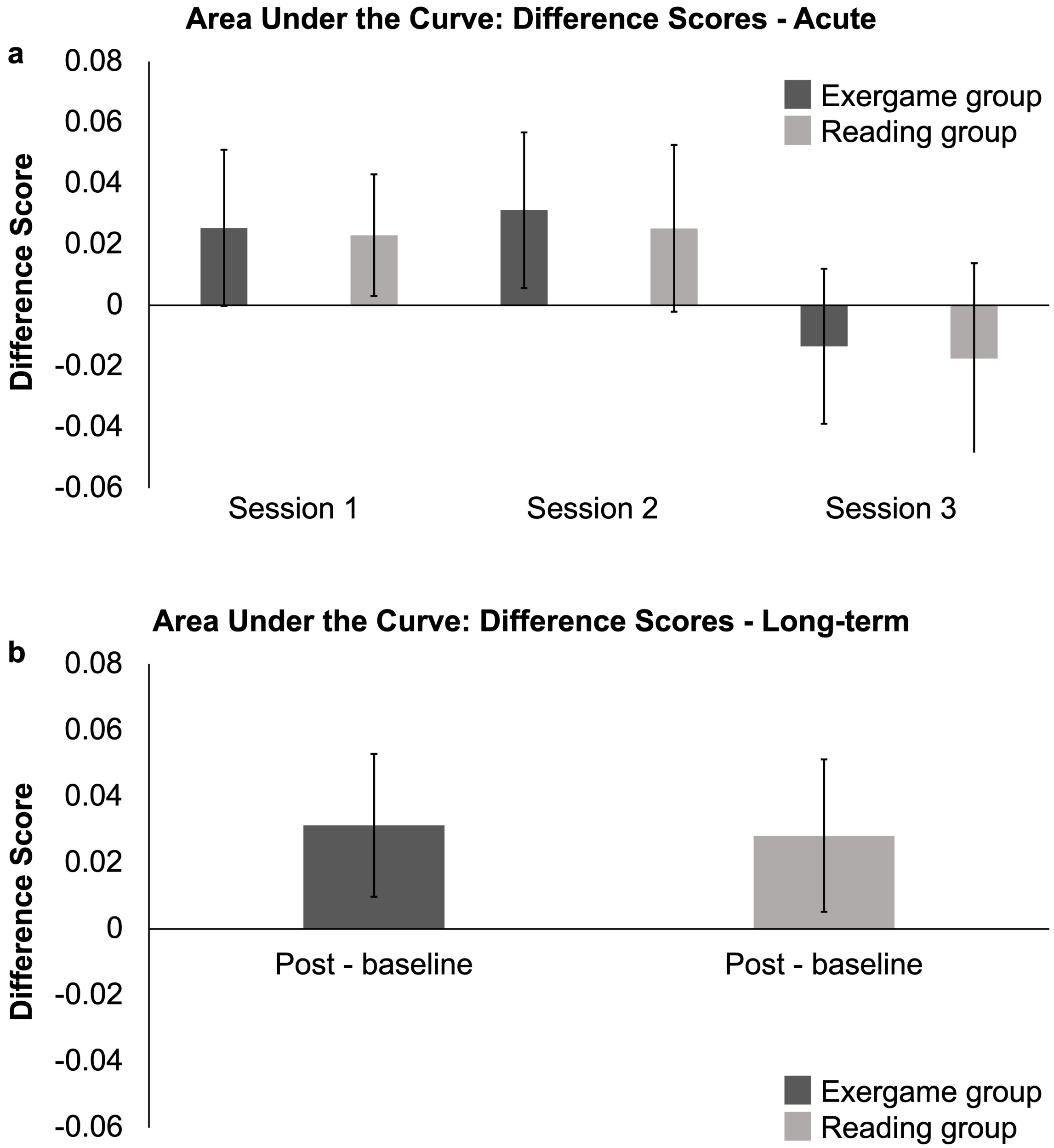


Figure 4.26: This figure depicts the difference scores calculated by subtracting pre-session AUC scores from post-session AUC scores. The AUC difference scores represented are from 3 times (session 1 post - pre, session 2 post - pre, and session 3 post - pre) in panel 'a' and 1 time (post - baseline) in panel 'b'. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. No significant effects or interactions were found from both the acute and long-term analyses. The error bars indicate the SEM.

4.5.4 Median Response Time

Median response time values were computed and a 2 (group) x 2 (time) x 3 (modality) mixed design ANOVA was conducted to determine the long-term effect of exergaming and reading on median response time. The analysis revealed a main effect of group ($F(1, 24) = 6.590$, $p = 0.017$; $\eta_p^2 = 0.215$), a main effect of modality ($F(1.4126, 33.897) = 71.377$, $p < 0.001$; $\eta_p^2 = 0.748$), and a significant interaction between time and modality ($F(1.598, 38.348) = 3.798$, $p = 0.040$; $\eta_p^2 = 0.137$). Here again, the pairwise comparisons revealed that those in the exergame group had faster response times as compared to those in the reading group ($p = 0.017$). Pairwise comparisons investigating the effect of modality revealed that that both auditory ($p < 0.001$) and visual ($p < 0.001$) stimuli had significantly longer response times as compared to audiovisual stimuli. Further, visual stimuli exhibited significantly longer response times as compared to auditory stimuli ($p < 0.001$). The pairwise comparisons investigating the interaction between modality and time revealed many significant outcomes (see Table 4.6), however of interest to this dissertation is the fact that compared to baseline auditory and visual median RTs, the median RTs for audiovisual cues, at both baseline and post-intervention, were significantly faster ($p < 0.01$). The analysis, however, failed to find a main effect of time ($F(1, 24) = 0.239$, $p = 0.629$; $\eta_p^2 = 0.010$). See Figure 4.27 for a graphical representation of the median response times obtained from baseline and post-intervention sessions. This section concludes that analyses that were used to assess the effects of intervention on median response time, what follows are exploratory analyses that investigate potential acute changes as well as difference scores obtained from longitudinal and acute sessions.

A 2 (group) x 6 (time) x 3 (modalities) mixed-design ANOVA was conducted to assess acute effects of exposure to exergaming and reading on median response time. The analysis revealed a main effect of group ($F(1, 23) = 6.573$, $p = 0.017$; $\eta_p^2 = 0.222$), a main effect of time ($F(2.646, 60.862) = 4.538$, $p = 0.008$; $\eta_p^2 = 0.165$), a main effect of modality ($F(1.276, 29.352) = 43.829$, $p < 0.001$; $\eta_p^2 = 0.656$), and a near-significant interaction between time, modality, and group ($F(4.816, 110.768) = 2.036$, $p = 0.082$; $\eta_p^2 = 0.081$). In line with the mean response time results, pairwise comparisons investigating the effect of group revealed that those in the reading group displayed longer median response times as compared to those in the exergame group ($p = 0.017$). Further, pairwise comparisons revealed that both auditory ($p < 0.001$) and visual ($p < 0.001$) stimuli had significantly longer response times as compared to audiovisual stimuli. Further, visual stimuli exhibited significantly longer response times as compared to auditory stimuli ($p = 0.035$). Further, the pairwise comparisons investigating the effect of time revealed that compared to the pre-intervention results from session 1, the post-intervention session 1 results exhibited significantly faster response time ($p = 0.004$). Finally, the pairwise comparisons investigating the interaction between group, time, and modality revealed multiple significant outcomes (see Table 4.7), however the overall pattern revealed that responses to the audiovisual trials were significantly faster across time as compared to auditory and visual trials and that those in the reading group had longer response times as compared to those in the exergaming group. See Figure 4.28 for a graphical representation of the median response times obtained from sessions 1 through 3.

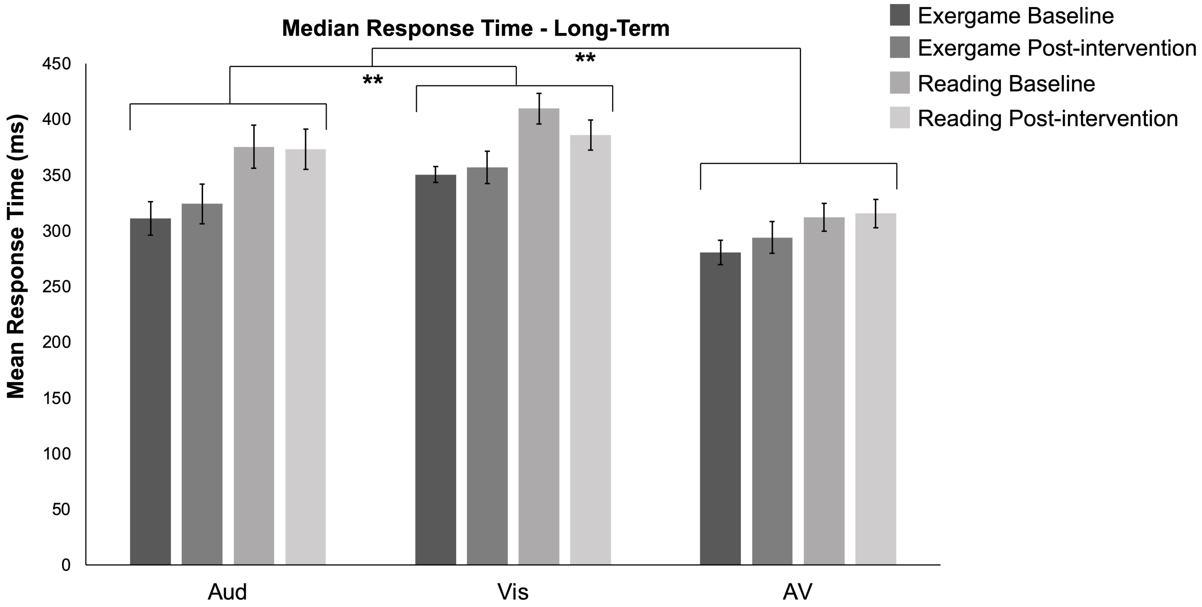


Figure 4.27: This figure depicts the median response time from baseline (darker shade) and post-intervention (lighter shade) sessions, obtained from those in the exergaming (dark grey) and reading (light grey) interventions for audiovisual, auditory, and visual trials. The results from long-term analyses echoed the results obtained from the acute sessions, where those in the reading group displayed longer median RTs (median = 362.041, s.e. = 16.10) as compared to those in the exergaming group (median = 319.641, s.e. = 12.404; $p = 0.017$). Further, median response times to the audiovisual stimuli (median = 300.691, s.e. = 8.161) were significantly faster as compared to the auditory (median = 346.016, s.e. = 16.573; $p < 0.001$) and visual (median = 375.816, s.e. = 13.670; $p < 0.001$) modalities. Additionally, responses to visual stimuli were significantly longer as compared to the auditory modality ($p < 0.001$). Further, compared to baseline auditory and visual median RTs, the RTs for both baseline and post-intervention sessions for audiovisual cues, were significantly faster ($p < 0.01$). Note, Aud = auditory stimuli, Vis = visual stimuli, AV = audiovisual stimuli, pre = baseline, and post = post-intervention. The error bars indicate the SEM.

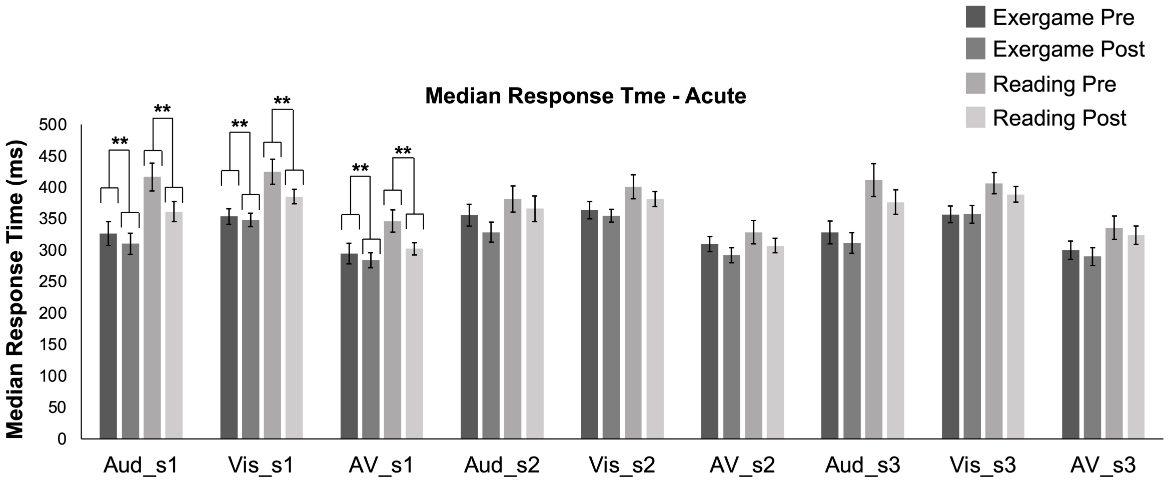


Figure 4.28: This figure depicts the median response time from acute sessions (1, 2, and 3 where dark shades represent pre-session and light shades represent post-session response times), obtained from those in the exergaming (dark grey) and reading (light grey) interventions for audiovisual, auditory, and visual trials. Those in the reading group displayed longer median RTs (median = 369.232, s.e. = 8.891) as compared to those in the exergaming group (median = 325.926, s.e. = 6.98; p = 0.017). Further, median response times to the audiovisual stimuli (median = 308.936, s.e. = 5.023) were significantly faster as compared to the auditory (median = 355.161, s.e. = 9.277; $p < 0.001$) and visual (median = 376.117, s.e. = 6.319; $p < 0.001$) modalities. Additionally, median responses to visual stimuli were significantly longer as compared to the auditory modality ($p = 0.035$). Further, compared to the pre-intervention results from session 1, the post-intervention session 1 results exhibited significantly faster median response time ($p = 0.004$). Note, 'S' = session, 'E' = exergaming group, and 'R' = reading group. The error bars indicate the SEM.

Time*Mod	Time*Mod	Mean Difference	SE	t	Cohen's d	p_{bonf}
B, A	B, V	−36.903	7.118	−5.185	−0.700	$< .001$
	B, AV	46.743	7.118	6.567	0.887	$< .001$
	PI, AV	36.528	10.162	3.595	0.693	0.010
PI, A	PI, V	−23.160	7.118	−3.254	−0.440	0.026
	B, AV	54.164	10.162	5.330	1.028	$< .001$
	PI, AV	43.950	7.118	6.175	0.834	$< .001$
B, V	B, AV	83.646	7.118	11.751	1.587	$< .001$
	PI, AV	73.432	10.162	7.226	1.394	$< .001$
PI, V	B, AV	77.324	10.162	7.609	1.467	$< .001$
	PI, AV	67.110	7.118	9.428	1.274	$< .001$

Table 4.6: Details regarding the post-hoc comparisons found for the median response time for the long-term sessions [baseline (B) and post-intervention (PI)] for the exergame and reading intervention groups. Results revealed that compared to auditory and visual median RTs at baseline, the RTs for audiovisual cues, both during baseline and post-intervention, were significantly faster ($p < 0.01$). Note that Mod = modality, B = baseline, PI = post-intervention A = audio, V = visual, and AV = audiovisual. Note also that only the significant results are presented here.

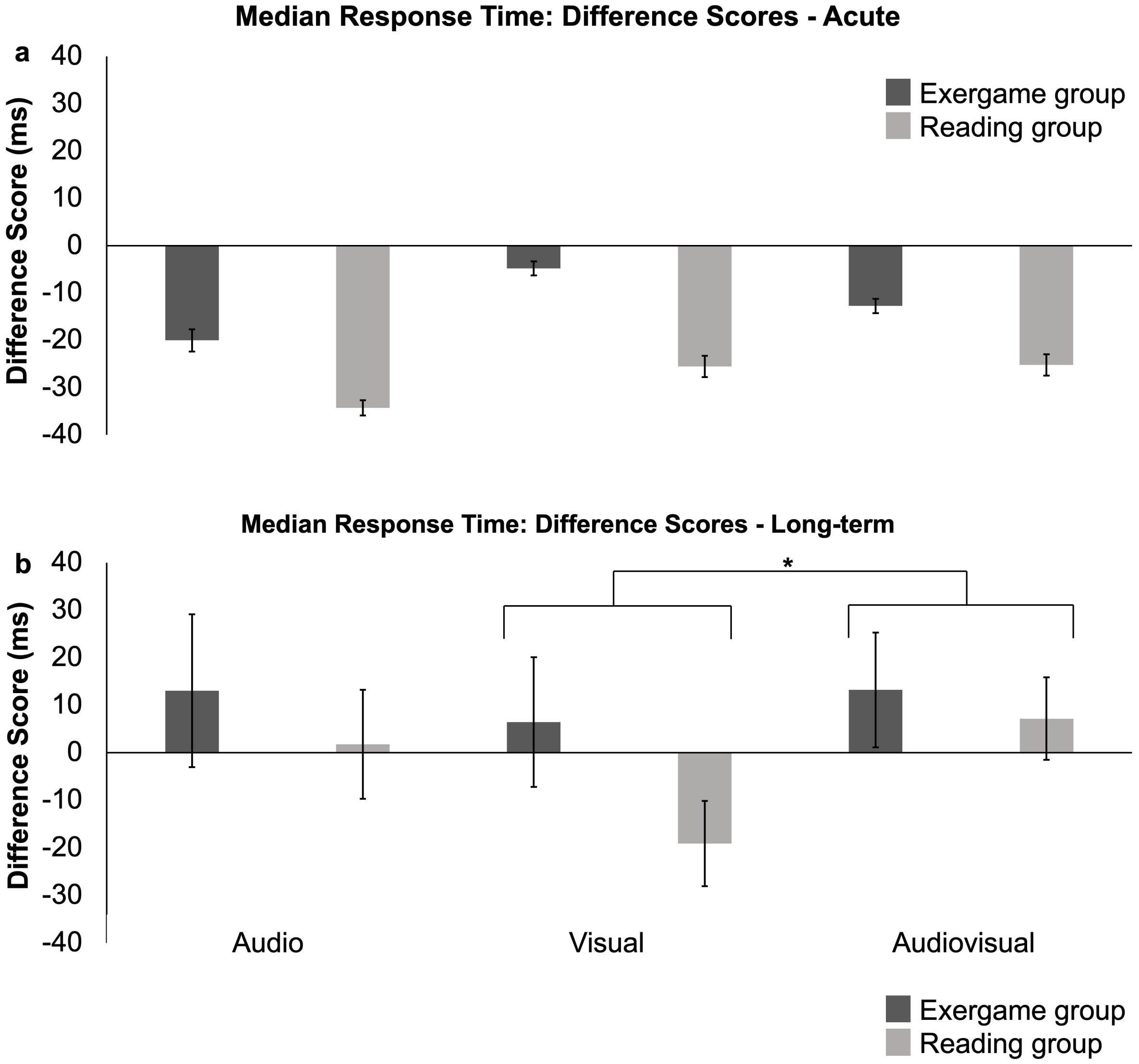
Gr*Tm*Mod	Gr*Tm*Mod	Mean Difference	SE	t	Cohen's d	p_{bonf}
G1, S1 pre, A	G2, S1 pre, A	−102.332	23.734	−4.312	−1.726	0.039
	G1, S1 pre, V	−106.278	23.734	−4.478	−1.793	0.022
G2, S1 pre, A	G1, S1 post, A	118.612	23.734	4.998	2.001	0.003
	G2, S1 post, A	63.079	13.610	4.635	1.064	0.005
	G2, S2 post, A	57.704	13.610	4.240	0.973	0.024
	G1, S3 pre, A	100.604	23.734	4.239	1.697	0.050
	G1, S3 post, A	117.331	23.734	4.944	1.979	0.004
	G1, S1 pre, AV	134.021	23.734	5.647	2.261	< .001
	G2, S1 pre, AV	72.137	12.115	5.954	1.217	< .001
	G1, S1 post, AV	144.809	23.734	6.101	2.442	< .001
	G2, S1 post, AV	123.733	17.034	7.264	2.087	< .001
	G1, S2 pre, AV	119.357	23.734	5.029	2.013	0.003
	G2, S2 pre, AV	92.417	17.034	5.426	1.559	< .001
	G1, S2 post, AV	136.760	23.734	5.762	2.307	< .001
	G2, S2 post, AV	119.892	17.034	7.039	2.022	< .001
	G1, S3 pre, AV	128.811	23.734	5.427	2.173	< .001
	G2, S3 pre, AV	93.092	17.034	5.465	1.570	< .001
	G1, S3 post, AV	138.928	23.734	5.854	2.343	< .001
	G2, S3 post, AV	103.392	17.034	6.070	1.744	< .001
G1, S1 post, A	G2, S1 pre, V	−122.558	23.734	−5.164	−2.067	0.002
G2, S1 post, A	G2, S1 post, AV	60.654	12.115	5.006	1.023	0.002
G1, S2 pre, A	G1, S1 post, AV	71.668	16.365	4.379	1.209	0.013
G2, S2 pre, A	G1, S1 post, AV	107.647	23.734	4.536	1.816	0.018
	G2, S1 post, AV	86.571	17.034	5.082	1.460	< .001
	G2, S2 pre, AV	55.254	12.115	4.561	0.932	0.012
	G2, S2 post, AV	82.729	17.034	4.857	1.395	0.002
	G1, S3 post, AV	101.766	23.734	4.288	1.716	0.043
G2, S3 pre, A	G1, S1 pre, AV	116.388	23.734	4.904	1.963	0.005
	G1, S1 post, AV	127.176	23.734	5.358	2.145	< .001
	G2, S1 post, AV	106.100	17.034	6.229	1.790	< .001
	G1, S2 pre, AV	101.724	23.734	4.286	1.716	0.043
	G2, S2 pre, AV	74.783	17.034	4.390	1.261	0.012
	G1, S2 post, AV	119.127	23.734	5.019	2.009	0.003
	G2, S2 post, AV	102.258	17.034	6.003	1.725	< .001
	G1, S3 pre, AV	111.178	23.734	4.684	1.875	0.011
	G2, S3 pre, AV	75.458	12.115	6.228	1.273	< .001
	G1, S3 post, AV	121.295	23.734	5.111	2.046	0.002
	G2, S3 post, AV	85.758	17.034	5.035	1.446	< .001
G1, S3 post, A	G2, S1 pre, V	−121.277	23.734	−5.110	−2.046	0.002
G2, S3 post, A	G2, S1 post, AV	73.321	17.034	4.304	1.237	0.018
	G2, S2 post, AV	69.479	17.034	4.079	1.172	0.044
	G2, S3 post, AV	52.979	12.115	4.373	0.894	0.024

G1, S1 pre, V	G1, S1 pre, AV	58.871	11.640	5.058	0.993	0.002
	G1, S1 post, AV	69.659	16.365	4.256	1.175	0.021
G2, S1 pre, V	G1, S1 pre, AV	137.967	23.734	5.813	2.327	$< .001$
	G2, S1 pre, AV	76.083	12.115	6.280	1.283	$< .001$
	G1, S1 post, AV	148.755	23.734	6.268	2.509	$< .001$
	G2, S1 post, AV	127.679	17.034	7.496	2.154	$< .001$
	G1, S2 pre, AV	123.303	23.734	5.195	2.080	0.002
	G2, S2 pre, AV	96.362	17.034	5.657	1.625	$< .001$
	G1, S2 post, AV	140.706	23.734	5.928	2.373	$< .001$
	G2, S2 post, AV	123.837	17.034	7.270	2.089	$< .001$
	G1, S3 pre, AV	132.757	23.734	5.594	2.239	$< .001$
	G2, S3 pre, AV	97.037	17.034	5.697	1.637	$< .001$
	G1, S3 post, AV	142.874	23.734	6.020	2.410	$< .001$
	G2, S3 post, AV	107.337	17.034	6.302	1.810	$< .001$
G1, S1 post, V	G1, S1 post, AV	64.093	11.640	5.506	1.081	$< .001$
G2, S1 post, V	G1, S1 post, AV	101.134	23.734	4.261	1.706	0.047
	G2, S1 post, AV	80.058	12.115	6.608	1.350	$< .001$
G1, S2 pre, V	G1, S1 pre, AV	68.877	16.365	4.209	1.162	0.026
	G1, S1 post, AV	79.665	16.365	4.868	1.344	0.002
	G1, S2 pre, AV	54.213	11.640	4.657	0.914	0.008
	G1, S2 post, AV	71.616	16.365	4.376	1.208	0.013
	G1, S3 post, AV	73.784	16.365	4.509	1.245	0.008
G2, S2 pre, V	G1, S1 pre, AV	113.338	23.734	4.775	1.912	0.008
	G1, S1 post, AV	124.126	23.734	5.230	2.094	0.001
	G2, S1 post, AV	103.050	17.034	6.050	1.738	$< .001$
	G2, S2 pre, AV	71.733	12.115	5.921	1.210	$< .001$
	G1, S2 post, AV	116.077	23.734	4.891	1.958	0.005
	G2, S2 post, AV	99.208	17.034	5.824	1.673	$< .001$
	G1, S3 pre, AV	108.128	23.734	4.556	1.824	0.017
	G2, S3 pre, AV	72.408	17.034	4.251	1.221	0.022
	G1, S3 post, AV	118.245	23.734	4.982	1.994	0.004
	G2, S3 post, AV	82.708	17.034	4.856	1.395	0.002
G1, S2 post, V	G1, S1 post, AV	70.567	16.365	4.312	1.190	0.017
	G1, S2 post, AV	62.517	11.640	5.371	1.054	$< .001$
G2, S2 post, V	G2, S1 post, AV	77.983	17.034	4.578	1.315	0.006
	G2, S2 post, AV	74.142	12.115	6.120	1.251	$< .001$
G1, S3 pre, V	G1, S1 post, AV	73.038	16.365	4.463	1.232	0.009
	G1, S3 pre, AV	57.040	11.640	4.900	0.962	0.003
	G1, S3 post, AV	67.157	16.365	4.104	1.133	0.039
G2, S3 pre, V	G1, S1 pre, AV	111.871	23.734	4.714	1.887	0.010
	G1, S1 post, AV	122.659	23.734	5.168	2.069	0.002
	G2, S1 post, AV	101.583	17.034	5.964	1.713	$< .001$
	G2, S2 pre, AV	70.267	17.034	4.125	1.185	0.036

	G1, S2 post, AV	114.610	23.734	4.829	1.933	0.006
	G2, S2 post, AV	97.742	17.034	5.738	1.649	$< .001$
	G1, S3 pre, AV	106.661	23.734	4.494	1.799	0.021
	G2, S3 pre, AV	70.942	12.115	5.856	1.197	$< .001$
	G1, S3 post, AV	116.778	23.734	4.920	1.970	0.005
	G2, S3 post, AV	81.242	17.034	4.769	1.370	0.002
G1, S3 post, V	G1, S1 post, AV	73.172	16.365	4.471	1.234	0.009
	G1, S3 post, AV	67.290	11.640	5.781	1.135	$< .001$
G2, S3 post, V	G1, S1 post, AV	105.038	23.734	4.426	1.772	0.026
	G2, S1 post, AV	83.963	17.034	4.929	1.416	0.001
	G2, S2 post, AV	80.121	17.034	4.704	1.351	0.003
	G2, S3 post, AV	63.621	12.115	5.251	1.073	$< .001$

Table 4.7: Details regarding the post-hoc comparisons found for the median response time for the acute sessions (sessions 1, 2, and 3) for the exergame and reading intervention groups. Results revealed that responses to the audiovisual trials were significantly faster across time as compared to auditory and visual trials and that those in the reading group had longer response times as compared to those in the exergaming group. Note that Gr = group, Tm = time, Mod = modality, G1 = exergaming group, G2 = reading group, A = audio, V = visual, and AV = audiovisual. Note also that only the significant results are presented here.

Additionally, difference scores of the median response time were also calculated to assess long-term and acute effects of exergaming and reading on median response times. A 2 (group) x 3 (modality) mixed-design ANOVA was conducted to assess long-term effects of intervention on median response time. The results revealed a significant effect of modality ($F(1.598, 38.348) = 3.798$, $p = 0.040$; $\eta_p^2 = 0.137$); pairwise comparisons revealed that although audiovisual stimuli were faster than auditory and visual stimuli, the difference obtained from subtracting baseline median RTs from post-intervention median RTs indicate that median response times increase after 6 weeks of intervention for audiovisual cues as compared to the visual modality ($p = 0.040$). As such, the improvement in performance was greater for the visual modality as compared to the audiovisual modality. The analysis failed to find a significant effect of group ($F(1, 24) = 0.861$, $p = 0.363$; $\eta_p^2 = 0.035$) or an interaction between group and modality ($F(1.598, 38.348) = 1.241$, $p = 0.298$; $\eta_p^2 = 0.049$). Further, a 2 (group) x 3 (time) x 3 (modality) mixed-design ANOVA was conducted to assess acute changes and failed to reveal a significant effect of group ($F(1, 23) = 3.131$, $p = 0.090$; $\eta_p^2 = 0.169$), however, pairwise comparisons revealed that those in the reading group showed larger improvement (i.e., greater difference score) as compared to those in the exergame group ($p = 0.090$). As Levene's test for Equality of Variance was violated, Friedman tests were conducted, which did not reveal a main effect of time (χ^2 (2) $= 4.570$, $p = 0.102$) or modality (χ^2 (2) $= 3.315$, $p = 0.191$). See Figure 4.29 for a graphical representation of the difference scores obtained for the auditory, visual, and audiovisual conditions for both the acute (panel a) and long-term (panel b) sessions.


Median Response Time: Difference Scores - Acute

Median Response Time: Difference Scores - Long-term

Figure 4.29: This figure depicts the difference scores calculated by subtracting pre-session response time for the auditory, visual, and audiovisual stimuli from post-session response time. The response times represented are collapsed across 3 times (session 1 post - pre session 1, session 2 post - pre session 2, and session 3 post - pre session 3; in panel a) for the acute condition and 1 time (post - baseline; panel b) for long-term effects. Scores obtained from the exergaming group are represented in dark grey, while scores obtained from the reading group are represented in light grey. For acute effects, albeit not significant, it was found that those in the reading group showed larger improvement (i.e., greater difference score) as compared to those in the exergame group ($p = 0.090$). For long-term effects, analyses revealed that median response times increase after 6 weeks of intervention for audiovisual cues as compared to the visual modality ($p = 0.040$). No other significant effects or interactions were observed for both acute and long-term sessions. The error bars indicate the SEM.

4.6 Discussion

This project is one of the first of its kind to investigate the impact of a 6 week exergame intervention on perception while also utilizing a control group to truly understand the effects of a custom-designed exergame intervention called 'Seas the Day' on multisensory processes. As this is the first experiment of its kind, various tasks and outcomes of interest were used to shed light on how acute bouts of exergaming as well as longitudinal effects of exergaming impact multisensory processing. Four perceptual tasks including the audiovisual response time (RT), the simultaneity judgment (SJ), the sound induced flash illusion (SIFI), and the temporal order judgment (TOJ) tasks were used. Although this was a fairly exploratory study, we hypothesized that 6-weeks of participation in our co-designed exergame intervention would: 1. reduce susceptibility to the SIFI compared to reading, 2. reduce the width of the TBW for both the SJ and TOJ tasks compared to the control group, and 3. reduce response time and increase race model violations compared to the control group. Mixed-design ANOVAs were conducted to understand not only the effect of time (acute bouts versus longitudinal effects) but also the effect of exergaming versus reading. In summary, our results provide some evidence for hypothesis 1, where after 6 weeks of intervention, participants in the exergaming intervention exhibited higher accuracy (i.e., reduced susceptibility to the SIFI; baseline accuracy to the illusion = 52.3% and post-intervention accuracy to the illusion = 76.1%) as compared to those in the reading (baseline accuracy to the illusion = 41.8% and post-intervention accuracy to the illusion = 66.4%) intervention. However, both groups exhibited improvements in their performance and a significant difference between the groups was not found. Further, some evidence was provided for our third hypothesis where we found that those in the exergaming group had faster mean and median response times as compared to those in the reading group, however no effect of time was found, suggesting that 6 weeks of participation in the intervention did not decrease response time as was expected. Additionally, although an increase in area under the curve was found post-intervention, there was no effect of group, suggesting that either both the interventions impacted area under the curve or practice effects may have played a role. Finally, contrary to hypothesis 3, we failed to find a significant effect of group for the SJ and TOJ tasks, however, we did find that participants had wider TBWs for the SJ task and although not significant, participants exhibited wider TBWs at baseline versus at post-intervention. This concludes the findings as they relate to assessment of specific hypotheses, what follows is a discussion regarding our exploratory analyses below. We will further discuss the findings from this study and interpret their meaning, below.

Overall, our results provide some evidence that the perceptual tasks used in this chapter discern significant and meaningful differences between the reading and exergaming groups. Firstly, through the acute analysis we found that those in the exergaming group achieved significantly higher accuracy scores on the audiovisual trials (i.e., audiovisual controls, the illusory trials) of the SIFI as compared to those in the reading group. Although not significant, a difference in performance was observed between the two groups even at baseline, with those in the exergame group achieving an overall accuracy of approximately 65%, while those in the reading group achieved an overall accuracy of approximately 58% on the audiovisual trials, suggesting that differences may have been present at baseline and were potentially exacerbated due to the intervention type. In addition to worse accuracy on the SIFI, those in the reading group were also found to exhibit longer mean (exergame group mean = 333.376; reading group mean = 386.359) and median (exergame group median = 324.977; reading group median = 372.469) response times on the RT task over acute sessions. Unlike the SIFI, group differences could be observed at baseline where those in the exergaming group had faster overall response times (mean = 336.100 ms; median = 314.178 ms) as compared to those in the reading group (mean = 391.312 ms; median = 365.808 ms). These results suggest that recruiting participants based on a known intervention may result in selection bias, as participants who are more technologically-literate are more likely participate in an exergame study, while such skills may not be perceived as crucial or necessary for the reading intervention. Thus, between-group differences on effects of type of intervention should be interpreted with caution. Note that group differences were also investigated using the SJ and TOJ tasks and these tasks failed to find any meaningful differences in TBW and PSS between the two groups, both at baseline, and at post-intervention. These results suggest the SJ and TOJ tasks may not be as sensitive at detecting minute differences between the two groups, and that perhaps accuracy and response time as assessed via the SIFI and the RT respectively are the more sensitive outcome variables.

Apart from group differences, time was also a significant factor of interest as data was collected across multiple sessions (baseline and post-intervention for all tasks and three additional pre- and post-sessions for the RT and SIFI tasks in between) to understand long-term and acute effects of exergaming or reading on multisensory processing. Starting with the long-term effects observed for the SIFI, we found that accuracy to the illusory condition was significantly lower at baseline as compared to post-intervention, suggesting that susceptibility to the illusory condition can decrease either because of repetition effects or because of the interventions that each group was exposed to. Further, the difference score analysis revealed that difference in accuracy to the illusory condition was larger than that for the 2 flash 2-beep condition suggesting that repetition or reading and engaging in exergames is more likely to impact components of perceptual performance that have greater potential for improvement. Further evidence for such a process is provided by the near-significant effect of group for the visual-only trials of the SIFI, where those in the reading group showed a larger difference in performance after 6 weeks of intervention. Our acute-analysis results from the RT task also indicate larger differences on trials with greater room for improvement, where although the mean response times to audiovisual trials were significantly faster than auditory and visual trials across time, the auditory modality showed a larger difference in performance as compared to the audiovisual modality. Additionally, both mean and median response time difference scores investigating acute and long-term effects also revealed that those in the reading group showed larger improvement (i.e., greater difference score) as compared to those in the exergame group. As the reading group had significantly longer response times to all modalities and showed a greater reduction in response time as compared to the exergaming group, this finding further suggests the potential of our interventions or repetition to target areas or populations that are most in need of improvement. Time of exposure to our interventions also impacted the outcome variables obtained from the SJ and TOJ tasks where although not significant, participants exhibited wider TBWs at baseline as compared to the post-intervention session. These results suggest that either reading and engaging with exergames can directly affect the width of the TBW, or that exposure to, and improvement on the SIFI and RT tasks, may have beneficial transferable effects.

Previous research provides some guidance related to transfer effects. A study conducted by Setti and colleagues [418] aimed to determine the impact of perceptual training on older adults where they trained twenty four older adults to judge the temporal order of auditory and visual stimuli using the TOJ task, while providing feedback after each trial, over five consecutive days. They found that majority (eighteen of the twenty four) of the participants were significantly more accurate on the TOJ task on the fifth as compared to the first day. Further, the researchers aimed to determine whether training participants on the TOJ task would reduce susceptibility to the SIFI and although training on the TOJ task did not improve susceptibility to the SIFI for all the stimulus onset asynchronies (SOAs), significant improvement appeared for the longest SOA of 270 ms.

Contrary to the narrative of transfer effects through training presented by Setti and colleagues [418], a more recent study conducted by Powers and colleagues [377] found that five days of training with feedback on the SJ and a variant of the SJ (refer to Powers and colleagues [375] for further information) tasks did not alter perception on the illusory trials of the SIFI in younger adults ($n = 14$ and $n = 20$ for the SJ and variant of the SJ respectively). However, they did find performance improvements in the two-flash conditions, whereby participants were more likely to correctly identify two flashes presented in close succession compared to pre-training baseline data. This improvement was driven by increased hits in the training group but not in the control group. Further, a direct relation between a decrease in the width of the TBW and an increase in sensitivity to the SIFI post-SJ training but not after training on the variant of the SJ task was found, suggesting that tasks that require participants to attend to fine temporal structures of audiovisual stimuli (SJ) rather than making judgments regarding 2 pairs of stimuli where one is objectively always simultaneous (variant of SJ), may increase hits and decrease false alarms, both of which positively impact a related task (SIFI). In another study conducted by O'Brien and colleagues [353], both young ($n = 20$) and older adults ($n = 23$) were trained on a 2-interval forced choice task for 3 days, where they were presented with two pairs of audiovisual stimuli where one pair was always synchronous while the other varied by the following SOAs: 50, 100, 150, 200, 250, and 300 ms, with no audio-lead conditions. Participants were asked to determine in which pair the stimuli were presented simultaneously and were provided with feedback both after correct (yellow happy face) and incorrect (blue sad face) responses. Pre- and post- performance on the SIFI was also obtained to quantify potential generalizability of training effects. As expected, training improved accuracy and led to a significant decrease in the TBW on the 2-IFC task in both younger and older adults. However, no significant improvement in susceptibility to the illusion were found in both groups; in fact older adults showed a reduction in sensitivity to the illusion post-training! The authors argued that these unexpected results may be due to fatigue and/or task difficulty. Thus, these studies do not provide support for a generalized improvement in multisensory perceptual processing following training on one task. If the improvements observed in the SJ and TOJ tasks are not entirely related to transfer effects, it may be that reading and exergaming are indeed affecting multisensory processing.

As single-bouts of exercise have been shown to impact not only higher-order cognitive function [371, 84, 303] but also sensory processing [351, 171, 19], it is not surprising that our exergame intervention 'Seas the Day' is impacting multisensory processing as assessed via the RT and SIFI tasks. One potential explanation for changes observed through exercise in multisensory processing could be related to increases in Gamma-aminobtyric acid (GABA), the chief inhibitory neurotransmitter in the central nervous system. GABA tends to decrease in concentration with aging and indeed, Goa and colleagues [166] found that the levels of GABA are reduced in frontal and parietal regions by approximately 5% per decade of life. Such a reduction in GABA can reduce the brain's ability to ignore or inhibit the integration of erroneous cues and can potentially increase the difficulty in discriminating the temporal order of information. GABA levels have been found to increase in concentration not only with chronic exercise [267] but also following acute bouts of exercise [286, 304]. In a study conducted by Maddock and colleagues [286], GABA levels were found to increase significantly after vigorous exercise ($\geq$ 80% of predicted maximal heart rate) in 38 young adults (mean age = 26.68). It is important to note however that although there is evidence to indicate that single bouts of aerobic exercise can increase GABA concentration, which may have an impact on multisensory processing, most of the neurophysiological research has been conducted with high or moderate intensity exercise, which is unlike the intensity utilized in our exergame. The participants in our study were asked to exert light to moderate effort and most participants reported exerting light effort. This can help to explain the lack of group differences observed for the SJ and TOJ tasks between the reading and exergaming groups. However, a meta-analysis conducted by Chang and colleagues [84] found that 20 minutes of light exercise can induce cognitive enhancement as long as cognition is tested within the first 20 minutes following exercise, which may help to explain the effects that were indeed observed. It is interesting however that the larger difference mean and median scores were observed for the reading group, suggesting that potentially a large improvement may have occurred in the reading group as compared to the exergaming group.

Although changes in multisensory processing were expected from engaging in exergames, the unexpected improvements from engaging in reading led us to further investigate the literature regarding why one may see changes from an activity that is thought to be more passive than engaging in physical activity. Firstly, reading is thought to be a relaxing activity which has been shown to improve mental health, maintain cognitive abilities, reduce the risk of mortality, and reduce stress in young and older adults [264, 41, 391]. Indeed, in a study conducted by Rizzolo and colleagues [391], a single session of 30 minutes of reading was found to reduce stress by reducing elevated systolic blood pressure, diastolic blood pressure, and heart rate in 24 young adults (mean age = 23). Most interestingly, it was found that 30-minutes of reading had similar effects as 30-minutes of yoga and watching a humorous video. In an older study, 60 minutes of reading was similarly found to reduce anxiety, heart rate, and blood pressure in 24 adults (mean age = 36.2), however in this study, Tai-Chi was found to have superior effects [220]. One possible mechanism through which reading can reduce stress is via easing of tension in the muscles of readers, which may occur when an individual becomes immersed into the topic of interest. Another potential mechanism, not dissimilar to exercise, is GABA, where reading could reduce stress through the modulation of the GABAering system. There is research to indicate that increases in GABA (via diazepam) are associated with a reduction in anxiety and stress in rats and humans [119, 282]. The evidence presented above indicates that the GABAergic system may underlie the changes in multisensory processes observed in this study and warrants further investigation from multisensory integration researchers.

One limitation of our study is that although the same inclusion and exclusion criteria were applied for the recruitment of participants for the exergame and reading interventions, significant differences in performance at baseline indicate that the groups were not entirely similar. Upon investigating the demographic, cognitive, and physical activity data obtained from both the exergaming and reading group, it was revealed that not only were there significantly more females in the reading group, but also that those in the reading group were also older (mean = 76.64, s.e. = 1.48) as compared to those in the exergaming group (mean = 68.46, s.e. = 1.34), which may explain the differences in performance found between the two groups. Revisiting the notion that those in the reading group may have improved because there was greater room for improvement, one explanation could also be that those in the reading group were significantly older than those in the exergaming group and thus had greater possibility to improve. Indeed in a study conducted by Powers and colleagues [375] a training paradigm was designed where participants ($n = 14$) were provided with feedback regarding their performance on an audiovisual simultaneity judgment task. They found that one hour of training for five consecutive days was able to improve the accuracy with which participants perceived which stimuli were and were not simultaneous by 40% (i.e., a 40% reduction in the temporal binding window; TBW). Most importantly, they found that a large temporal binding window at baseline predicted success during training. They were able to divide their participants into two groups, those whose mean temporal binding windows (TBW) were quite wide prior to training and decreased with training (i.e., dynamic participants; TBWs = 391.12 ms baseline) and those whose TBWs either remained the same or increased with training (i.e., static participants; TBWs = 149.45 ms baseline). They found that post-intervention, the TBWs of the dynamic participants became narrower until they were similar to the size of TBWs obtained for the static participants. Interestingly, the baseline TBWs for those in the dynamic group are comparable, if not higher, to the TBWs typically found from older adults for the SJ task (e.g., 250 ms, 257 ms, 179 ms; [43, 36, 37]. Given that those in the reading group were older, this may help to explain why (a) wider TBWs were found both at baseline and post-intervention in this group and (b) why exposure to our intervention may have a higher potential to be more helpful for the more elderly old adults in our study, as there may have been more room for improvement at baseline. Regardless of the mechanism involved, these results suggest that the inclusion of a control group is necessary for the assessment of the effect of any given exergame on perception and cognition because it helps to guide interpretation of the data. However, participant selection should follow a more systematic approach, where participants are recruited concurrently and without prior knowledge of which condition they will be placed in. Further, if time and resources allow, a larger sample size of both groups can help to reduce bias and can be used by future researchers to reduce baseline differences that impact statistical outcomes and their subsequent interpretation.

Another limitation specific to the design of this study, participants in the control group were not asked to complete the perceived enjoyment questionnaire as the questionnaire was initially incorporated only to assess the enjoyment of engagement with our exergames, however, such a questionnaire could have also yielded perceived enjoyment of engagement with reading. Moving forward, we recommend that researchers critically evaluate whether the same questionnaires can yield meaningful information for their work, so as not only to maintain experimental consistency across the groups, but also to obtain meaningful data that can be used to compare another parameter between the groups. Finally, these results indicate that although reading is used readily in exercise studies as a control condition, it may not be the optimal 'control' condition for researchers investigating multisensory processing. Indeed, research suggests that reading is a multisensory activity with individuals not only utilizing visual imagery while reading [54, 64], but also producing an 'inner voice' when reading silently, as indicated by activation of the primary auditory cortex [501, 363]. Further, there is evidence that readers can imagine non-speech sounds that are evoked by a passage that is silently read [68] and that participants can give different characters varying voices as well [5]. Thus, researchers investigating the effects of physical activity on multisensory processing may want to consider utilizing a different control condition moving forward. Finally, to address the limitation of age and sex, we recommend that the age and sex of the control is matched to the the age of the intervention group.

4.7 Conclusion

Here, we have demonstrated that exergaming and reading interventions may impact perceptual processing. The current data suggests that those in the exergaming group may have benefited more from the intervention as their accuracy scores were higher on the SIFI and response times faster on the audiovisual RT task as compared to those in the reading group. However, our results must be interpret with caution as group differences may have contributed to the significant differences, for example those in the reading group were older as compared to those in the exergaming group and thus those in the reading group may have had a greater potential of improvement as compared to the exergaming group, as indicated by greater difference scores obtained for the SIFI and the RT task. Investigation of the GABAergic system may help future researchers to better understand how both reading and engaging in exercise can potentially impact perceptual processing. Our results suggest that future researchers should include a control group to better understand the effects of exergaming, however, reading may not necessarily be the best control condition for those investigating the effects of exercise on multisensory processing.

Chapter 5

A Scoping Review of Audiovisual Integration Methodology: Screening for Auditory and Visual Impairment in Younger and in Older Adults

Adapted from: Basharat A, Thayanithy A, Barnett-Cowan M (2021). A Scoping Review of Audiovisual Integration Methodology: Screening for Auditory and Visual Impairment in Younger and Older Adults. Frontiers in Aging Neuroscience. 13:772112. DOI: 10.3389/fnagi.2021.772112

5.1 Abstract

With the rise of the aging population, many scientists studying multisensory integration have turned towards understanding how this process may change with increasing age. This scoping review was conducted to understand and describe the scope and rigour with which researchers studying audiovisual sensory integration screen for hearing and vision impairment. A structured search in three licensed databases (Scopus, PubMed, and PsychInfo) using the key concepts of multisensory integration, audiovisual modality, and aging revealed 2,462 articles, which were screened for inclusion by two reviewers. Articles were included if they 1) tested healthy older adults (minimum mean or median age of 60) with younger adults as a comparison (mean or median age between 18-35), 2) measured auditory and visual integration, 3) were written in English, and 4) reported behavioural outcomes. Articles that included the following were excluded: 1) tested taste exclusively, 2) tested olfaction exclusively, 3) tested somatosensation exclusively, 4) tested emotion perception, 5) were not written in English, 6) were clinical commentaries, editorials, interviews, letters, newspaper articles, abstracts only, or non-peer reviewed literature (e.g., theses), and 7) focused on neuroimaging without a behavioural component. Data pertaining to the details of the study (e.g., country of publication, year of publication, etc.) were extracted, however,

of higher importance to our research question, data pertaining to screening measures used for hearing and vision impairment (e.g., type of test used, whether hearing- and visual-aids were worn, thresholds used, etc.) were extracted, collated, and summarized. Our search revealed that only 64% of studies screened for age-abnormal hearing impairment, 51% screened for age-abnormal vision impairment, and that consistent definitions of normal or abnormal vision and hearing were not used among the studies that screened for sensory abilities. A total of 1,624 younger adults and 4,778 older participants were included in the scoping review with males composing approximately 44% and females composing 56% of the total sample and most of the data was obtained from only 4 countries. We recommend that studies investigating the effects of aging on multisensory integration should screen for normal vision and hearing by using the World Health Organization's (WHO) hearing loss and visual impairment cut-off scores in order to maintain consistency among other aging researchers. As mild cognitive impairment (MCI) has been defined as a 'transitional' or a 'transitory' stage between normal aging and dementia and because approximately 3 to 5% of the aging population will develop MCI each year, it is therefore important that when researchers aim to study a healthy aging population, that they appropriately screen for MCI. One of our secondary aims was to determine how often researchers were screening for cognitive impairment and the types of tests that were used to do so. Our results revealed that only 55 out of 72 studies tested for neurological and cognitive function, and only a subset used standardized tests. Additionally, among the studies that used standardized tests, the cut-off scores used were not always adequate for screening out mild cognitive impairment. An additional secondary aim of this scoping review was to determine the feasibility of whether a meta-analysis could be conducted in the future to further quantitatively evaluate the results (i.e., are the findings obtained from studies using self-reported vision and hearing impairment screening methods significantly different from those measuring vision and hearing impairment in the laboratory) and to assess the scope of this problem. We found that it may not be feasible to conduct a meta-analysis with the entire dataset of this scoping review. However, a meta-analysis can be conducted if stricter parameters are used (e.g., focusing on accuracy or response time data only).

5.2 Introduction

The proportion of the world's population over 60 years of age is estimated to increase to approximately 2 billion individuals by 2050, nearly doubling from 12% of the world population to 22% [42]. With such a drastic shift in global demographics, the incidence of age-related chronic health conditions is also expected to increase. Indeed, the prevalence of audition and vision degradation increases with age and can have global impacts on cognition [401, 374, 25] and temporal perception [182, 188, 115, 62]. Combining information across the senses can improve localization, discrimination, and speed of responses to objects, however, the central nervous system (CNS) must bind together the appropriate signals [72]. One cue that the CNS can use to determine whether or not stimuli should be bound together into a single percept (multisensory integration) is the temporal relation, how close in time two or more signals are to one another; research has revealed, using not only non-human animal models but also through studies conducted with humans, that signals that appear closer in time are more likely to be integrated [[483]; see also King and colleagues [238] for a review of strategies used by the CNS to bind appropriate cues]. As temporal perception is affected by changes in unisensory processing, changes in auditory and visual acuities can act as indicators that may provide insight into changes associated with the multisensory integration processes within the aging population. Within the auditory domain, an estimated 466 million people worldwide have disabling hearing loss [345] and it is estimated that between 25%-40% of older adults aged 65 and over, can be classified as having hearing impairment [506]. It has been found that the prevalence of hearing loss rises with age, ranging from 40%-66% in adults over the age of 75 years and more than 80% in those older than 85 years of age [100, 506, 487]. Further it has been found that after the age of 60, hearing typically declines by about 1 dB annually and that men usually experience greater hearing loss and earlier onset compared to women [257].

More than 90% of older individuals with hearing loss have age-related sensorineural hearing loss, which is a gradual symmetric loss of hearing – predominately of higher frequencies – that is worse in noisy environments [506]. Note however, that in an epidemiology study conducted by Lin and colleagues [269] where data related to hearing abilities of older adults aged 70 and over was used from the 2005–2006 cycle of the National Health and Nutritional Examination Survey, it was found that the prevalence of hearing loss varied depending on the tonal frequencies, the audiometric thresholds used to define hearing loss, and whether hearing loss was considered in the better or worse hearing ear. They reported hearing loss prevalence rates from 16.5% when hearing loss was defined as using 0.5, 1, and 2 kHz (standard pure tone averages; PTA) with a 40 dB threshold in the better ear to 99.7% when hearing loss was defined as using 3, 4, 6, and 8 kHz (high-frequency PTAs) with a 15 dB threshold in the worse ear. Although they found that most reports of hearing loss prevalence used a 25 dB threshold, standard PTA (0.5, 1, and 2 kHz) or speech frequency PTA (0.5, 1, 2, and 4 kHz), and obtained measures in either the worse or better ear, there was still a high degree of variability of hearing loss reported. The range was narrower but spanned 44.8% when using the standard PTA in the better ear to 75.1% when using speech frequency PTA in the worse ear. Thus, the definition used when measuring hearing loss is crucial especially when some researchers may be utilizing a more rigid inclusion criteria as compared to others.

Shifting our focus towards the visual domain, worldwide, approximately 185 million people over the age of 50 years are visually impaired [346], with cataracts, age-related macular disease, and refractive errors being the most common causes of visual impairment in older adults [346, 69]. Although cost effective interventions such as cataract surgery and corrective glasses have shown to be effective, only 22% and 37% of individuals living in upper-middle and high-income countries respectively have reported having an eye exam during the preceding year [346]. The World Health Organization (WHO) defines visual impairment based on the International Classification of Diseases 11 [343] classification in the following categories for acuities measured at a distance of 2 to 4 meters: mild visual impairment is defined as acuity worse than 6/12 to 6/18, moderate visual impairment is defined as acuity worse than 6/18 to 6/60, and severe visual impairment is defined as visual acuity that is worse than 6/60 to 3/60 in both eyes. In other words, the WHO defines visual impairment as best corrected visual acuity of less than 20/40 but greater than or equal to 20/400, while many researchers (especially in the US) commonly define visual impairment as best corrected visual acuity that is worse than 20/40 but better than 20/200 in the better eye [[69, 342]; also see Table 1 in the appendix for details regarding the WHO's definition of visual impairment. This table contains Snellen and LogMAR values]. In a study conducted by Buch and colleagues [69] comparing the prevalence of visual impairment in 944 individuals as defined by the WHO and the criteria most commonly used in the US, it was found that 2.6% of those aged 70-74 years and 4.8% of those aged 75-80 years had visual impairments according to the WHO's definition (worse than 20/60–20/400 in the better eye; 2004 definition). However, these values differed based on the criteria used in most US studies where 3.1% of those aged 70-74 years and 8.0% of those between 75-80 years of age had visual impairment. Here, once again, we are reminded that the definition of impairment used by researchers is crucial and that some researchers may be excluding more participants than others.

Given the changes in sensory acuities associated with aging, accounting for such changes in hearing and vision is crucial as it may increase the quality and validity of the data obtained. The integration of auditory and visual cues into a unified percept is a fundamental process with an evolutionary benefit as it allows the observer to respond to external events more quickly and accurately relative to unisensory information alone [440]. Such an ability to integrate auditory and visual cues into a coherent percept has been thought to be beneficial for everyday function, for example in improving perception of speech in noise [453] and in improving driving performance [381], both of which are especially relevant for the aging population. Research has time and again revealed that there are three principles that underlie multisensory processing, the first two principles suggest that the more temporally and spatially coincident [313, 444, 40] two sensory cues are, the more likely they are to be bound together and result in a unified percept. The third principle states that unisensory signals that are weakly effective on their own are more likely to benefit from integration [443, 444, 40]. This third principle of inverse effectiveness however does not hold true when the unisensory component that would be bound into a multisensory percept becomes unreliable and can result in a reduction in multisensory benefits as observed through models of optimal integration [393, 284, 40]. Indeed, effective multisensory integration is dependent on both peripheral sensory organs as well as higher cognitive processes. As significant changes in sensory systems (e.g., decrease in visual acuity and an increase in auditory acuity thresholds) and cognitive function (e.g., decline in executive function and memory) are associated with healthy aging, it is not surprising that multisensory integration also changes with age [382, 224, 273, 331, 155, 40]. Indeed, older adults have been found to have longer response times in audiovisual detection tasks [255, 291, 106, 37], exhibit wider temporal binding windows (TBWs; the window of time within which information from different modalities is integrated and perceived as simultaneous; [43, 37, 416]), are more likely to be distracted by irrelevant stimuli within and across modalities [370]; see [117] for a detailed review regarding the effects of aging on multisensory integration), but they are also more likely to exhibit greater multisensory enhancement (see [331] and [117] for detailed reviews) compared to younger adults. Further, it has been found that such changes in multisensory integration are exacerbated in those living with mild cognitive impairment and dementia. Research has revealed that those living with MCI and dementia tend to have slower response times, exhibit wider temporal binding windows, are more likely to experience attention impairment, and are less likely to benefit from multisensory enhancement compared to healthy controls [496, 399, 332]. These results suggest that both cognitive function and sensory abilities must be accounted for when conducting multisensory integration related research with the aging population.

A decline in sensory abilities can affect the reliability, or the precision of a sensory estimate, with which the central nervous system integrates cues from auditory and visual modalities and can thus reduce the benefits typically gained through the multisensory process [146, 338]. Note however, that reduced acuity may also help to explain the increased benefits of multisensory integration in the aging population through the lens of the principle of inverse effectiveness [331]. With a decline in auditory and visual acuity, the unisensory cues from these modalities would be presented just above threshold levels, thus the principal of inverse effectiveness would predict that integration of these weakly effective cues would produce gains much larger than the sum of their parts, suggesting that individuals with reduced sensitivity or acuity (i.e., older adults) may experience enhanced sensory integration. Thus accounting for age-related sensory loss is essential in multisensory literature as it impacts the reliability of the incoming information and thus the likelihood of integration. It should however be noted that in a recent review conducted by de Dieuleveult and colleagues [117] where the performance of older adults was compared to younger adults on unisensory and multisensory stimuli, it was found that although older adults did not always exhibit slower response times on the unisensory stimuli, they continued to show multisensory facilitation, indicating that inverse effectiveness may be one of many processes involved in the enhancement observed for multisensory cues in older populations [361, 190, 191].

Regardless of the underlying mechanisms, some research shows that changes in audition and vision impact temporal perception, not just within each modality, but also between these sensory modalities. Within the auditory domain, older age impairs temporal order judgments [182], duration discrimination [153, 154, 182], and reduces sensitivity to temporal fine structure [188]. Within the visual modality, age also impairs visual temporal judgments [115], reduces flicker sensitivity [299, 233], and reduces critical flicker frequency [247]. When assessing age-related changes to audiovisual temporal perception, researchers find that older adults are more susceptible to the sound-induced flash illusion [415, 301], are more susceptible to the temporal ventriloquist effect [115], and have wider temporal binding windows [43, 36, 37]. Further, as aging increases the prevalence of ocular disease and hearing loss, this can lead to impairment in temporal perception [366, 169, 163]. Although many, but not all, audiovisual multisensory paradigms include auditory- and visual-only conditions to gain insight into the workings of auditory and visual systems, we believe that accounting and screening for age-abnormal changes in the auditory and visual modalities will allow researchers to draw more reliable conclusions related to how audiovisual integration changes with age without being confounded by uncorrected vision and hearing. Our preliminary search revealed that researchers are not employing as much scientific rigour as would be necessary to account for auditory and visual acuity changes within the multisensory integration literature. While some researchers rely on self-reported measures obtained from participants, and others measure acuities in the laboratories or research centers to determine eligibility, some researchers however do not collect or account for visual and/or auditory acuities whatsoever. Further, a standardized criterion for what constitutes 'normal' vision and hearing does not seem to be used and does not exist within the multisensory integration literature [62].

Here, we aimed to determine the scope of this problem and collected information regarding what practices researchers are following in the literature to screen for vision and hearing impairment. We collected descriptive statistics regarding the number of researchers who screened for auditory and visual acuities (and how they reported them), those who used self-reported measures, and finally those who did not utilize any form of acuity measurements. We also aimed to determine what cut-off scores are being used when researchers do measure the acuities within a research or laboratory setting and what types of questions are asked to obtain self-reported perceptions of auditory and visual acuities. In addition to visual and auditory acuity measures, we also assessed how researchers define healthy aging (e.g., if cognitive impairment is accounted for and if so, how it is being measured). This scoping study will help provide a map of the methods researchers are utilizing and will help determine whether or not a meta-analysis can be conducted to further understand the scope of the issue with the current dataset.

5.3 Materials and Methods

The methods of the current study have been registered with Open Science Framework (https://doi.org/10.17605/OSF.IO/V3SNZ; [33]). The scoping review was conducted according to the framework proposed by Arksey and O'Malley [17] and the suggestions that have been developed by Levac, Colquhoun, and O'Brien [262]. These frameworks suggest that the scoping review process be organized into at least 5 stages, with an optional 6th stage.

Stage 1: Identifying the research question, Stage 2: Identifying relevant studies, Stage 3: Study selection, Stage 4: Charting the data, Stage 5: Collating, summarizing, and reporting the results, Stage 6: Consultation

5.3.1 Identifying the research question

We posed our research questions as follows: what is known from existing literature about the types of auditory and visual impairment screening methods that are employed in the literature on multisensory integration perception in healthy aging to screen for inclusion. Based on the results obtained in this scoping study, a recommendation of whether or not a meta-analysis can be conducted to determine if significant differences exist in the findings and or conclusions drawn in studies that used self-reported vision and hearing impairment screening methods compared to studies that measured vision and hearing impairment in the laboratory will be made. We further aimed to determine the methods used to assess and classify cognitive impairment in this literature.

5.3.2 Identifying relevant studies

Following the Arskey and O'Malley framework [17], this stage aimed to identify the criteria that were used to select studies for inclusion in the scoping study. Although scoping studies are designed to be broad, we chose a more specific criteria that would help guide the search.

Data source and searches: Relevant articles were identified in MEDLINE Pubmed (earliest records available – June 30th, 2020), MEDLINE Scopus (earliest records available – June 30th, 2020), and PsychInfo (earliest records available – June 30th). We chose these databases to ensure a comprehensive coverage of health, engineering, social sciences, and psychology journals. We believe that Pubmed comprehensively covers health related articles, Scopus acts as a complimentary multidisciplinary database that covers articles from engineering, social sciences, and health, and finally PsychInfo provides coverage of articles specifically from the psychology domain.

The key concepts used in the searchers were as follows: multisensory integration, audiovisual modality, and aging (with younger adults as a comparator). The key concepts were combined using the Boolean operator AND, and the search words within each concept were combined with OR. As suggested by Levac and colleagues [262], the team used an iterative process to identify key search terms. Initially, AB identified key articles and created keywords for each category for this review. A research librarian was consulted and advised on and helped modify the search strategy for the various databases used. Once the search strategies had been finalized, articles were retrieved from each database and imported into the Mendeley reference management software. Note that if an article did not contain a combination of all the search terms (i.e., multisensory, audiovisual, and aging) in the abstract, title, or in the 'keywords', it most likely did not appear in our search results.

Search strategies used for Scopus, PubMed, and PsychInfo:

Scopus: (TITLE-ABS-KEY (multisensory OR sensory OR crossmodal OR cross-modal OR cross-sensory OR intersensory OR multimodal OR multi-modal OR asynchrony OR temporal OR temporal-order OR "temporal window" OR integration OR "window of integration" OR "temporal binding window" OR "sound-induced flash illusion" OR "reaction time" OR "response time" OR "race model" OR simultaneity OR "redundant target")) AND TITLE-ABS-KEY (audiovisual OR "audio-visual" OR "visual-audio" OR "auditory-visual" OR "visual-auditory") AND TITLE-ABS-KEY (aging OR ageing OR "older adult*" OR older OR aged OR geriatr* OR gerontol* OR elderly OR "older persons"); 1,368 results obtained

PubMed: (multisensory[tw] OR Sensory[tw] OR crossmodal[tw] OR cross-modal[tw] OR cross-sensory[tw] OR intersensory[tw] OR multimodal[tw] OR multi-modal[tw] OR asynchrony[tw] OR temporal[tw] OR "temporal window" OR temporal-order[tw] OR integration[tw] OR "temporal binding window"[tw] OR "sound-induced flash illusion"[tw] OR "reaction time"[tw] OR "response time"[tw] OR "redundant target"[tw] OR "race model"[tw] OR simultaneity[tw] OR Reaction Time [MESH] OR Discrimination, Psychological [MESH]) AND (Audiovisual[tw] OR Audio-visual[tw] or visual-audio[tw] OR auditory-visual[tw] OR visual-auditory[tw]) AND (aging[tw] OR ageing[tw] OR older[tw] OR aged[tw] OR geriatr*[tw] OR gerontol*[tw] OR elderly[tw] OR Aged [MESH] OR Aged, 80 and over [MESH] OR Geriatrics [MESH]); 790 results obtained

PsychInfo: ((title: (multisensory) OR title: (sensory) OR title: (crossmodal) OR title: (cross-modal) OR title: (cross-sensory) OR title: (intersensory) OR title: (multimodal) OR title: (multi-modal) OR title: (asynchrony) OR title: (temporal) OR title: (temporal-order) OR title: ("temporal window") OR title: (integration) OR title: ("window of integration") OR title: ("temporal binding window") OR title: ("sound-induced flash illusion") OR title: ("reaction time") OR title: ("response time") OR title: ("race model") OR title: (simultaneity) OR title: ("redundant target")) OR (abstract: (multisensory) OR abstract: (sensory) OR abstract: (crossmodal) OR abstract: (cross-modal) OR abstract: (cross-sensory) OR abstract: (intersensory) OR abstract: (multimodal) OR abstract: (multi-modal) OR abstract: (asynchrony) OR abstract: (temporal) OR abstract: (temporal-order) OR abstract: ("temporal window") OR abstract: (integration) OR abstract: ("window of integration") OR abstract: ("temporal binding window") OR abstract: ("sound-induced flash illusion") OR abstract: ("reaction time") OR abstract: ("response time") OR abstract: ("race model") OR abstract: (simultaneity) OR abstract: ("redundant target")) OR (Index Terms: ("Sensory Integration") OR Index Terms: ("Intersensory Processing") OR Index Terms: ("Reaction Time") OR Index Terms: ("Causality") OR Index Terms: ("Perceptual Discrimination") OR Index Terms: ("Time Perception") OR Index Terms: ("Temporal Order (Judgment)"))) AND Any Field: ((title: (audiovisual) OR title: ("audio-visual") OR title: ("visual-audio") OR title: ("auditory-visual") OR title: ("visual-auditory")) OR (abstract: (audiovisual) OR abstract: ("audio-visual") OR abstract: ("visual-audio") OR abstract: ("auditory-visual") OR abstract: ("visual-auditory")) OR (Index Terms: ("Audiovisual Communication") OR Index Terms: ("Visual Perception") OR Index Terms: ("Auditory Perception"))) AND Any Field: ((title: (aging) OR title: (ageing) OR title: ("older adult*") OR title: (older) OR title: (aged) OR title: (geriatr*) OR title: (gerontol*) OR title: (elderly) OR title: ("older persons")) OR (abstract: (aging) OR abstract: (ageing) OR abstract: ("older adult*") OR abstract: (older) OR abstract: (aged) OR abstract: (geriatr*) OR abstract: (gerontol*) OR abstract: (elderly) OR abstract: ("older persons")) OR (Index Terms: (Aging) OR Index Terms: ("Age Differences") OR Index Terms: (Geriatrics) OR Index Terms: ("Individual Differences"))); 304 results obtained

5.3.3 Study selection

The third stage of the Arksey and O'Malley framework is to identify the studies that were to be included in the scoping study. Thus, following the Arksey and O'Malley framework [17], articles were identified to be included in the scoping study. All articles generated from the search for each journal were imported into Mendeley where duplicates were removed. Two team members (AB and AT) read the abstracts and titles of all the articles to screen the studies for inclusion based inclusion criteria mentioned above: 1) healthy older adults (participants must have been at a minimum mean or median age of 60) were tested; where 'healthy' was defined as not having a neurological disease (e.g., Parkinson's disease, Alzheimer's disease, cognitive impairment, depression), 2) healthy younger adults were tested (18-35); where healthy was defined as no current, acute, or chronic disease, 3) auditory and visual integration was measured (audiovisual integration), 4) the article was written in English, 5) had behavioural results. Studies that included the following were excluded: 1) tested taste exclusively, 2) tested olfaction exclusively, 3) tested somatosensation exclusively, 4) tested emotion perception, 5) were not written in English, 6) were clinical commentaries, editorials, interviews, letters, newspaper articles, abstracts only, or non-peer reviewed literature (e.g., theses), 7) focused on neuroimaging without a behavioural component. AB and AT met every week to compare their results and to discuss any issues. Any disagreements were discussed between the two reviewers until a consensus was reached or by arbitration of a third reviewer (MBC). Once this step was complete, full articles were retrieved for further evaluation. Note here, that five studies were included that tested only older adults (3,133 participants). Since they provided meaningful information, and because the primary question relates to auditory and visual thresholds, which are more affected in the older population, we decided to make an exception for these studies and included them in the scoping review.

5.3.4 Collating, summarizing, and reporting the results

The results are presented below as described in the registered protocol for the current scoping review (https://doi.org/10.17605/OSF.IO/V3SNZ; [33]). Descriptive data are presented in table format for variables of interest including but not limited to: title, author(s), year of publication, location(s); if the primary research question is addressed (i.e., if acuity was measured and if so, what the inclusion cut-off was, whether acuity was self-reported and if so, what questions were asked, or if acuity was unaccounted for); type of research article (original experimental research); description of participants (age, sex, inclusion/exclusion criteria); aim(s) of each study; methodology used [e.g., type of task used (e,g., detection response time (RT) task, simultaneity judgment (SJ), temporal order judgment (TOJ), etc.)]; outcome measures.

5.4 Results

5.4.1 Description of Studies and Participant Characteristics

For this scoping review, 2,462 articles were retrieved, 903 duplicates were automatically removed by Mendeley ($n = 1{,}559$), Mendeley was then manually checked for duplicates and 13 pairs of duplicates were found which were subsequently removed, leaving 1,546 original articles. The titles and abstracts of all 1,546 articles were reviewed. Through this process, 105 articles were selected for full article review and for further evaluation; 35 articles did not meet the inclusion criteria due to reasons spanning from age (either older adults were not included, or age was not listed), not being related to audiovisual integration, not peer reviewed (thesis), or because they were reviews that did not provide sufficient information or provided information that was not relevant to this scoping study (refer to Figure 5.1

for further information). Note that two additional studies were included during the review process, as such, a total of 72 studies were used to assess the research questions.

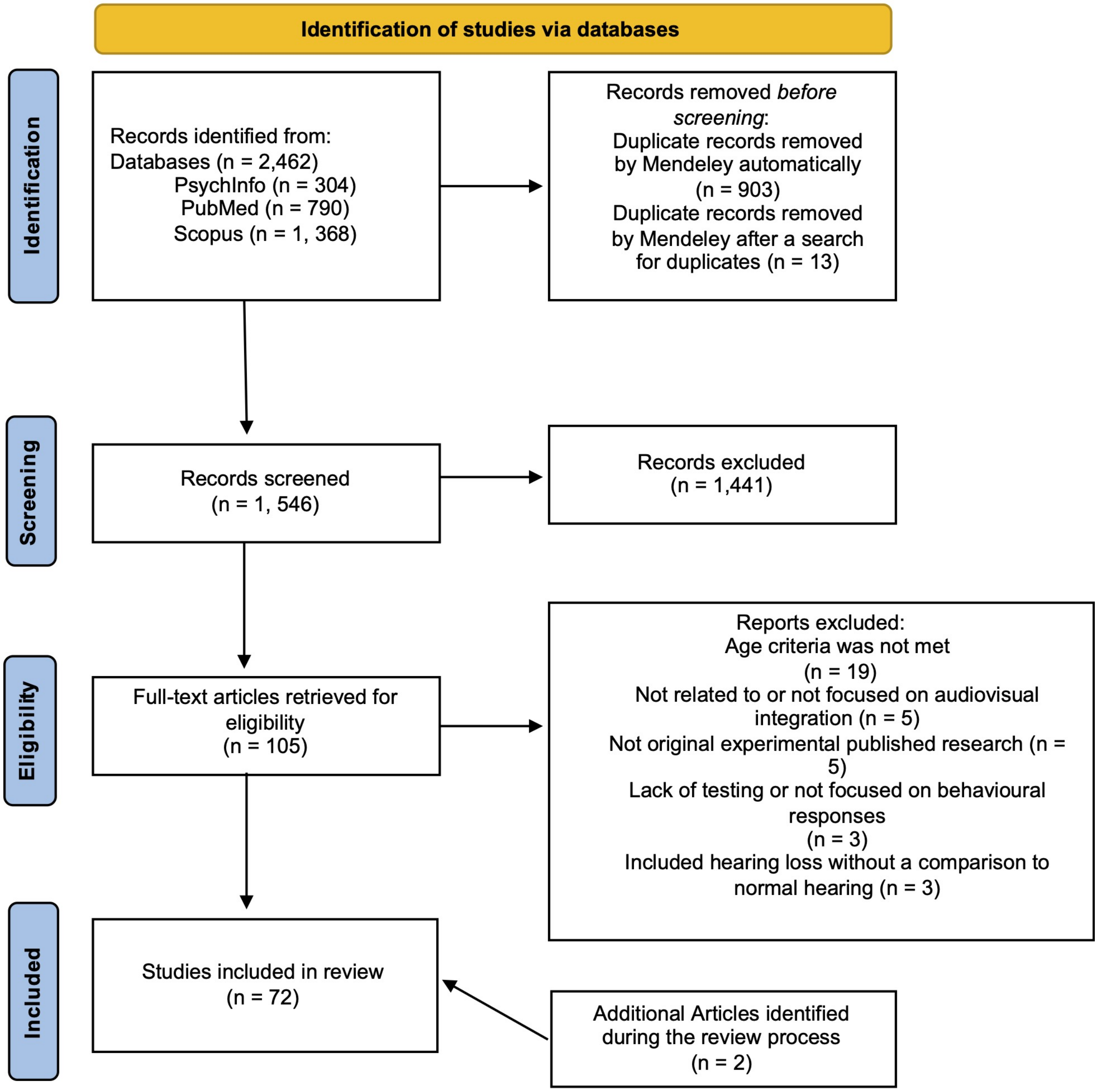


Figure 5.1: This flow diagram is adopted for this scoping study from the PRISMA flow diagram for systematic review [356] and includes searches of databases only.

We found that the United States produced the largest number of articles (see Tables 5.2 and 3 in the appendix for further details regarding the country of origin of the articles; note that the country of origin was determined by the affiliation of the all the authors listed on each manuscript). Various behavioural outcomes of interest were identified from the 72 studies; note that most studies extracted multiple outcomes of interest, thus the inclusion in one category does not preclude it from another category. The outcome variables of interest that were used by more than 5% of the studies are as follows: accuracy or proportion correct or percent correct ($n = 42$), mean or median response time ($n = 32$), race model as a measurement of enhancement ($n = 13$), enhancement in speech perception ($n = 11$), hit rate ($n = 10$), and the temporal binding window or temporal window of integration or the just noticeable difference ($n = 10$) ; see Tables 3 and 4 in the appendix for further information regarding the tasks used, the aim of each study, and the outcomes of interest. See also Figure 5.2 for a visualization of the behavioural outcomes of interest.

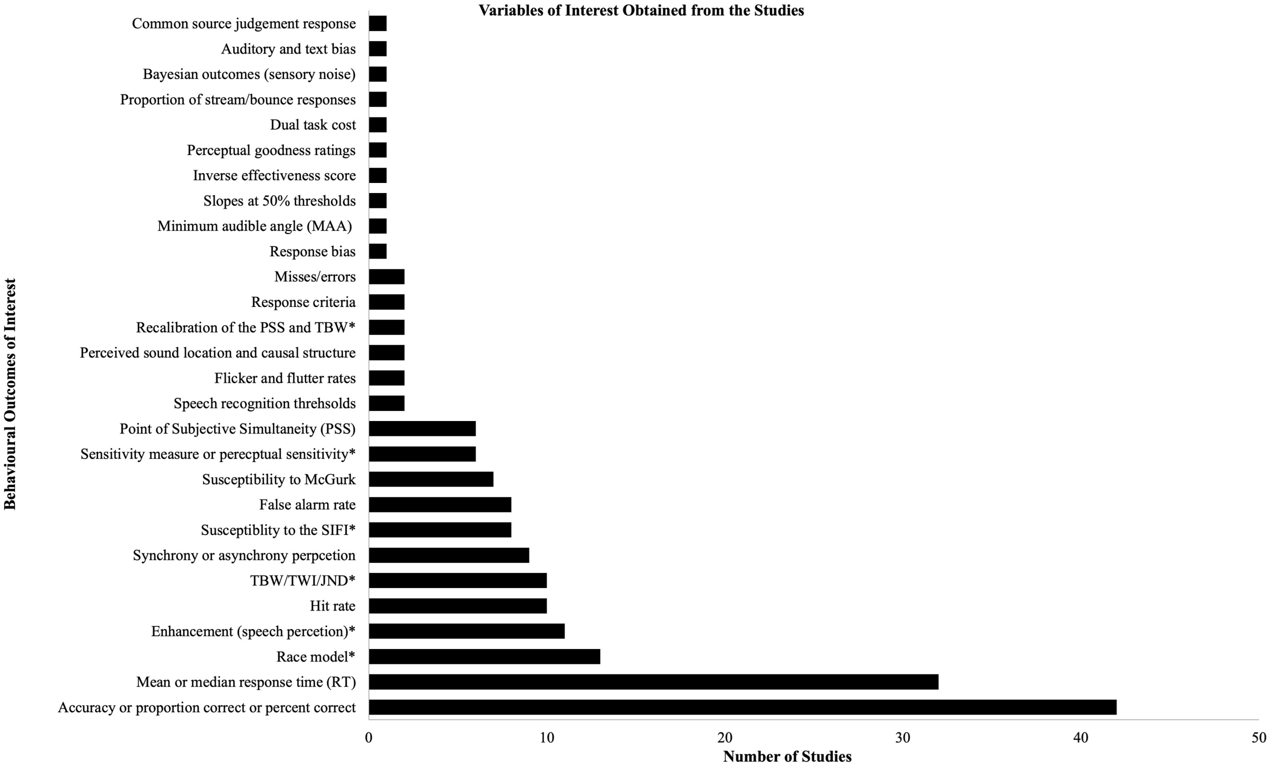


Figure 5.2: This figure provides a visual breakdown of the behavioural outcomes of interest for the studies included in this scoping review in the form of a bar graph. Please refer to Table 3 in the appendix for further information regarding the behavioural outcomes of interest for each study as well as the type of tasks used to extract this information. Asterisks (*) in the figure indicate that further information is provided regarding their definition. Recalibration of the PSS and TBW = Recalibration of the point of subjective simultaneity and temporal binding window; sensitivity measure or perceptual sensitivity = an example is *d'*; susceptibility to the SIFI = susceptibility to the sound-induced flash illusion; TBW/TWI/JND = temporal binding window/temporal window of integration/just noticeable difference; enhancement (speech perception) = auditory and/or visual enhancement for speech perception; race model = race model as a measure of enhancement (may include any or all of: cumulative distribution, difference probability, and area under the curve).

As mentioned above, older adults were tested in all the articles, however, five studies did not include younger adults as a comparison. In total 6,402 participants were included where 1,624 participants consisted of younger adults while the majority of the participants (4,778) were older adults (see Table 5.1 and 5.2 for further breakdown of age and sex). Although age ranges were not included for all the studies, the majority of the studies did provide an age range for both younger and older adults (67.4% and 72.9% respectively). The following age ranges were reported for the younger group: 16 – 50 and 50 – 90 years were reported for older adults; we calculated the average range of 20.5 – 29.8 for younger adults and 62.0 – 78.7 for older adults based on the ranges provided by these studies. For studies that did not provide an age range, they provided mean ages; the following mean ages were found for younger and older adults: 22.3 and 67.8 years respectively. Many studies used normal vision (91.7%) and hearing (95.8%) as part of their inclusion criteria (measured or self-reported; see Table 5 in the appendix for further details). Further, 76.4% of studies screened for neurological or cognitive disorders (measured in lab or self-reported) and of the studies that used a cognitive assessment to account for cognitive impairment, 47.2% used the Mini-Mental State Examination (MMSE) as part of their screening protocol, while only 18.1% used the Montreal Cognitive Assessment (MoCA; see Table 5.3 as well as Table 5 in the appendix for a comparison of cut off scores used for inclusion in studies using MMSE and MoCA). Further, 13.9% of studies screened for traumatic brain injury (TBI). In total 35 inclusion criteria were used (see Table 5 in the appendix for details).

Age Group	**Young Adults**	**Older Adults**	**Total Males**	**Total Females**
Number of participants	406	686	1,944	2,297
Percentage of sample (%)	37.18	62.82	45.84	54.16

Table 5.1: This table provides a breakdown of the participants included. Note here that the percent of sample was calculated separately for young and older adults (e.g., males made 37% of the sample in the younger group and 46% in the older group). Further, note here that 5 studies were included that tested only older adults (3,133 participants) which may help to explain the large difference in numbers found between young and older adults (see Table 2 for further information). Please also note that some studies did not specify the gender of their participants.

Age Group	**Young Adults (age range)**	**Older Adults (age range)**	**Total Males**	**Total Females**
Sample size	1,624 (16-50)	4,778 (50-90)	2,350	2,983
Percentage of sample (%)	25.37	74.63	44.06	55.93

Table 5.2: This table provides a further breakdown of the sample. Note, again that there are more older adults and more females compared to younger adults and males included in this scoping review. Note, that some studies did not specify the gender of their participants.

MMSE score	Number of Studies	MoCA score	Number of studies
$>$ or ≥ 24	6	≥ 22	1
≥ 25	2	$>$ or ≥ 23	3
> 26	1	≥ 24	1
$>$ or ≥ 27	2	≥ 26	2
≥ 28	1	-	-
$<$ 2.5 SD from mean	6	-	-

Table 5.3: This table provides details regarding the number of studies that used and reported the Mini Mental State Examination (MMSE) and/or Montreal Cognitive Assessment (MoCA) scores to assess cognitive function and the various scores used as part of the inclusion criteria. Note that some of the studies that used the MMSE and the MoCA (14 and 4 studies respectively) presented average values the participants achieved instead of a cut off score and are not reported in the table (see Table 10 in the appendix for further information). The average values for those additional studies ranged from 27.09 to 29.6 for the MMSE and 27.28 to 29 for the MoCA. Note that 2 studies utilizing the MMSE and 2 studies utilizing the MoCA did not present any results from the two tests. SD = standard deviation.

5.4.2 Research Question 1: Description of auditory and visual acuity reporting

Of the 72 studies included 69 accounted for auditory acuity (i.e., measured or self-reported or both) while only 66 studies accounted for visual acuity. Of the studies investigated in this scoping review, substantially more studies both measured (46 versus 37) and used self-reported acuity perception (41 versus 39) to screen for auditory impairment as compared to visual impairment (see Table 5.4 and 5.5 for further details). The exclusion criteria used to screen for auditory impairment were quite heterogeneous even when pure tone audiometry tests were used, with thresholds ranging from frequencies of 0.25 kHz on the lower end to 8 kHz on the higher end and intensities of 25 – 55 dB (see Table 6 in the appendix as well as Tables 5.6-5.8 below for details). Most studies used an auditory device (e.g., audiometer) to screen for hearing impairment, however a large majority of studies failed to report the type of test (e.g., device or custom) they used for screening eligibility. Further, only 7 studies reported whether or not participants wore hearing aids, while 22 studies did not report which ear was used to screen for hearing impairment, indicating a need for improvement in reporting methods (see Table 5.9 below for further details). The visual modality on the other hand was slightly more homogeneous, where 36.7% of the studies that measured visual acuity used the same criteria [e.g., $\geq$ 20/40 (6/12 or 0.3 LogMAR)] (see Table 6 in the appendix and Tables 5.10 and 5.11 below for further details). Interestingly, only 9 studies reported questions that were used for self-reported inclusion assessments for the auditory modality while only 6 studies reported the questions they used to screen for self-reported visual impairments. For the Auditory modality, these questions ranged from requiring simple ‘yes’ or ‘no’ responses to having more options for the participants to choose from such as ‘excellent’, ‘very good’, ‘good’, ‘fair’, and ‘poor’. For vision, similar questions were reported (e.g., “do you have normal or corrected to normal vision?” ‘yes’ or ‘no’ and “is your vision: excellent, very good, good, fair, poor”) with an additional option of ‘or are you registered as legally blind’ (see Table 6 in the appendix and Table 5.4 below for further details).

Methods of accounting for auditory and visual acuity	**Hearing (percentage)**	**Vision (percentage)**	**Hearing and vision (percentage)**
Acuity criteria mentioned	69 (95.83)	66 (91.66)	64 (88.88)
Acuity self-reported	41 (56.94)	39 (54.16)	37 (51.39)
Studies that reported self-reported questions in the manuscript	9 (12.50)	6 (8.33)	6 (8.33)
Acuity measured objectively	46 (63.88)	37 (51.39)	33 (45.83)

Table 5.4: This table provides details regarding the number of studies that reported auditory and visual acuity information. Note here, that inclusion in one category (e.g., auditory acuity measured objectively) does not exclude inclusion from a different category (e.g., auditory acuity self-reported measures).

Modality of interest	**self-reported only (percentage)**	**Objectively measured only (percentage)**	**Self-reported and objectively measured (percentage)**	**Measured and self-reported (percentage)**	**None (percentage)**
Hearing	23 (31.94)	26 (36.11)	20 (27.78)	46 (63.89)	3 (4.17)
Vision	29 (40.28)	25 (34.72)	12 (16.67)	37 (51.39)	6 (8.33)

Table 5.5: This table provides details regarding the number of studies that measured auditory and visual acuities in the lab, used self-reported measures, or used a combination of both to screen for inclusion.

Frequency (kHz) used	Number of Studies
0.125	2
0.2/0.25	15
0.5	22
1	25
1.25	1
1.5	2
1.6	1
2	27
2.5	3
3	6
3.15	1
4	20
5	1
6	3
6.3	1
8	6

Table 5.6: This table provides details regarding the frequencies used to assess auditory acuity for inclusion found in the studies included in this scoping review. Note that inclusion in one category does not preclude it from inclusion in another category. kHz = kilohertz.

Thresholds reported	Number of Studies
Hearing threshold lower than or equal to 15dB	2
Hearing threshold lower than or equal to 20 dB	10
Hearing threshold lower than or equal to 25 dB	15
Hearing threshold lower than or equal to 30 dB	1
Hearing threshold lower than or equal to 35 dB	7
Hearing threshold lower than or equal to 40 dB	3
Hearing threshold lower than or equal to 50 dB	1
Hearing threshold lower than or equal to 55 dB	1

Table 5.7: This table provides details regarding the thresholds used to assess auditory acuity for inclusion found in the studies included in this scoping review. Note that inclusion in one category does not preclude it from inclusion in another category. dB = decibel.

5.4.3 Research Question 2: Can a meta-analysis be conducted?

It is quite difficult to determine whether a meta-analysis can be conducted with the articles included in this scoping review. The data reveals heterogeneity not only in tasks that were used to measure multisensory integration (e.g., target discrimination, sound localization tasks, simultaneity judgment, temporal order judgment, etc.) and the behavioural outcome of interest (e.g., accuracy/proportion correct, mean or median response time, temporal

Most common auditory acuity criteria used for inclusion	Number of Studies
$\leq$ 25 dB hearing level (HL) at 0.25 - 3 kHz (both ears	3
$\leq$ 20 dB HL from 0.25 to 4 kHz (in both ears or not specified	3
$<$ or $\leq$ 35 dB HL at 4KHz and $<$ or $\leq$ 25 dB HL at 0.25, 0.5, 1, and 2 kHz	3
$\leq$ 25 dB HL for 0.5,1, 2, 4 kHz	2
0.2 - 4 kHz: no hearing loss up to 2 kHz (at $\leq$ 20 dB HL) and no more than mild hearing loss at 4 kHz (at $\leq$ 35 dB HL)	2
$\leq$ 25 dB HL for 0.5, 1, 2 kHz in the better ear or in both ears	2

Table 5.8: This table provides details regarding the most commonly utilized auditory acuity inclusion criteria found in the studies included in this scoping review. dB = decibels, kHz = kilohertz.

Type of test and administration conditions	Number of Studies
Audiometer used to test acuity	22
Custom test used to test acuity	8
Studies that did not report the type of test they used	16
Studies where participants wore hearing aids during testing	1
Studies where participants did not wear hearing aids during testing	8
Measured in both ears	22
Measured in better ear	4
Did not report which ear was used to measure acuity	26
Studies that included a control for auditory performance	55

Table 5.9: This table provides details regarding the most commonly utilized auditory acuity inclusion criteria found in the studies included in this scoping review. dB = decibels, kHz = kilohertz.

binding window, etc.) but also in how hearing and visual impairment were screened. If meta-analyses are to be used to address specific research questions, we recommend that they use specific behavioural outcomes that were most used in the literature included in this scoping review (see Tables 3, 4, and 7 in the appendix as well as Figure 5.2 above for further information regarding the behavioural outcomes of interest). Additionally, many of the studies used unique stimuli and some did not to use control conditions, which may also impact the behavioural outcomes observed and thus should also be taken into consideration when thinking about conducting a meta-analysis (see Tables 5.9 and 5.11 above as well as Tables 8 and 9 in the appendix).

Visual acuity criteria used for inclusion	**Number of Studies**
Approximately 20/20 (6/6 or 0 LogMAR)	4
$\geq$ 20/25 (6/7.5 or 0.1 LogMAR)	8
$\geq$ 20/30 (6/9.5 or 0.2 LogMAR)	5
$\geq$ 20/40 (6/12 or 0.3 LogMAR)	11
$\geq$ 20/50 (6/15 or 0.4 LogMAR)	1
$\geq$ 20/125 (or 6/38 or 0.8 LogMAR)	1

Table 5.10: This table provides details regarding the criteria used to assess visual acuity for inclusion found in the studies included in this scoping review as obtained through various tests. Note that the most commonly used criteria for exclusion was if vision was worse than: 20/40, followed by 20/25, and thirdly 20/30.

Type of test and administration conditions	**Number of Studies**
Computerized test or a specialized machine used to test acuity	2
Chart used to test acuity	21
Custom test used to test acuity	4
Didn't specify the type of test used to test acuity	12
Binocular testing	10
Did not report which eye the test was conducted in	28
Near viewing distance (defined by authors as $\leq$ 1 m or if defined as 'near' in the study)	8
Far viewing distance (defined by authors as $>$ 1 m or if defined as 'far' in the study)	11
Viewing distance not reported	25
Vision health conditions (history of cataracts, glaucoma, age-related macular degeneration, visual impairment, etc.)	17
Studies that required eye exams	2
Optical correction used (if explicitly stated)	14
Contrast sensitivity reported measured	19
Studies that included a control for visual performance	49

Table 5.11: This table provides details regarding the type of test (computerized, chart, custom) used to test vision, the required conditions to administer this test (e.g., whether a participant used optical correction, whether binocular vision was tested, the viewing distance, etc.), if vision impairment was accounted for, and if a control condition was included for measuring only visual performance as compared to audiovisual (experimental) condition.

5.5 Discussion

Our review demonstrates that only 63.8% and 51.4% of studies examining audiovisual integration in aging, measure auditory thresholds and visual acuities respectively and that less than half of the studies (45.8%) that measure acuities screen both sensory modalities for age-abnormal changes. Further, a key finding is that a consistent definition of what constitutes normal hearing and vision is not employed within studies that screen for audiometric thresholds and visual acuities. Additionally, we found that although 41 and 39 studies use self-reported measures to screen for normal hearing and vision respectively, only nine studies reported the questions that were presented to participants for auditory screening, while only six studies reported the questions used to screen for self-reported visual impairment (see Tables 5.4 and 5.5 above and Table 6 in the appendix for further information). In addition, as one may expect, a variety of tasks and behavioural outcomes of interest (e.g., discrimination or detection, mean response time, susceptibility to the sound induced flash illusion, etc.; see Tables 3 and 4 in the appendix and Figure 5.2 above for details) were used in the studies selected for this scoping review; thus, the variability present in the data, from the screening measures to the multiple different tasks used makes it difficult to recommend a meta-analysis at the moment. It should however be noted that of the 2,462 articles, the 72 that were selected based on the inclusion and exclusion criteria specified above in the methods section and in the protocol for this review (https://osf.io/v3snz/; [33]) were more focused on the aging process rather than on behavioural outcomes related to any specific task. Thus, future researchers whose research questions can be addressed using a meta-analysis can use either a rigid criterion (e.g., include studies that tested discrimination or detection response time only) to look for studies that use the same tasks or a more lenient criteria (e.g., compare the impact of aging on additional sensory modalities including somatosensation in a given task such as for detection or discrimination tasks) to capture a larger set of studies.

Our results indicate that more studies measured auditory thresholds compared to visual acuity (46 versus 37 respectively; see Table 5.4 for further information). This is not surprising given that the prevalence of hearing loss rises with age ranging from 46 to 60% to more than 80% in adults aged 75 and 85 years respectively [100, 506, 487] and is much higher than the prevalence for visual disorders that range from 2.6% to 8.0% in adults aged 70-74 and 75-80 respectively [69]. However, we recommend testing both sensory modalities to ensure that stimuli presented to all participants are perceived at the appropriate thresholds (e.g., suprathreshold) required for accurate results. Note however that depending on the study design and the types of stimuli used, additional control conditions may be required. Further, and as alluded to above, the studies of audiovisual integration included in this review have adopted inconsistent screening definitions, especially for the auditory acuity, making it difficult to compare results between studies. To solve this problem of lack of standardization, we suggest using the definitions of hearing loss and visual impairment that are recommended by the world health organization; hearing loss is defined as 'a speech-frequency pure-tone average at 0.5, 1, 2, and 4 kHz frequencies of $>$ 25dB HL in both ears' and visual impairment is defined as '$<$ 20/40 but greater than or equal to 20/400 (severe visual impairment) in both eyes'[345, 344, 343, 298]. We also found that more females than males were tested, both in the younger (62.8%) and older (54.2%) adult populations. Surprisingly, 29.2% and 34.7% of the studies failed to report gender for older and younger adults respectively, which may impact the ratio of men to women currently seen in this review. Note here that five studies were included that only tested older adults and if those studies were removed, we would be left with a comparable sample of older and younger population of 461 older males and 657 older females (compared to 406 younger males and 688 younger females). We decided to keep these articles in the scoping review as they provide useful information regarding the screening procedures for inclusion of older adults, utilized in the literature.

Although a large number of studies (76.39%) used cognitive reporting to ensure that the participants included were cognitively intact (MMSE, MoCA, and DemTect, a dementia screening test, self-reported lack of cognitive impairment), many different scores were used to include or exclude individuals (see Table 5.3 above and Table 5 in the appendix below for further information regarding the inclusion criteria used for cognitive impairment and for various other inclusion criteria used by the studies included in this review). Although the variability in scores was somewhat expected as various cut off scores have been used for the detection of mild cognitive impairment (MCI) for both the MoCA (26, 25, 24, and 23; [334, 111, 317, 93, 278]) and the MMSE (28, 27, 26, 24; [143, 297, 246, 11, 107]), we were surprised by the preferred use of the MMSE over the MoCA. As the MMSE was designed to screen for dementia at a time where the concept of MCI did not exist, the MoCA has been found to be a more sensitive test for detection and screening for early cognitive impairment compared to the MMSE [297, 107]. Further, research reveals that performance on the MMSE is affected by race, education, language, and gender [464, 187, 495], while the MoCA was designed as an alternative method of cognitive screening and is thought to account for the limitations that affect the MMSE [[334, 93]; however please see a review by Siqueira and colleagues [426]. Moving forward, we recommend that researchers use the MoCA to detect MCI as it was specifically designed to screen for mild cognitive impairment and it accounts for educational level differences through the addition of a point to the final score for those with less than 12 years of formal schooling [334, 426].

Further, we found that the 72 studies included in this scoping review used different tasks with various methodology, aims, and varying behavioural outcomes of interest (refer to Tables 3, 4, 6, 8, and 9 in the appendix as well as Figures 5.2 above for details). Overall, the most common behavioural outcomes were ‘accuracy or proportion correct or percent correct’ and ‘mean and median response time’ measures. Given that the articles included used 28 different outcomes of interest to assess multisensory integration, it is difficult to suggest conducting a meta-analysis with the specific articles that we have used in this scoping review. However, we strongly believe that there is a sufficient amount of data available in the 1500+ articles that were screened for this scoping review and thus suggest utilizing either a more rigid inclusion criteria (e.g., utilizing only speech recognition or response time tasks) or a broader inclusion criteria (e.g., including studies that do not mention the aging process) for those interested in conducting a meta-analysis.

This scoping review is not without its limitations. An inherent limitation of any given scoping review is that it provides breadth rather than depth on a topic [17, 262]. While this scoping review provides a broad view of how studies are screening for age-abnormal sensory changes through the use of auditory and visual acuities, we are unable to determine the effectiveness of accounting for unisensory changes in multisensory integration research within this scoping review. As such, future research using meta-analyses is necessary to determine whether the results obtained from studies that screen for auditory and visual acuities differ from those that only use self-reported measures. We do however believe that providing a breath of knowledge will prove to be useful for researchers in understanding and further investigating multisensory integration within the aging population. Another limitation is that the majority of the literature in this review stems from developed countries and therefore it is not clear whether these findings extend to developing countries [335]. However, it is also not clear whether the recommendations to correct the limitations associated with accounting for sensory acuities would not be applicable to the research conducted in developing nations, thus, we would extend our recommendations to developing nations unless future research indicates otherwise. Additional research with the inclusion of studies from developing nations is necessary to elucidate this matter. An additional limitation of the current study is that only studies published in English were included, limiting the review to articles that were either published in English-speaking countries, which may explain the predominance of the literature stemming from developed countries, or to those that had the funds for translation services. Finally, we conducted this scoping review using behavioural studies as we were concerned that behavioural studies may be conducted with less rigour as compared to neuroimaging studies, however, further research investigating the use of auditory and visual acuity screening methods with neuroimaging studies will not only provide insight, but is necessary to ensure standardized methods are used throughout the literature.

5.6 Conclusion

In conclusion, we found that only approximately 64% and 51% of studies measure for age-abnormal hearing and vision respectively and that within these studies a consistent definition of what constitutes normal hearing and vision is not found. Further, we found that many studies screen for one sensory modality (audition) more than the other modality. Here, we recommend screening for both age-abnormal hearing and vision and using the World Health Organization's definitions of hearing loss and visual impairment. Further, we find that many researchers use the MMSE for MCI screening instead of the MoCA and we recommend the utilization of the latter cognitive assessment as it has been found to be more sensitive toward the detection of MCI. We found that many different tasks were used to assess audiovisual integration in younger and older adults ranging from speech recognition to the stream bounce task, thus various behavioural outcomes were obtained ranging from accuracy to stream bounce susceptibility, making it difficult to suggest conducting a meta-analysis with this particular dataset. We do however believe that a meta-analysis can be conducted with the abundant data that exists within audiovisual literature; if you wish to conduct a meta-analysis, we recommend using either a more strict or a less strict inclusion criteria depending on your research question of interest.

Chapter 6

General Discussion

The aim of this dissertation was three-fold: (1) to understand the relation between audiovisual tasks that are commonly utilized to investigate multisensory integration, (2) to investigate how performance on these tasks changes when participants are stressed or aroused through the use of exercise (both in-person and virtually), and (3) to investigate the limitations and shortcomings of the current practices in the multisensory literature, all through the lens of aging. Although various tasks have been used in the literature to investigate multisensory processing, the simple response time (RT), simultaneity judgement (SJ), and temporal order judgement (TOJ) tasks are some of the most commonly utilized tasks by multisensory integration researchers, especially those studying aging, and thus were utilized within this dissertation to increase the scope and applicability to the wider literature. Although previous research has focused on comparing performance of participants on the RT and TOJ tasks, research comparing the RT to SJ, and the relation between RT, SJ, and TOJ has yet to be conducted. Thus, the results of this dissertation fill an important gap in the literature as we were the first to make such a comparison. Our work reveals that the TOJ and the RT tasks may share a common underlying mechanism in young adults, as a moderate positive correlation was found between the point of subjective simultaneity (PSS) obtained from the TOJ task and the estimate of integration, obtained from the RT task; however, such a relation was not found between the RT and the SJ tasks. Thus, this novel investigation of the three tasks revealed further evidence that the SJ and TOJ tasks may be subserved via different neural mechanisms. Further, our work adds to the growing body of literature that the mechanisms that underlie multisensory processing change with age, as the relation found between the RT and the TOJ tasks were not found in older adults. With knowledge of the relation between the three tasks and their association with aging, this dissertation was able to further determine the malleability of the underlying mechanisms through the use of acute and 'chronic' physical activity. The results revealed that despite the limitations associated with both the in-person and exergaming studies, both in-person (effect sizes for effect of intervention ranged from medium to large: η_p^2 = 0.12 - 0.24) and virtual forms (effect sizes for significant effect of intervention were large, ranging from η_p^2 = 0.215 - 0.234) of physical activity directly impacted multisensory processing. Finally, this dissertation encompasses a scoping review that revealed a lack of utilization of consistent acuity screening procedures by researchers investigating multisensory processing in older adults. In light of this information, suggestions were made by the author of this dissertation to ensure that consistent standards are used to screen for hearing- and visual-impairments by scientists moving forward. The experiments and scoping study conducted in this dissertation highlight the feasibility of utilizing simple behavioural tasks to investigate the changes in multisensory processing associated with aging, however, they also reveal lessons for future scientists. I will begin this chapter by first summarizing the main results obtained from each study, followed by a discussion regarding the molecular and functional changes that may underlie the malleability captured by exercise in this dissertation. I will end this chapter by presenting the limitations associated with the work presented within this dissertation and by discussing future directions.

6.1 Summary of Research Findings

The first chapter of this dissertation was designed to better understand the relation among some of the most utilized tasks in multisensory integration literature. This chapter revealed that older adults are impaired in judging temporal order and simultaneity, due to an extended temporal binding window (TBW), as assessed using the TOJ and SJ tasks. However, results also revealed that older adults exhibited greater enhancement in performance on the RT task as indicated by a higher likelihood of race model violation (i.e., increased integration). Notably, correlations among the three tasks revealed that the likelihood of violating the race model was only associated with the point at which simultaneity was perceived for the TOJ task in young adults, while no significant correlations were found for the SJ task and for the older adults tested in the study. These results echo the findings of previous literature where significant correlations were found between the TBW [131, 307] and PSS estimates [75] from the TOJ task with the RT task in young adults. Upon understanding the relation among the three tasks, the second study of this dissertation was designed to investigate the malleability of the underlying systems that subserve the outcomes measured by the three tasks of interest.

Our research revealed that multisensory integration is indeed malleable, as changes in TBW and PSS were found after resting, performing a cognitively demanding task, and after exercising at a moderate intensity for 20 minutes. Of note, our results revealed that aerobic exercise may target the underlying mechanisms that subserve the general integration process rather than the specific mechanisms that subserve each of the tasks utilized in this study, as we found consistent reductions in the TBW for both the SJ and TOJ tasks as well as an increase in race model violations (i.e., increased integration) only after the exercise condition. To further assess the acute and long-term effects of exergaming and reading on multisensory integration, a short-term longitudinal study was designed where an additional task, the sound induced flash illusion (SIFI), an illusion that has been used to test multisensory processing in the literature, was added to assess any potential changes. The study revealed once again a malleability of the multisensory processing system, where both exergaming and reading affected the outcomes of interest from the four perceptual tasks. Importantly, the results indicate that those in the exergaming group may have benefited more from the intervention as opposed to those in the reading group, as they exhibited faster response times on the RT task as well as higher accuracy on SIFI. Our results however also revealed that significant differences at baseline may have impacted the outcomes of interest, as those in the reading group had more potential for improvement, and indeed did show, more improvement at the end of the 6 weeks of intervention as compared to those in the exergaming group. Both of the exercise studies indicate the importance of the inclusion of control groups or control conditions, however the latter chapter suggests that reading may not necessarily be the best control condition for those investigating the effects of physical activity on multisensory processing.

A secondary aim of this dissertation was to investigate the methodologies that researchers studying multisensory processing from the aging lens are currently utilizing in their studies. Given the changes in auditory and visual acuities associated with aging, accounting for such changes in hearing and vision is crucial as it may increase the quality and validity of the data obtained. Thus, the scoping review contained within this dissertation aimed to determine how often unisensory acuities were accounted for in the multisensory integration literature. The scoping review revealed that only approximately 64% and 51% of studies measured for age-abnormal hearing and vision respectively and that within these studies a consistent definition of what constitutes normal hearing and vision was not found. Further, the review revealed that many of the studies screened for only one sensory modality, namely audition, more than the other modality. These results suggest that the data obtained from the current literature may not be optimally reliable and that the quality of the data can be improved by the inclusion of consistent auditory and visual acuity testing. Thus, the author of this dissertation recommended the use of the World Health Organization's definition of visual impairment and hearing loss [345, 344, 343], in order to ensure consistency across the field. Further, the results revealed that many researchers used the Mini-Mental State Examination to screen for Mild Cognitive Impairment (MCI) instead of the Montreal cognitive Assessment in spite of the fact that the latter cognitive assessment has been found to be more sensitive toward the detection of MCI. These findings further highlight the need for improvement in the current methods utilized by aging researchers studying multisensory integration.

6.2 Multisensory Processing, Exercise, and GABA

The work in this dissertation highlights that physical activity, in the form of acute bouts of aerobic exercise performed at a moderate intensity and chronic exergaming completed at light to moderate intensity, has a direct impact on multisensory processing. However, it raises the question as to why engagement in physical activity would change multisensory processing and although experimental investigation of such a question falls outside the scope of this dissertation, below I will briefly discuss a potential neurotransmitter that may underlie the potential changes associated with exercise and multisensory integration.

Gamma-aminobutyric acid (GABA) is the chief inhibitory neurotransmitter in the central nervous system that decreases in concentration by approximately 5% per decade of life [166, 285, 286]. Such a reduction in GABA can reduce the brain's ability to ignore or inhibit the integration of erroneous cues and can potentially increase the difficulty in discriminating the temporal order of information, suggesting that GABA may affect the integration process. Both chronic as well as acute bouts of aerobic exercise have been found to increase the production of GABA. For example, in a study conducted by Maddock and colleagues [286] to assess changes in GABA post acute-bout of exercise, healthy participants were asked to strenuously exercise on a stationary bicycle for 8 - 20 minutes. Proton magnetic resonance spectroscopy (MRS) scans of the visual and the anterior cingulate cortex revealed an increase in production of GABA of approximately 6.8% in the visual cortex compared to baseline GABA production [286]. Inhibition plays a necessary and major role in the control of many cognitive and perceptual processes such as focusing on the task at hand and re-direction of attention from irrelevant stimuli. As many behavioural findings indicate that a single bout of exercise improves inhibitory control and because inhibition is largely mediated through the activation of GABA receptors, many researchers have used neurophysiological techniques to explore the underlying mechanisms associated between the two. Neuroimaging studies have found that exercise can indeed increase GABA-ergic signaling, facilitate cognitive inhibition processes, and intensify compensatory recruitment of prefrontal-parietal pathways [4, 89, 210, 223, 499, 308].

Although there is limited research investigating the relation between the GABA-ergic system and multisensory integration, some research has found a significant relation between the two. In a study conducted by Balz and colleagues [26], 39 participants completed the SIFI, a task that is thought to be an indicator of the integrity of temporal multisensory integration processing [420, 421, 422, 418], while EEG and MRS were recorded. The study revealed a positive relationship between GABA concentration in the superior temporal sulcus (STS) and the likelihood to perceive the SIFI, indicating that those with higher concentrations of GABA were more susceptible to the SIFI. This finding is somewhat counter-intuitive as one would expect that those with higher resources (i.e., higher concentration of GABA) to inhibit irrelevant stimuli would be less susceptible to such an illusion . It should be noted however that the high susceptibility to the illusion (i.e., participants incorrectly reported perceiving two flashes in the illusory condition for 64% of the trials), may be related to the use of a very short stimulus onset asynchrony of 57 ms for all the trials. In contrast to GABA increasing thresholds (i.e., increase in GABA leads to higher susceptibility to the SIFI illusion), results from within the visual cortex revealed the opposite results. In a study conducted by Edden and colleagues [137], thirteen male participants were asked to complete a two-alternative forced choice task from which their orientation discrimination thresholds were obtained. Seven of the participants were scanned using magnetoencephalography (MEG) and MRS on separate days. The results from their study revealed that orientation discrimination was negatively correlated with resting GABA concentration indicating that those with higher levels of GABA performed better on the orientation discrimination task [137]. These results indicate that the variability in an individual's perceptual performance can at least in part be explained by variability in the neurophysiological traits (i.e., concentration of the neurotransitter GABA) of that individual; I expect that similar principles would apply to multisensory integration. Indeed, the maturation of GABA circuits is believed to play an important role in the emergence of multisensory integration properties in the cortex. In a study conducted by Gogolla and colleagues [175], when juvenile mice lacking multisensory integration capability (BTBR T+tf/J model) were treated for 14 days with diazepam, a medication that works by increasing GABA, their multisensory integration abilities were restored during an early critical development stage. Note, that the pharmacological enhancement of inhibition did not restore MSI in older mice, suggesting an early sensitivity period of GABA-ergic pharmacological intervention. Given however the findings that aerobic exercise can increase GABA production [373, 412, 285, 286, 39], can facilitate cognitive inhibition processes [4, 89, 210, 223, 499, 308] in older adults, and has the potential to affect the general mechanisms associated with multisensory processing regardless of age, as suggested by this dissertation, exercise may thus offer an interesting and unconventional form of rehabilitation intervention to improve multisensory integration, and therefore the quality of life of older adults.

A question that remains however is how an increase in neurotransmitters (and various growth factors) can lead to such significant changes in cognitive and perceptual processing. Recently, it has been argued by Sandroff and colleagues [405] that the molecular changes that contribute to neurogensis, synaptogenesis, and angiogenesis observed post exercise, fail to provide an adequate explanation regarding why chronic exercise results in long-term adaptations within the brain. The integration of sensory information plays a central role in their framework.

6.3 Efficient Multisensory Integration as a Model to Explain Beneficial Effects of Exercise

Exercise has been acknowledged in the literature to be a highly complex and stressful activity that requires the participation and activation of multiple physiological systems [121]. Further, it is known that exercise requires integrative effort of multiple brain regions to be successfully executed. In acknowledgement of these factors and to help explain the molecular, cellular, and functional changes exercise leads to, the PRIMERS (PRocessing, Integration of Multisensory Exercise-Related Stimuli) framework was proposed by Sandroff and colleagues [405]. Sandroff and colleagues [405] argue that just as physiological systems need to adapt to the demands of chronic exercise training, so too does the CNS by becoming more efficient at integrating the information presented from multisensory inputs. Thus, the beneficial effects of exercise-related brain adaptations may involve enhanced efficiency of communication within and across brain regions and networks involved in regulating neurophysiological processes and associated motor outputs during exercise. The authors argue that it is the challenging nature of exercise that requires the continuous and efficient integration of multiple sensory information in a coordinated manner, that may give rise to molecular (e.g., increased brain-derived neurotrophic factor (BDNF), Vascular endothelial growth factor (VEGF), GABA, etc.), cellular (e.g., angiogenesis and neurogenesis), brain systems (e.g., more efficient communication), and behavioural (e.g., better inhibition control) level changes that result in the observed benefits associated with chronic exercise. Efficient communication that occurs within and across brain networks to support mobility and cognition is the key to this model, and it is likely that efficiency arises from improved connectivity by strengthening existing adaptive networks, forming new adaptive connections, and/or removing maladaptive connections between brain regions. The role of acute exercise is crucial to this model, as single bouts of exercise would provide the CNS with progressively difficult challenges that would lead to long-term adaptation required to support mobility and cognition. Consistent with the concept of activity-dependent neuroplasticity, each bout of exercise is suggested to induce small improvements in baseline connectivity, which may accumulate over time with chronic exercise and lead to meaningful adaptations.

The PRIMER framework may help guide our understanding of the changes observed in multisensory processing with exercise and exergaming within this dissertation. As the tasks completed prior to engaging in physical activity were also multisensory in nature, they could have primed the nervous system to better process the sensory cues during exercise, leading to larger improvements on the multisensory tasks post-exercise. Researchers may consider administering unisensory temporal perception tasks pre- and post-exercise and comparing the results to the multisensory tasks to determine if larger changes are observed if the CNS is primed one way versus another. Further, just as the tasks participants complete prior to engaging in exercise may impact the outcomes of interest post-exercise, the exercise that the participants engage in may also impact the outcome. Indeed, the PRIMERS framework suggests that the complexity of the physical activity may impact cognitive and perceptual outcomes [405], where the authors argue that the more complex modalities of exercise (e.g., walking versus seated biking; [504]) would involve greater processing and integration of multisensory output, which could lead to larger improvements in cognition and perception not only after sustained chronic exercise, but also post-acute exercise. In this dissertation however, participants either biked at a moderate intensity, or they were seated on a chair while engaging in exergames; perhaps the effects may have been larger if participants were asked to walk on a treadmill or completed a more complex 'open skill' bout of aerobic exercise [351]. The choice of seated exercise was decided upon to ensure the safety of participants, especially for the exergaming study, as the exergames were designed with those living with cognitive impairment and with lower-limb mobility concerns in mind. However, in a more controlled setting, future researchers can utilize and test the underlying theory of the PRIMERS framework by having participants engage in seated (e.g., cycling), standing (e.g., treadmill), and open-skill (e.g., fitness-focused dancing) exercise to assess which modality of exercise has the largest effect. Such research can help to create guidelines regarding the types of exercises that are best suited to help improve multisensory processing and therefore the quality of life of older adults. Experimental protocols that incorporate not only behavioural tasks such as the ones utilized here, but also functional imaging, such as functional near-infrared spectroscopy (fNIRS), can further help to elucidate which modalities of exercise elicit greater CNS activation and how they interact with outcomes related to multisensory processing. There are however other factors that may impact the likelihood of improvement in multisensory processing, including adherence to engagement in regular exercise.

6.4 Motivation and Exercise

Despite the benefits of exercise on cognition and perception, initiation and adherence to exercise can be challenging, especially for older adults. This was highlighted in a publication by the Federal Interagency Forum on Aging-Related Statistics [340], where they found that only 15% of older adults between 60 and 70 years of age and only 7% of older adults in their 80s adhered to physical activity guidelines suggested for adults. Lack of motivation and enjoyment, limited access to exercise programs and/or equipment, and physical limitations are some of the main reasons for physical inactivity among the older population [160]. This raises the question of how motivation can impact the benefits that are reaped not only from acute bouts, but also from chronic exercise by those who are more motivated to exercise. Motivation is multifaceted and is impacted by behaviour, cognition, physiology, and social structures.

Physiologically, the mesolimbic reward pathway, influences motivation through the neurotransmitter dopamine, with greater dopamine activity being associated with greater motivation [360, 60]. A consistent finding in the literature is that dopamine increases in concentration post exercise. Bliss and Ailion [52] were one of the first researchers to report that mice that swam for one hour or spontaneously ran for 30 minutes exhibited increased dopamine and dopamine metabolite, homovanillic acid, concentration in the whole brain immediately after exercise. On a neurophysiological level, cortical-subcortical networks have been thought to generate, maintain, and regulate human motivation with the prefrontal cortex playing a central role [235, 236]. The prefrontal cortex is thought to demonstrate control over internal goals by planning, retaining the goal, monitoring performance, and regulating action, for example by deciding that exercise is beneficial, and then adhering to the exercise program even when it becomes difficult to do so [240, 235, 365]. Further, as stated above, cognition and behaviour can also impact motivation. Social cognitive theory asserts that motivation for behaviour change results from reciprocal interactions among behavioural, environmental, and personal (e.g., cognition, emotion, etc.) influences where all three influence one another [411]. The theory posits that what one thinks can affect their actions and environment, while actions can alter thoughts and environments, and likewise, the environment can influence thoughts and actions of an individual. The effects of physiological, behavioural, and cognitive mechanisms on motivation can help to explain why some individuals may be more motivated than others to be physically active. Although there are no direct studies measuring the relation between cognitive function and motivation to exercise, there is indirect research that suggests that the two are related. Indeed, in a recent study by Lutz and colleagues [281], it was found that variables associated with goal process cognition, defined as thoughts about the journey of achieving a goal, which consists of self-monitoring, planning, and positive affect, were positively correlated with the frequency of strenuous exercise.

Given that cognitive outcomes may be mediated by motivation to exercise, moving forward, researchers studying the effects of exercise on mulitsensory integration may want to consider how motivation may impact their outcomes of interest. For instance, could motivation account for some of the variability observed from the SJ, TOJ, SIFI, and RT tasks? Perhaps accounting for motivation to exercise could yield stronger effects for outcomes of multisensory processing, especially if the participants were all motivated to exercise and exert themselves. Various self-efficacy scales can be utilized by future researchers to account for motivation. Indeed in a recent study conducted by O'Neil-Pirozzi and colleagues [355], 1,424 healthy individuals between the ages of 40 - 80 years completed the Behavioural Regulation in Exercise Questionnaire-3 (BREQ-3), and the results revealed small to moderate correlations among motivation (e.g., amotivation, intrinsic regulation, external regulation, etc.) and self-reported exercise activity as measured through the International Physical Activity Questionnaire (IPAQ) Short Form. Their results support the notion that motivation to exercise is indeed associated with the actual behaviour of engaging in exercise.

Motivation may especially be relevant for the exergame study enclosed within this dissertation, where participants engaged with custom-designed games over the span of 8 weeks; with the intervention itself spanning 6 weeks. Although previous research has found that exergaming interventions that are shorter in duration (1-6 weeks) as compared to longer interventions (7-12 weeks), are more likely to lead to enhanced cognitive function [465], the lack of significant effects observed for some outcomes of interest in our study may be related to lack of motivation. Indeed, informal and formal interviews with the participants of the exergame intervention did reveal that some participants were bored with the exergames near the end of the intervention. Thus, accounting for motivation not only at the beginning of the intervention, but throughout may help to further elucidate some of the factors that may be contributing to the variability associated with the outcomes of interest in this dissertation and in future research. Below, I further highlight the limitations associated with this dissertation and present future directions for the field.

6.5 Limitations and Future Directions

In this section of the dissertation, I will address the limitations of the work presented and comment on how future researchers can mitigate and prevent such limitations. Although in line with previous literature, one of the primary limitations of this dissertation is the sample size that has ranged from 13 - 30 participants per group. In an ideal world, the sample size of each group would be significantly larger, as to increase the power of the statistical analyses. The small sample size can provide further insights regarding why some of the results need to be interpreted with caution. For example, in Chapter 4, only 13 participants were included in the exergame or experimental condition while the reading or control group was comprised of 14 participants and although significant effects of intervention were found, where those in the exergaming group were significantly faster and more accurate than those in the reading group, baseline differences between the groups indicate that such results must be interpreted with caution. These baseline differences, including age differences, may have been easily accounted for, had a larger sample been recruited. Similar concerns arise for Chapter 2 and 3. Here, as mentioned above, recruiting a large sample would not only help researchers to avoid concerns of limited power, but it would also enable researchers to uncover the relation among various outcomes of interest with more confidence, especially given the variability observed in psychophysical tasks. Another major limitation of this dissertation is the utilization of a limited number of behavioural tasks to investigate the effects of aging on, and the malleability of, the multisensory processing system. Although this decision may have limited the external validity of the results, using fewer tasks allows this dissertation to investigate in detail, the relation among the chosen tasks. I believe that the use some of the most commonly studied tasks in the multisensory literature does provide researchers in the field with further information regarding the potential mechanisms that may underlie the relations that were unveiled using behavioural outcomes.

Although the psychophysical behavioural tasks utilized in this dissertation allow us to gauge how the CNS processes multisensory cues and provide potential theories regarding the neural mechanisms that give rise to such experimental results, there are limitations associated with the use of such tasks. One primary limitation is the inter-individual variability that is typically associated with psychophysical tasks, making it difficult to interpret the results without large samples. However, recent research has shown that such inter-individual variability is persistent and stable over a longitudinal period of testing [185], and thus offers meaningful information regarding how the CNS is perceiving and responding to multisensory cues. In the future, researchers should consider the use of distinct and yet complementary techniques to better understand the variability, as a better understanding of the underlying processes of multinsensory integration may help to design better therapeutic interventions for the aging population. As follows, an additional limitation associated with this dissertation is the utilization of only behavioural outcomes to assess the effects of aging, exercise, and exergaming on multisensory processing. The utilization of neuroimaging techniques may help to explain the large variability observed in literature investigating multisensory processing.

Future work investigating the effects of exercise and exergaming on young and older adults should design randomized control trials with sufficient samples ($n \geq 50$ in each group), where participants in the control group are age-, sex-, socioeconomic status- and education-matched to reduce baseline differences. As physical activity levels have been shown to impact cognition and multisensory integration, matching control and experimental groups on this outcome variable is also advised. One neuroimaging technique that future researchers can utilize is MRS. An exemplar experimental protocol for testing potential changes in multisensory processing would involve the use of MRS to measure GABA concentration before and after acute bouts and throughout a chronic exercise intervention and correlating the GABA concentrations with performance on one or two tasks measuring multisensory processing; SIFI and RT tasks are recommended as previous literature and our dissertation have revealed that the processes underlying these tasks are potentially the most affected by exercise. Note here, that utilizing tasks that take longer than 10-15 minutes may negate the effects of exercise, therefore only one or two tasks are recommended. Such a study could provide information regarding how GABA may explain potential individual differences between participants, how long it takes to increase GABA concentration, and how these potential changes in GABA concentration impact multisensory processing relative to a control group. Relatedly, future researchers can manipulate the complexity (e.g., open-skill versus closed-skill), modality (standing or sitting), and exposure to multisensory input (e.g., exposure to audiovisual cues through an exercise program) during exercise in older adults to test the predictions of the PRIMERS framework (i.e., the more complex the activity, the larger the effect due to increased communication within and across neural networks to efficiently produce the desired behavioural output), and its effects on multisensory processing.

It is important to note here that when an individual engages in aerobic exercise, there are a number of physiological effects that occur. These include increased pupil dilation [423, 225], temporary improvement in hearing thresholds [108], and increased arousal [250, 302]. One of the limitations associated with the work presented within this dissertation is the lack of a distinction between the effects of exercise and the components mentioned above. A more optimal design would control for changes in factors such as pupil dilation and hearing threshold improvement by taking measurements before and after exercise.

Further, researchers can assess the effects of motivation on exercise engagement and multisensoy processing. One method of increasing motivation to exercise is by educating older adults regarding the benefits of exercise prior to their engagement in the exercise intervention. If researchers were to manipulate education regarding exercise as one of the independent variables, they could expose some participants to educational material, while others would be exposed to non-educational material, and they could assess the effect of education on motivation (through the self-efficacy scale) at baseline and throughout a chronic-exercise intervention to determine if differences exist between the two groups and how such differences effect multisensory processing. Another method of potentially increasing motivation to participate in, and to adhere to, an exercise intervention is to incorporate groups activities, as research has revealed that socializing during exercise interventions can help to increase the desire to exercise [87, 24].

Finally, another future direction that researchers can take is to utilize a method that can reduce the timing required for testing; this is especially relevant when conducting research with clinical populations, as a reduction in time will increase the likelihood that a participant is attending to the task, reduce fatigue, and therefore increase quality of the data. When making a decision, individuals have the ability to not only use all available information, but many also consider the likelihood of whether their decision is correct. Confidence ratings have been used in the literature in conjunction with perceptual tasks and are thought to reflect this process, often referred to as introspection or meta-cognition [156, 157, 27, 380]. Confidence ratings utilized after participants have made their response on each trial of a psychometric task have been shown to reduce variability [503] and have the potential to train the aging population to improve their performance without long periods of time that are typically associated with training paradigms [375, 376, 446, 418, 377]. In a study conducted by Yi and Merfeld [503], four participants reported their confidence ratings on a slider after indicating their response to the psychometric task. Their results revealed that contrary to the recommendations of utilizing more than 100 forced-choice trials to obtain accurate and precise psychometric fits, when confidence ratings were taken into account, 20 trials yielded psychometric parametric estimates that were as precise as those obtained from 100 trials using conventional psychometric analyses. They also found that the parameter estimates obtained from the conventional psychometric analysis were more variable for both mean (i.e., PSS) and width (i.e., TBW) parameters compared to the variables obtained when confidence ratings were taken into account. Further, their work provides evidence for a relation between the perceptual processes and decision-making, higher-order cognitive processes, which suggest that participants may be updating their internal model related to the perceptual task at hand when they are asked to reflect on their performance and rate their confidence. Future researchers can build on the work of Yi and Merfeld [503] by testing older adults using similar methods to assess the optimal number of trials needed to obtain meaningful data from various clinical populations.

6.6 Conclusion

The aim of this dissertation was to investigate the changes associated with audiovisual integration in the aging population. Firstly, I aimed to understand the relation between three tasks (response time; RT, simultaneity; SJ judgment, and temporal order judgment; TOJ) that are commonly used in the multisensory integration literature. I found that older adults are impaired in judging temporal order of events, however they also exhibit greater performance gains in response time to multisensory, compared to uni-sensory stimuli. Further, a correlational analysis between the tasks revealed that the likelihood of violating the race model was only associated with the point at which simultaneity was perceived for the TOJ task in young adults. Such a relation was not found for older adults, and it was also not found for the SJ task, providing further evidence that indeed the SJ and TOJ tasks may be subserved via different neural mechanisms and that these mechanisms change with age. Upon understanding the relation between the three tasks, I then aimed to investigate how performance on these tasks changed when the central nervous system was aroused or stressed through the use of exercise (both in-person and virtually). The results associated with in-person exercise revealed that exercise may target the underlying mechanisms that subserve the general integration processes rather than specific mechanisms that subserve each of the tasks, as we found consistent reductions in the temporal binding window for both the SJ and TOJ tasks, as well as an increase in race model violations (i.e., increased integration) only after the exercise condition. Similarly, results from the virtual exergaming study revealed that engaging in exergames 3 times a week for 6 weeks positively modified multisensory integration, as improvements in response times and reductions in susceptibility to the SIFI were observed. However, given the limited number of participants in the exercise and exergaming studies, the results should be interpreted with caution. The final aim of this dissertation was to investigate the limitations and shortcomings of the current practices in the multisensory integration literature through a scoping review. The scoping review revealed that only approximately 64% and 51% of studies measure for age-abnormal hearing and vision respectively and that within these studies a consistent definition of what constitutes normal hearing and vision is not found. Further, many studies utilized the Mini-Mental State Examination to screen for Mild Cognitive Impairment (MCI) instead of the Montreal cognitive Assessment in spite of the fact that the latter cognitive assessment has been found to be more sensitive toward the detection of MCI. Overall, our results indicate that the multisensory processing system is malleable and trainable and that future studies should expend efforts on designing randomized control trials to better investigate the effects of exercise on this system. Further, given the variance found between participants, future researchers should focus on understanding how to account for and reduce such variability in the data, by using imaging techniques (e.g., magnetic resonance spectroscopy) and by incorporating design and analysis methods known to reduce variability (e.g., use of confidence ratings).

Bibliography

[1] W. J. Adams. The development of audio-visual integration for temporal judgements. *PLOS Computational Biology*, 12(4):e1004865, 2016.

[2] W. J. Adams and P. Mamassian. The effects of task and saliency on latencies for colour and motion processing. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 271(1535):139–146, 2004.

[3] B. M. Adhikari, E. S. Goshorn, B. Lamichhane, and M. Dhamala. Temporal-order judgment of audiovisual events involves network activity between parietal and prefrontal cortices. *Brain connectivity*, 3(5):536–545, 2013.

[4] K. Akatsuka, K. Yamashiro, S. Nakazawa, R. Mitsuzono, and A. Maruyama. Acute aerobic exercise influences the inhibitory process in the go/no-go task in humans. *Neuroscience letters*, 600:80–84, 2015.

[5] J. D. Alexander and L. C. Nygaard. Reading voices and hearing text: Talker-specific auditory imagery in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 34(2):446, 2008.

[6] L. G. Allan. The relationship between judgments of successiveness. *Perception & psychophysics*, 18(1):29–36, 1975.

[7] M. Alm and D. Behne. Audio-visual speech experience with age influences perceived audio-visual asynchrony in speech. *The Journal of the Acoustical Society of America*, 134(4):3001–3010, 2013.

[8] N. Altieri and J. T. Townsend. An assessment of behavioral dynamic information processing measures in audiovisual speech perception. *Frontiers in psychology*, 2:238, 2011.

[9] J. S. C. Amorim, R. C. Leite, R. Brizola, and C. Y. Yonamine. Virtual reality therapy for rehabilitation of balance in the elderly: a systematic review and meta-analysis. *Advances in Rheumatology*, 58, 2018.

[10] R. A. Andersen, L. H. Snyder, D. C. Bradley, and J. Xing. Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual review of neuroscience*, 20(1):303–330, 1997.

[11] T. M. Anderson, P. S. Sachdev, H. Brodaty, J. N. Trollor, and G. Andrews. Effects of sociodemographic and health variables on mini-mental state exam scores in older australians. *The American Journal of Geriatric Psychiatry*, 15(6):467–476, 2007.

[12] C. Anderson-Hanley, A. L. Snyder, J. P. Nimon, and P. J. Arciero. Social facilitation in virtual reality-enhanced exercise: competitiveness moderates exercise effort of older adults. *Clinical interventions in aging*, 6:275, 2011.

[13] C. Anderson-Hanley, P. J. Arciero, A. M. Brickman, J. P. Nimon, N. Okuma, S. C. Westen, M. E. Merz, B. D. Pence, J. A. Woods, A. F. Kramer, et al. Exergaming and older adult cognition: a cluster randomized clinical trial. *American journal of preventive medicine*, 42(2):109–119, 2012.

[14] P. Andrés, F. B. Parmentier, and C. Escera. The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging. *Neuropsychologia*, 44(12):2564–2568, 2006.

[15] D. E. Angelaki and K. E. Cullen. Vestibular system: the many facets of a multimodal sense. *Annu. Rev. Neurosci.*, 31:125–150, 2008.

[16] K. J. Anstey and G. A. Smith. Interrelationships among biological markers of aging, health, activity, acculturation, and cognitive performance in late adulthood. *Psychology and aging*, 14(4):605, 1999.

[17] H. Arksey and L. O'Malley. Scoping studies: towards a methodological framework. *International journal of social research methodology*, 8(1):19–32, 2005.

[18] R. Armitage and L. B. Nellums. Covid-19 and the consequences of isolating the elderly. *The Lancet Public Health*, 5(5):e256, 2020.

[19] M. Audiffren, P. D. Tomporowski, and J. Zagrodnik. Acute aerobic exercise and information processing: energizing motor processes during a choice reaction time task. *Acta Psychologica*, 129(3):410–419, 2008.

[20] M. Avivi-Reich, K. Puka, and B. A. Schneider. Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? *Attention, Perception, & Psychophysics*, 80(1):242–261, 2018.

[21] H. Babkoff and L. Fostick. Age-related changes in auditory processing and speech perception: cross-sectional and longitudinal analyses. *European journal of ageing*, 14 (3):269–281, 2017.

[22] M. Bach et al. The freiburg visual acuity test-automatic measurement of visual acuity. *Optometry and vision science*, 73(1):49–53, 1996.

[23] S. Ballesteros, A. Prieto, J. Mayas, P. Toril, C. Pita, L. Ponce de León, J. M. Reales, and J. Waterworth. Brain training with non-action video games enhances aspects of cognition in older adults: a randomized controlled trial. *Frontiers in aging neuroscience*, 6:277, 2014.

[24] S. Ballesteros, E. Kraft, S. Santana, and C. Tziraki. Maintaining older brain functionality: a targeted review. *Neuroscience & Biobehavioral Reviews*, 55:453–477, 2015.

[25] P. B. Baltes and U. Lindenberger. Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychology and aging*, 12(1):12, 1997.

[26] J. Balz, J. Keil, Y. R. Romero, R. Mekle, F. Schubert, S. Aydin, B. Ittermann, J. Gallinat, and D. Senkowski. Gaba concentration in superior temporal sulcus predicts gamma power and perception in the sound-induced flash illusion. *Neuroimage*, 125: 724–730, 2016.

[27] J. W. Bang, M. Shekhar, and D. Rahnev. Sensory noise increases metacognitive efficiency. *Journal of Experimental Psychology: General*, 148(3):437, 2019.

[28] M. Barnett-Cowan. Vestibular perception is slow: a review. *Multisensory research*, 26(4):387–403, 2013.

[29] M. Barnett-Cowan and L. R. Harris. Perceived timing of vestibular stimulation relative to touch, light and sound. *Experimental brain research*, 198(2-3):221–231, 2009.

[30] M. Barnett-Cowan and L. R. Harris. Temporal processing of active and passive head movement. *Experimental brain research*, 214(1):27, 2011.

[31] N. E. Barraclough, D. Xiao, C. I. Baker, M. W. Oram, and D. I. Perrett. Integration of visual and auditory information by superior temporal sulcus neurons responsive to the sight of actions. *Journal of Cognitive Neuroscience*, 17(3):377–391, 2005.

[32] M. M. Barrett and F. N. Newell. Task-specific, age related effects in the cross-modal identification and localisation of objects. *Multisensory research*, 28(1-2):111–151, 2015.

[33] A. Basharat and M. Barnett-Cowan. Scoping review protocol, Dec 2021. URL `osf.io/v3snz`.

[34] A. Basharat and M. Barnett-Cowan. The effect of rest, a cognitively demanding task, and aerobic exercise on the sj, toj, and rt tasks in community-dwelling older adults. *Multisensory research*, MSR-1686R1, 2022.

[35] A. Basharat and M. Barnett-Cowan. The effects of virtual exergaming on the sj, toj, rt, and sifi tasks in community-dwelling older adults. *TBD*, 000, 2022.

[36] A. Basharat, M. S. Adams, W. R. Staines, and M. Barnett-Cowan. Simultaneity and temporal order judgments are coded differently and change with age: an event-related potential study. *Frontiers in integrative neuroscience*, 12:15, 2018.

[37] A. Basharat, J. R. Mahoney, and M. Barnett-Cowan. Temporal metrics of multisensory processing change in the elderly. *Multisensory research*, 32(8):715–744, 2019.

[38] A. Basharat, A. Thayanithy, and M. Barnett-Cowan. A scoping review of audiovisual integration methodology: Screening for auditory and visual impairment in younger and older adults. *Frontiers in Aging Neuroscience*, 13, 2021.

[39] J. C. Basso and W. A. Suzuki. The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: A review. *Brain Plasticity*, 2(2): 127–152, 2017.

[40] S. H. Baum and R. A. Stevenson. Shifts in audiovisual processing in healthy aging. *Current behavioral neuroscience reports*, 4(3):198–208, 2017.

[41] A. Bavishi, M. D. Slade, and B. R. Levy. A chapter a day: Association of book reading with longevity. *Social Science & Medicine*, 164:44–48, 2016.

[42] J. Beard, A. Officer, A. Cassels, and F. Bustreo. *World Report on Ageing and Health*. World Health Organization, 2015.

[43] G. Bedard and M. Barnett-Cowan. Impaired timing of audiovisual events in the elderly. *Experimental brain research*, 234(1):331–340, 2016.

[44] G. v. Békésy. Interaction of paired sensory stimuli and conduction in peripheral nerves. *Journal of Applied Physiology*, 18(6):1276–1284, 1963.

[45] L. A. Benevento, J. Fallon, B. Davis, and M. Rezak. Auditory-visual interaction in single cells in the cortex of the superior temporal sulcus and the orbital frontal cortex of the macaque monkey. *Experimental neurology*, 57(3):849–872, 1977.

[46] L. Bherer. Cognitive plasticity in older adults: effects of cognitive training and physical exercise. *Annals of the New York Academy of Sciences*, 1337(1):1–6, 2015.

[47] L. Bherer, A. F. Kramer, M. S. Peterson, S. Colcombe, K. Erickson, and E. Becic. Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychology and aging*, 20(4):695, 2005.

[48] L. Bherer, A. F. Kramer, M. S. Peterson, S. Colcombe, K. Erickson, and E. Becic. Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Experimental aging research*, 34(3):188–219, 2008.

[49] L. Bherer, K. I. Erickson, and T. Liu-Ambrose. A review of the effects of physical activity and exercise on cognitive and brain functions in older adults. *Journal of aging research*, 2013, 2013.

[50] M. Binder. Neural correlates of audiovisual temporal processing–comparison of temporal order and simultaneity judgments. *Neuroscience*, 300:432–447, 2015.

[51] J. E. Black, K. R. Isaacs, B. J. Anderson, A. A. Alcantara, and W. T. Greenough. Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. *Proceedings of the National Academy of Sciences*, 87(14): 5568–5572, 1990.

[52] E. L. Bliss and J. Ailion. Relationship of stress and activity to brain dopamine and homovanillic acid. *Life Sciences*, 10(20):1161–1169, 1971.

[53] E. S. Bliss, R. H. Wong, P. R. Howe, and D. E. Mills. Benefits of exercise training on cerebrovascular and cognitive function in ageing. *Journal of Cerebral Blood Flow & Metabolism*, 41(3):447–470, 2021.

[54] I. E. Boerma, S. E. Mol, and J. Jolles. Reading pictures for story comprehension requires mental imagery skills. *Frontiers in psychology*, 7:1630, 2016.

[55] G. Borg. *Borg's perceived exertion and pain scales.* Human kinetics, 1998.

[56] A. Bowes, A. Dawson, R. Jepson, and L. McCabe. Physical activity for people with dementia: a scoping study. *BMC geriatrics*, 13(1):1–10, 2013.

[57] S. Branković. Boredom, dopamine, and the thrill of psychosis: psychiatry in a new key. *Psychiatria Danubina*, 27(2):0–137, 2015.

[58] D. Bridges, A. Pitiot, M. R. MacAskill, and J. W. Peirce. The timing mega-study: comparing a range of experiment generators, both lab-based and online. *PeerJ*, 8: e9414, 2020.

[59] T. Bright, D. Pallawela, et al. Validated smartphone-based apps for ear and hearing assessments: a review. *JMIR rehabilitation and assistive technologies*, 3(2):e6074, 2016.

[60] E. S. Bromberg-Martin, M. Matsumoto, and O. Hikosaka. Dopamine in motivational control: rewarding, aversive, and alerting. *Neuron*, 68(5):815–834, 2010.

[61] C. J. Brooks, A. J. Anderson, N. W. Roach, P. V. McGraw, and A. M. McKendrick. Age-related changes in auditory and visual interactions in temporal rate perception. *Journal of vision*, 15(16):2–2, 2015.

[62] C. J. Brooks, Y. M. Chan, A. J. Anderson, and A. M. McKendrick. Audiovisual temporal perception in aging: The role of multisensory integration and age-related sensory loss. *Frontiers in Human Neuroscience*, 12:192, 2018.

[63] S. K. Brooks, R. K. Webster, L. E. Smith, L. Woodland, S. Wessely, N. Greenberg, and G. J. Rubin. The psychological impact of quarantine and how to reduce it: rapid review of the evidence. *The lancet*, 395(10227):912–920, 2020.

[64] R. Brosch. What we 'see'when we read: Visualization and vividness in reading fictional narratives. *Cortex*, 105:135–143, 2018.

[65] J. Brown, C. M. Cooper-Kuhn, G. Kempermann, H. Van Praag, J. Winkler, F. H. Gage, and H. G. Kuhn. Enriched environment and physical activity stimulate hippocampal but not olfactory bulb neurogenesis. *European journal of Neuroscience*, 17 (10):2042–2046, 2003.

[66] C. Bruce, R. Desimone, and C. G. Gross. Visual properties of neurons in a polysensory area in superior temporal sulcus of the macaque. *Journal of neurophysiology*, 46(2):369–384, 1981.

[67] J. F. Brugge, I. O. Volkov, P. C. Garell, R. A. Reale, and M. A. Howard III. Functional connections between auditory cortex on heschl's gyrus and on the lateral superior temporal gyrus in humans. *Journal of Neurophysiology*, 90(6):3750–3763, 2003.

[68] T. T. Brunyé, T. Ditman, C. R. Mahoney, E. K. Walters, and H. A. Taylor. You heard it here first: Readers mentally simulate described sounds. *Acta Psychologica*, 135(2):209–215, 2010.

[69] H. Buch, T. Vinding, and N. V. Nielsen. Prevalence and causes of visual impairment according to world health organization and united states criteria in an aged, urban scandinavian population: the copenhagen city eye study. *Ophthalmology*, 108(12): 2347–2357, 2001.

[70] R. L. Buckner. Memory and executive function in aging and ad: multiple factors that cause decline and reserve factors that compensate. *Neuron*, 44(1):195–208, 2004.

[71] T. Busey, J. Craig, C. Clark, and L. Humes. Age-related changes in visual temporal order judgment performance: Relation to sensory and cognitive capacities. *Vision Research*, 50(17):1628–1640, 2010.

[72] G. Calvert, C. Spence, B. E. Stein, et al. *The handbook of multisensory processes*. MIT press, 2004.

[73] G. A. Calvert, P. C. Hansen, S. D. Iversen, and M. J. Brammer. Detection of audio-visual integration sites in humans by application of electrophysiological criteria to the bold effect. *Neuroimage*, 14(2):427–438, 2001.

[74] C. Cappe and P. Barone. Heteromodal connections supporting multisensory integration at low levels of cortical processing in the monkey. *European Journal of Neuroscience*, 22(11):2886–2902, 2005.

[75] P. Cardoso-Leite, A. Gorea, and P. Mamassian. Temporal order judgment and simple reaction times: Evidence for a common processing system. *Journal of Vision*, 7(6): 11–11, 2007.

[76] E. Carro, J. L. Trejo, S. Busiguina, and I. Torres-Aleman. Circulating insulin-like growth factor i mediates the protective effects of physical exercise against brain insults of different etiology and anatomy. *Journal of Neuroscience*, 21(15):5678–5684, 2001.

[77] C. J. Caspersen, K. E. Powell, and G. M. Christenson. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public health reports*, 100(2):126, 1985.

[78] J. Cerella and S. Hale. The rise and fall in information-processing rates over the life span. *Acta psychologica*, 86(2-3):109–197, 1994.

[79] C. L. Chan, E. K. Ngai, P. K. Leung, and S. Wong. Effect of the adapted virtual reality cognitive training program among chinese older adults with chronic schizophrenia: a pilot study. *International Journal of Geriatric Psychiatry: A journal of the psychiatry of late life and allied sciences*, 25(6):643–649, 2010.

[80] Y. M. Chan, M. J. Pianta, and A. M. McKendrick. Older age results in difficulties separating auditory and visual signals in time. *Journal of vision*, 14(11):13–13, 2014.

[81] Y. M. Chan, M. J. Pianta, and A. M. McKendrick. Reduced audiovisual recalibration in the elderly. *Frontiers in aging neuroscience*, 6:226, 2014.

[82] Y. M. Chan, M. J. Pianta, S. Bode, and A. M. McKendrick. Spatio-temporal patterns of event-related potentials related to audiovisual synchrony judgments in older adults. *Neurobiology of aging*, 55:38–48, 2017.

[83] N.-Y. N. Chang, R. M. Uchanski, and T. E. Hullar. Temporal integration of auditory and vestibular stimuli. *The Laryngoscope*, 122(6):1379–1384, 2012.

[84] Y.-K. Chang, J. D. Labban, J. I. Gapin, and J. L. Etnier. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain research*, 1453:87–101, 2012.

[85] Y.-Y. Chao, Y. K. Scherer, and C. A. Montgomery. Effects of using nintendo wii™ exergames in older adults: a review of the literature. *Journal of aging and health*, 27 (3):379–402, 2015.

[86] W. J. Chodzko-Zajko, D. N. Proctor, M. A. F. Singh, C. T. Minson, C. R. Nigg, G. J. Salem, and J. S. Skinner. Exercise and physical activity for older adults. *Medicine & science in sports & exercise*, 41(7):1510–1530, 2009.

[87] U. Christensen, L. Schmidt, E. Budtz-Jørgensen, and K. Avlund. Group cohesion and social support in exercise classes: Results from a danish intervention study. *Health education & behavior*, 33(5):677–689, 2006.

[88] B. R. Christie, B. D. Eadie, T. S. Kannangara, J. M. Robillard, J. Shin, and A. K. Titterness. Exercising our brains: how physical activity impacts synaptic plasticity in the dentate gyrus. *Neuromolecular medicine*, 10(2):47–58, 2008.

[89] C.-H. Chu, B. L. Alderman, G.-X. Wei, and Y.-K. Chang. Effects of acute aerobic exercise on motor response inhibition: an erp study using the stop-signal task. *Journal of Sport and Health Science*, 4(1):73–81, 2015.

[90] S. Cid-Fernández, M. Lindín, and F. Díaz. Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus. *Frontiers in human neuroscience*, 8:745, 2014.

[91] S. Cid-Fernández, M. Lindín, and F. Díaz. Information processing becomes slower and predominantly serial in aging: characterization of response-related brain potentials in an auditory–visual distraction–attention task. *Biological psychology*, 113: 12–23, 2016.

[92] K. M. Cienkowski and A. E. Carney. Auditory-visual speech perception and aging. *Ear and hearing*, 23(5):439–449, 2002.

[93] N. Ciesielska, R. Sokołowski, E. Mazur, M. Podhorecka, A. Polak-Szabela, and K. Kędziora-Kornatowska. Is the montreal cognitive assessment (moca) test better suited than the mini-mental state examination (mmse) in mild cognitive impairment (mci) detection among people aged over 60? meta-analysis. *Psychiatr Pol*, 50(5): 1039–1052, 2016.

[94] V. P. Clark, S. Fan, and s. A. Hillyard. Identification of early visual evoked potential generators by retinotopic and topographic analyses. *Human brain mapping*, 2(3): 170–187, 1994.

[95] S. Colcombe and A. F. Kramer. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological science*, 14(2):125–130, 2003.

[96] S. J. Colcombe, K. I. Erickson, P. E. Scalf, J. S. Kim, R. Prakash, E. McAuley, S. Elavsky, D. X. Marquez, L. Hu, and A. F. Kramer. Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 61(11):1166–1170, 2006.

[97] H. Colonius and A. Diederich. The race model inequality: interpreting a geometric measure of the amount of violation. *Psychological review*, 113(1):148, 2006.

[98] H. Colonius and A. Diederich. The optimal time window of visual-auditory integration: a reaction time analysis. *Frontiers in integrative neuroscience*, 4:11, 2010.

[99] C. Cooper. Anatomical and physiological mechanisms of arousal, with special reference to the effects of exercise. *Ergonomics*, 16(5):601–609, 1973.

[100] J. Cooper Jr and G. A. Gates. Hearing in the elderly–the framingham cohort, 1983-1985: Part ii. prevalence of central auditory processing disorders. *Ear and hearing*, 12(5):304–311, 1991.

[101] C. Córdova, V. Silva, C. F. Moraes, H. G. Simões, and O. d. T. Nóbrega. Acute exercise performed close to the anaerobic threshold improves cognitive performance in elderly females. *Brazilian Journal of Medical and Biological Research*, 42(5):458–464, 2009.

[102] D. Corey and A. Hudspeth. Ionic basis of the receptor potential in a vertebrate hair cell. *Nature*, 281(5733):675–677, 1979.

[103] K. S. Correa-Jaraba, S. Cid-Fernández, M. Lindín, and F. Díaz. Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants. *Frontiers in human neuroscience*, 10:129, 2016.

[104] C. W. Cotman and N. C. Berchtold. Exercise: a behavioral intervention to enhance brain health and plasticity. *Trends in neurosciences*, 25(6):295–301, 2002.

[105] C. W. Cotman, N. C. Berchtold, and L.-A. Christie. Exercise builds brain health: key roles of growth factor cascades and inflammation. *Trends in neurosciences*, 30 (9):464–472, 2007.

[106] S. Couth, E. Gowen, and E. Poliakoff. Using race model violation to explore multisensory responses in older adults: enhanced multisensory integration or slower unisensory processing? *Multisensory research*, 31(3-4):151–174, 2018.

[107] S. T. Creavin, S. Wisniewski, A. H. Noel-Storr, C. M. Trevelyan, T. Hampton, D. Rayment, V. M. Thom, K. J. Nash, H. Elhamoui, R. Milligan, et al. Mini-mental state examination (mmse) for the detection of dementia in clinically unevaluated people aged 65 and over in community and primary care populations. *Cochrane Database of Systematic Reviews*, 1, 2016.

[108] M. Cristell, K. M. Hutchinson, and H. M. Alessio. Effects of exercise training on hearing ability. *Scandinavian audiology*, 27(4):219–224, 1998.

[109] S. Croezen, M. Avendano, A. Burdorf, and F. J. Van Lenthe. Social participation and depression in old age: a fixed-effects analysis in 10 european countries. *American journal of epidemiology*, 182(2):168–176, 2015.

[110] C. Daskalopoulou, B. Stubbs, C. Kralj, A. Koukounari, M. Prince, and A. M. Prina. Physical activity and healthy ageing: A systematic review and meta-analysis of longitudinal cohort studies. *Ageing research reviews*, 38:6–17, 2017.

[111] D. H. Davis, S. T. Creavin, J. L. Yip, A. H. Noel-Storr, C. Brayne, and S. Cullum. Montreal cognitive assessment for the diagnosis of alzheimer's disease and other dementias. *Cochrane Database of Systematic Reviews*, 10, 2015.

[112] S. W. Davis, N. A. Dennis, S. M. Daselaar, M. S. Fleck, and R. Cabeza. Que pasa? the posterior–anterior shift in aging. *Cerebral cortex*, 18(5):1201–1209, 2008.

[113] K. Davranche and M. Audiffren. Facilitating effects of exercise on information processing. *Journal of Sports Sciences*, 22(5):419–428, 2004.

[114] K. Davranche and A. Pichon. Critical flicker frequency threshold increment after an exhausting exercise. *Journal of Sport and Exercise Psychology*, 27(4):515–520, 2005.

[115] L. de Boer-Schellekens and J. Vroomen. Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly. *Experimental brain research*, 232(1):253–262, 2014.

[116] E. D. de Bruin, D. Schoene, G. Pichierri, and S. T. Smith. Use of virtual reality technique for the training of motor control in the elderly. *Zeitschrift für Gerontologie und Geriatrie*, 43(4):229–234, 2010.

[117] A. L. de Dieuleveult, P. C. Siemonsma, J. B. van Erp, and A.-M. Brouwer. Effects of aging in multisensory integration: a systematic review. *Frontiers in aging neuroscience*, 9:80, 2017.

[118] A. De la Rosa, G. Olaso-Gonzalez, C. Arc-Chagnaud, F. Millan, A. Salvador-Pascual, C. García-Lucerga, C. Blasco-Lafarga, E. Garcia-Dominguez, A. Carretero, A. G. Correas, et al. Physical exercise in the prevention and treatment of alzheimer's disease. *Journal of Sport and Health Science*, 2020.

[119] H. de Souza Spinosa, S. Stilck, and M. Bernardi. Possible anxiolytic effects of ivermectin in rats. *Veterinary research communications*, 26(4):309–321, 2002.

[120] D. J. DeLoss, R. S. Pierce, and G. J. Andersen. Multisensory integration, aging, and the sound-induced flash illusion. *Psychology and aging*, 28(3):802, 2013.

[121] M. D. Delp, R. Armstrong, D. A. Godfrey, M. H. Laughlin, C. D. Ross, and M. K. Wilkerson. Exercise increases blood flow to locomotor, vestibular, cardiorespiratory and visual regions of the brain in miniature swine. *The Journal of Physiology*, 533 (3):849–859, 2001.

[122] S. Denervaud, E. Gentaz, P. J. Matusz, and M. M. Murray. Multisensory gains in simple detection predict global cognition in schoolchildren. *Scientific reports*, 10(1): 1–11, 2020.

[123] G. Der. Reaction time age changes and sex differences in adulthood. results from a large, population based study: the uk health and lifestyle survey. *Psychol Aging*, 21: 62–73, 2006.

[124] G. Der and I. J. Deary. The relationship between intelligence and reaction time varies with age: Results from three representative narrow-age age cohorts at 30, 50 and 69 years. *Intelligence*, 64:89–97, 2017.

[125] A. Dey and M. S. Sommers. Age-related differences in inhibitory control predict audiovisual speech perception. *Psychology and aging*, 30(3):634, 2015.

[126] M. Dhamala, C. G. Assisi, V. K. Jirsa, F. L. Steinberg, and J. S. Kelso. Multisensory integration for timing engages different brain networks. *Neuroimage*, 34(2):764–773, 2007.

[127] A. O. Diaconescu, L. Hasher, and A. R. McIntosh. Visual dominance and multisensory integration changes with age. *Neuroimage*, 65:152–166, 2013.

[128] A. Diederich and H. Colonius. Intersensory facilitation in the motor component? *Psychological Research*, 49(1):23–29, 1987.

[129] A. Diederich and H. Colonius. Bimodal and trimodal multisensory enhancement: effects of stimulus onset and intensity on reaction time. *Perception & psychophysics*, 66(8):1388–1404, 2004.

[130] A. Diederich and H. Colonius. Crossmodal interaction in speeded responses: time window of integration model. *Progress in brain research*, 174:119–135, 2009.

[131] A. Diederich and H. Colonius. The time window of multisensory integration: Relating reaction times and judgments of temporal order. *Psychological review*, 122(2):232, 2015.

[132] A. Diederich, H. Colonius, and A. Schomburg. Assessing age-related multisensory enhancement with the time-window-of-integration model. *Neuropsychologia*, 46(10): 2556–2562, 2008.

[133] A. Dietrich and M. Audiffren. The reticular-activating hypofrontality (rah) model of acute exercise. *Neuroscience & Biobehavioral Reviews*, 35(6):1305–1325, 2011.

[134] R. K. Dishman. Brain monoamines, exercise, and behavioral stress: animal models. *Medicine & Science in Sports & Exercise*, 1997.

[135] O. A. Donoghue, H. Ryan, E. Duggan, C. Finucane, G. M. Savva, H. Cronin, J. Loughman, and R. A. Kenny. Relationship between fear of falling and mobility varies with visual function among older adults. *Geriatrics & gerontology international*, 14(4):827–836, 2014.

[136] D. Dykiert, G. Der, J. M. Starr, and I. J. Deary. Sex differences in reaction time mean and intraindividual variability across the life span. *Developmental psychology*, 48(5):1262, 2012.

[137] R. A. Edden, S. D. Muthukumaraswamy, T. C. Freeman, and K. D. Singh. Orientation discrimination performance is predicted by gaba concentration and gamma oscillation frequency in human primary visual cortex. *Journal of Neuroscience*, 29 (50):15721–15726, 2009.

[138] M. Eisapour, S. Cao, and J. Boger. Game design for users with constraint: Exergame for older adults with cognitive impairment. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*, pages 128–130, 2018.

[139] M. Eisapour, S. Cao, L. Domenicucci, and J. Boger. Participatory design of a virtual reality exercise for people with mild cognitive impairment. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–9, 2018.

[140] M. Eisapour, S. Cao, L. Domenicucci, and J. Boger. Virtual reality exergames for people living with dementia based on exercise therapy best practices. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 62, pages 528–532. SAGE Publications Sage CA: Los Angeles, CA, 2018.

[141] J. El-Sayes, D. Harasym, C. V. Turco, M. B. Locke, and A. J. Nelson. Exercise-induced neuroplasticity: a mechanistic model and prospects for promoting plasticity. *The Neuroscientist*, 25(1):65–85, 2019.

[142] C. F. Emery, V. J. Honn, D. J. Frid, K. R. Lebowitz, and P. T. Diaz. Acute effects of exercise on cognition in patients with chronic obstructive pulmonary disease. *American journal of respiratory and critical care medicine*, 164(9):1624–1627, 2001.

[143] L. A. Erdődi, A. G. Shahein, F. Fareez, N. Rykulski, A. G. Sabelli, and R. M. Roth. Increasing the cutoff on the mmse and drs-2 improves clinical classification accuracy in highly educated older adults. *Psychology & Neuroscience*, 13(1):93, 2020.

[144] K. I. Erickson, M. W. Voss, R. S. Prakash, C. Basak, A. Szabo, L. Chaddock, J. S. Kim, S. Heo, H. Alves, S. M. White, et al. Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences*, 108(7):3017–3022, 2011.

[145] K. I. Erickson, A. G. Gildengers, and M. A. Butters. Physical activity and brain plasticity in late adulthood. *Dialogues in clinical neuroscience*, 2022.

[146] M. O. Ernst and H. H. Bülthoff. Merging the senses into a robust percept. *Trends in cognitive sciences*, 8(4):162–169, 2004.

[147] J. L. Etnier, W. Salazar, D. M. Landers, S. J. Petruzzello, M. Han, and P. Nowell. The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. *Journal of sport and Exercise Psychology*, 19(3):249–277, 1997.

[148] H. Eyre, R. Kahn, R. M. Robertson, ACS/ADA/AHA, and C. W. Committee. Preventing cancer, cardiovascular disease, and diabetes: a common agenda for the american cancer society, the american diabetes association, and the american heart association. *Circulation*, 109(25):3244–3255, 2004.

[149] M. Fabiani. It was the best of times, it was the worst of times: A psychophysiologist's view of cognitive aging. *Psychophysiology*, 49(3):283–304, 2012.

[150] M. Falkenstein, J. Yordanova, and V. Kolev. Effects of aging on slowing of motor-response generation. *International Journal of Psychophysiology*, 59(1):22–29, 2006.

[151] E. K. Festa, A. P. Katz, B. R. Ott, G. Tremont, and W. C. Heindel. Dissociable effects of aging and mild cognitive impairment on bottom-up audiovisual integration. *Journal of Alzheimer's Disease*, 59(1):155–167, 2017.

[152] C. M. Fiacconi, E. C. Harvey, A. B. Sekuler, and P. J. Bennett. The influence of aging on audiovisual temporal order judgments. *Experimental aging research*, 39(2): 179–193, 2013.

[153] P. J. Fitzgibbons and S. Gordon-Salant. Age effects on measures of auditory duration discrimination. *Journal of Speech, Language, and Hearing Research*, 37(3):662–670, 1994.

[154] P. J. Fitzgibbons and S. Gordon-Salant. Age effects on duration discrimination with simple and complex stimuli. *The Journal of the Acoustical Society of America*, 98 (6):3140–3145, 1995.

[155] A. M. Fjell, M. H. Sneve, H. Grydeland, A. B. Storsve, and K. B. Walhovd. The disconnected brain and executive function decline in aging. *Cerebral cortex*, 27(3): 2303–2317, 2017.

[156] S. M. Fleming, R. S. Weil, Z. Nagy, R. J. Dolan, and G. Rees. Relating introspective accuracy to individual differences in brain structure. *Science*, 329(5998):1541–1543, 2010.

[157] S. M. Fleming, J. Huijgen, and R. J. Dolan. Prefrontal contributions to metacognition in perceptual decision making. *Journal of Neuroscience*, 32(18):6117–6125, 2012.

[158] C. S. for Exercise Physiology. Csep, canadian 24-hour movement guidelines for adults ages 65 years and older: An integration of physical activity, sedentary behaviour, and sleep, 2021. URL https://csepguidelines.ca/adults-65/.

[159] J. J. Foxe, E. C. Strugstad, P. Sehatpour, S. Molholm, W. Pasieka, C. E. Schroeder, and M. E. McCourt. Parvocellular and magnocellular contributions to the initial generators of the visual evoked potential: high-density electrical mapping of the "c1" component. *Brain topography*, 21(1):11–21, 2008.

[160] M. R. Franco, A. Tong, K. Howard, C. Sherrington, P. H. Ferreira, R. Z. Pinto, and M. L. Ferreira. Older people's perspectives on participation in physical activity: a systematic review and thematic synthesis of qualitative literature. *British journal of sports medicine*, 49(19):1268–1276, 2015.

[161] J. Freiherr, J. N. Lundström, U. Habel, and K. Reetz. Multisensory integration mechanisms during aging. *Frontiers in human neuroscience*, 7:863, 2013.

[162] J. M. Fuster. The prefrontal cortex—an update: time is of the essence. *Neuron*, 30 (2):319–333, 2001.

[163] F. J. Gallun, G. P. McMillan, M. R. Molis, S. D. Kampel, S. M. Dann, and D. L. Konrad-Martin. Relating age and hearing loss to monaural, bilateral, and binaural temporal sensitivity1. *Frontiers in Neuroscience*, 8:172, 2014.

[164] F. Galton. Mental tests and measurements. *Mind*, 15(59):373–381, 1890.

[165] A. C. Ganesh, F. Berthommier, and J.-L. Schwartz. Audiovisual binding for speech perception in noise and in aging. *Language Learning*, 68:193–220, 2018.

[166] F. Gao, R. A. Edden, M. Li, N. A. Puts, G. Wang, C. Liu, B. Zhao, H. Wang, X. Bai, C. Zhao, et al. Edited magnetic resonance spectroscopy detects an age-related decline in brain gaba levels. *Neuroimage*, 78:75–82, 2013.

[167] A. A. Ghazanfar and C. E. Schroeder. Is neocortex essentially multisensory? *Trends in cognitive sciences*, 10(6):278–285, 2006.

[168] M. H. Giard and F. Peronnet. Auditory-visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study. *Journal of cognitive neuroscience*, 11(5):473–490, 1999.

[169] T. J. Gin, C. D. Luu, and R. H. Guymer. Central retinal function as measured by the multifocal electroretinogram and flicker perimetry in early age-related macular degeneration. *Investigative ophthalmology & visual science*, 52(12):9267–9274, 2011.

[170] S. Givre, C. Schroeder, and J. C. Arezzo. Contribution of extrastriate area v4 to the surface-recorded flash vep in the awake macaque. *Vision research*, 34(4):415–428, 1994.

[171] D. Godefroy, C. Rousseu, F. Vercruyssen, J. Cremieux, and J. Brisswalter. Influence of physical exercise on perceptual response in aerobically trained subjects. *Perceptual and motor skills*, 94(1):68–70, 2002.

[172] B. Godey, D. Schwartz, J. De Graaf, P. Chauvel, and C. Liegeois-Chauvel. Neuromagnetic source localization of auditory evoked fields and intracerebral evoked potentials: a comparison of data in the same patients. *Clinical neurophysiology*, 112 (10):1850–1859, 2001.

[173] M. Goekint, I. Bos, E. Heyman, R. Meeusen, Y. Michotte, and S. Sarre. Acute running stimulates hippocampal dopaminergic neurotransmission in rats, but has no influence on brain-derived neurotrophic factor. *Journal of applied physiology*, 2012.

[174] L. Goethals, N. Barth, J. Guyot, D. Hupin, T. Celarier, and B. Bongue. Impact of home quarantine on physical activity among older adults living at home during the covid-19 pandemic: qualitative interview study. *JMIR aging*, 3(1):e19007, 2020.

[175] N. Gogolla, A. E. Takesian, G. Feng, M. Fagiolini, and T. K. Hensch. Sensory integration in mouse insular cortex reflects gaba circuit maturation. *Neuron*, 83(4): 894–905, 2014.

[176] D. Gomez-Merino, F. Béquet, M. Berthelot, M. Chennaoui, and C. Y. Guezennec. Site-dependent effects of an acute intensive exercise on extracellular 5-ht and 5-hiaa levels in rat brain. *Neuroscience letters*, 301(2):143–146, 2001.

[177] D. Gomez-Merino, F. Bequet, M. Berthelot, S. Riverain, M. Chennaoui, and C. Guezennec. Evidence that the branched-chain amino acid l-valine prevents exercise-induced release of 5-ht in rat hippocampus. *International journal of sports medicine*, 22(05):317–322, 2001.

[178] M. Gondan. A permutation test for the race model inequality. *Behavior research methods*, 42(1):23–28, 2010.

[179] M. Gondan and K. Minakata. A tutorial on testing the race model inequality. *Attention, Perception, & Psychophysics*, 78(3):723–735, 2016.

[180] M. A. Goodale, G. Króliczak, and D. A. Westwood. Dual routes to action: contributions of the dorsal and ventral streams to adaptive behavior. *Progress in brain research*, 149:269–283, 2005.

[181] M. S. Gordon and S. Allen. Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise. *Experimental aging research*, 35(2):202–219, 2009.

[182] S. Gordon-Salant and P. J. Fitzgibbons. Profile of auditory temporal processing in older listeners. *Journal of Speech, Language, and Hearing Research*, 42(2):300–311, 1999.

[183] S. Gordon-Salant, G. H. Yeni-Komshian, P. J. Fitzgibbons, H. M. Willison, and M. S. Freund. Recognition of asynchronous auditory-visual speech by younger and older listeners: a preliminary study. *The Journal of the Acoustical Society of America*, 142 (1):151–159, 2017.

[184] P. A. Gosselin and J.-P. Gagné. Older adults expend more listening effort than young adults recognizing audiovisual speech in noise. *International journal of audiology*, 50 (11):786–792, 2011.

[185] L. Grabot and V. van Wassenhove. Time order as psychological bias. *Psychological science*, 28(5):670–678, 2017.

[186] C. L. Grady, J. M. Maisog, B. Horwitz, L. G. Ungerleider, M. J. Mentis, J. A. Salerno, P. Pietrini, E. Wagner, and J. V. Haxby. Age-related changes in cortical blood flow activation during visual processing of faces and location. *Journal of Neuroscience*, 14(3):1450–1462, 1994.

[187] F. Grigoletto, G. Zappalà, D. W. Anderson, and B. D. Lebowitz. Norms for the mini-mental state examination in a healthy population. *Neurology*, 53(2):315–315, 1999.

[188] J. H. Grose and S. K. Mamo. Processing of temporal fine structure as a function of age. *Ear and hearing*, 31(6):755, 2010.

[189] B. Guderian, L. Borreson, L. Sletten, K. Cable, T. Stecker, M. Probst, and L. Dalleck. The cardiovascular and metabolic responses to wii fit video game playing in middle-aged and older adults. *The Journal of sports medicine and physical fitness*, 50(4): 436–442, 2010.

[190] M. J. Guerreiro, J. A. Anguera, J. Mishra, P. W. Van Gerven, and A. Gazzaley. Age-equivalent top–down modulation during cross-modal selective attention. *Journal of Cognitive Neuroscience*, 26(12):2827–2839, 2014.

[191] M. J. Guerreiro, J. Eck, M. Moerel, E. A. Evers, and P. W. Van Gerven. Top-down modulation of visual and auditory cortical processing in aging. *Behavioural Brain Research*, 278:226–234, 2015.

[192] W. D. Hairston, P. J. Laurienti, G. Mishra, J. H. Burdette, and M. T. Wallace. Multisensory enhancement of localization under conditions of induced myopia. *Experimental brain research*, 152(3):404–408, 2003.

[193] L. Harris, V. Harrar, P. JAEkL, and A. Kopinska. Mechanisms of simultaneity constancy. *Space and time in perception and action*, pages 232–253, 2010.

[194] H. Hasegawa, T. Yazawa, M. Yasumatsu, M. Otokawa, and Y. Aihara. Alteration in dopamine metabolism in the thermoregulatory center of exercising rats. *Neuroscience letters*, 289(3):161–164, 2000.

[195] H. Hasegawa, S. Takatsu, T. Ishiwata, H. Tanaka, S. Sarre, and R. Meeusen. Continuous monitoring of hypothalamic neurotransmitters and thermoregulatory responses in exercising rats. *Journal of neuroscience methods*, 202(2):119–123, 2011.

[196] S. Hattori, Q. Li, N. Matsui, and H. Nishino. Treadmill running combined with microdialysis can evaluate motor deficit and improvement following dopaminergic grafts in 6-ohda lesioned rats. *Restorative neurology and neuroscience*, 6(1):65–72, 1993.

[197] S. Hattori, M. Naoi, and H. Nishino. Striatal dopamine turnover during treadmill running in the rat: relation to the speed of running. *Brain research bulletin*, 35(1): 41–49, 1994.

[198] M. J. Hay-McCutcheon, D. B. Pisoni, and K. K. Hunt. Audiovisual asynchrony detection and speech perception in hearing-impaired listeners with cochlear implants: a preliminary analysis. *International journal of audiology*, 48(6):321–333, 2009.

[199] D. Hayashi, C. G. Gonçalves, R. B. Parreira, K. B. Fernandes, D. C. Teixeira, R. A. Silva, and V. S. Probst. Postural balance and physical activity in daily life (padl) in physically independent older adults with different levels of aerobic exercise capacity. *Archives of gerontology and geriatrics*, 55(2):480–485, 2012.

[200] B. Hernández, A. Setti, R. A. Kenny, and F. N. Newell. Individual differences in ageing, cognitive status, and sex on susceptibility to the sound-induced flash illusion: A large-scale study. *Psychology and aging*, 34(7):978, 2019.

[201] P. Heyn, B. C. Abreu, and K. J. Ottenbacher. The effects of exercise training on elderly persons with cognitive impairment and dementia: a meta-analysis. *Archives of physical medicine and rehabilitation*, 85(10):1694–1704, 2004.

[202] K. Hikosaka, E. Iwai, H. Saito, and K. Tanaka. Polysensory properties of neurons in the anterior bank of the caudal superior temporal sulcus of the macaque monkey. *Journal of neurophysiology*, 60(5):1615–1637, 1988.

[203] C. H. Hillman, K. I. Erickson, and A. F. Kramer. Be smart, exercise your heart: exercise effects on brain and cognition. *Nature reviews neuroscience*, 9(1):58–65, 2008.

[204] A. R. Hillock, A. R. Powers, and M. T. Wallace. Binding of sights and sounds: age-related changes in multisensory temporal processing. *Neuropsychologia*, 49(3): 461–467, 2011.

[205] A. Hillock-Dunn and M. T. Wallace. Developmental changes in the multisensory temporal binding window persist into adolescence. *Developmental science*, 15(5): 688–696, 2012.

[206] I. J. Hirsh and C. E. Sherrick Jr. Perceived order in different sense modalities. *Journal of experimental psychology*, 62(5):423, 1961.

[207] R. J. Hirst, A. Setti, R. A. Kenny, and F. N. Newell. Age-related sensory decline mediates the sound-induced flash illusion: Evidence for reliability weighting models of multisensory perception. *Scientific reports*, 9(1):1–12, 2019.

[208] E. Hogervorst, W. Riedel, A. Jeukendrup, and J. Jolles. Cognitive performance after strenuous physical exercise. *Perceptual and motor skills*, 83(2):479–488, 1996.

[209] R. Houdeib. *Age-related differences in Cognitive Plasticity of Executive Control Mechanisms: Exploring Transfer Effects Following iPad-based Dual-Task and N-Back Training*. PhD thesis, Concordia University, 2018.

[210] S.-S. Hsieh, C.-J. Huang, C.-T. Wu, Y.-K. Chang, and T.-M. Hung. Acute exercise facilitates the n450 inhibition marker and p3 attention marker during stroop test in young and older adults. *Journal of clinical medicine*, 7(11):391, 2018.

[211] A. Huyse, J. Leybaert, and F. Berthommier. Effects of aging on audio-visual speech integration. *The Journal of the Acoustical Society of America*, 136(4):1918–1931, 2014.

[212] B. R. Innes and T. U. Otto. A comparative analysis of response times shows that multisensory benefits and interactions are not equivalent. *Scientific reports*, 9(1): 1–10, 2019.

[213] W. James. The principles of psychology, vol. 2. In *Henry Holt and Company*, pages 1–720. Dover Publications; Revised ed. edition (June 1 1950), 1890.

[214] P. Jaśkowski. Perceived onset simultaneity of stimuli with unequal durations. *Perception*, 20(6):715–726, 1991.

[215] P. Jaśkowski. Temporal-order judgment and reaction time for short and long stimuli. *Psychological Research*, 54(3):141–145, 1992.

[216] P. Jaskowski and R. Verleger. Attentional bias toward low-intensity stimuli: An explanation for the intensity dissociation between reaction time and temporal order judgment? *Consciousness and Cognition*, 9(3):435–456, 2000.

[217] P. Jaśkowski, F. Jaroszyk, and D. Hojan-Jezierska. Temporal-order judgments and reaction time for stimuli of different modalities. *Psychological Research*, 52(1):35–38, 1990.

[218] A. R. Jensen. *Clocking the mind: Mental chronometry and individual differences*. Elsevier, 2006.

[219] L. Ji, D. C. Steffens, and L. Wang. Effects of physical exercise on the aging brain across imaging modalities: A meta-analysis of neuroimaging studies in randomized controlled trials. *International Journal of Geriatric Psychiatry*, 2021.

[220] P. Jin. Efficacy of tai chi, brisk walking, meditation, and reading in reducing mental and emotional stress. *Journal of psychosomatic research*, 36(4):361–370, 1992.

[221] E. Jones and T. Powell. An anatomical study of converging sensory pathways within the cerebral cortex of the monkey. *Brain*, 93(4):793–820, 1970.

[222] S. A. Jones, U. Beierholm, D. Meijer, and U. Noppeney. Older adults sacrifice response speed to preserve multisensory integration performance. *Neurobiology of aging*, 84:148–157, 2019.

[223] J. Joyce, J. Graydon, T. McMorris, and K. Davranche. The time course effect of moderate intensity exercise on response execution and response inhibition. *Brain and cognition*, 71(1):14–19, 2009.

[224] R. E. Kalina. Seeing into the future. vision and aging. *Western journal of medicine*, 167(4):253, 1997.

[225] A. Kaltsatou, E. Kouidi, D. Fotiou, and P. Deligiannis. The use of pupillometry in the assessment of cardiac autonomic function in elite different type trained athletes. *European journal of applied physiology*, 111(9):2079–2087, 2011.

[226] K. Kamijo, Y. Hayashi, T. Sakai, T. Yahiro, K. Tanaka, and Y. Nishihira. Acute effects of aerobic exercise on cognitive function in older adults. *Journals of Gerontology: Series B*, 64(3):356–363, 2009.

[227] D. L. Kappen, P. Mirza-Babaei, and L. E. Nacke. Older adults' physical activity and exergames: a systematic review. *International Journal of Human–Computer Interaction*, 35(2):140–167, 2019.

[228] K. Kashihara and Y. Nakahara. Short-term effect of physical exercise at lactate threshold on choice reaction time. *Perceptual and motor skills*, 100(2):275–291, 2005.

[229] C. Kayser and L. Shams. Multisensory causal inference in the brain. *PLoS Biol*, 13 (2):e1002075, 2015.

[230] M. Keetels and J. Vroomen. The role of spatial disparity and hemifields in audio-visual temporal order judgments. *Experimental Brain Research*, 167(4):635–640, 2005.

[231] M. Keetels and J. Vroomen. Perception of synchrony between the senses. In *The Neural Bases of Multisensory Processes*, page 147–177, Boca Raton, 2012. CRC Press/Taylor & Francis.

[232] G. Kempermann, K. Fabel, D. Ehninger, H. Babu, P. Leal-Galicia, A. Garthe, and S. Wolf. Why and how physical activity promotes experience-induced brain plasticity. *Frontiers in neuroscience*, 4:189, 2010.

[233] C. B. Kim and M. J. Mayer. Foveal flicker sensitivity in healthy aging eyes. ii. cross-sectional aging trends from 18 through 77 years of age. *JOSA A*, 11(7):1958–1969, 1994.

[234] J. Kim, J. Son, N. Ko, and B. Yoon. Unsupervised virtual reality-based exercise program improves hip muscle strength and balance control in older adults: a pilot study. *Archives of physical medicine and rehabilitation*, 94(5):937–943, 2013.

[235] S.-i. Kim. Neuroscientific model of motivational process. *Frontiers in psychology*, 4: 98, 2013.

[236] S.-i. Kim, J. Reeve, and M. Bong. Introduction to motivational neuroscience. In *Recent developments in neuroscience research on human motivation*. Emerald Group Publishing Limited, 2016.

[237] A. King and A. Palmer. Integration of visual and auditory information in bimodal neurones in the guinea-pig superior colliculus. *Experimental brain research*, 60(3): 492–500, 1985.

[238] A. J. King. Multisensory integration: strategies for synchronization. *Current Biology*, 15(9):R339–R341, 2005.

[239] H. R. Konrad, M. Girardi, and R. Helfert. Balance and aging. *The Laryngoscope*, 109(9):1454–1460, 1999.

[240] F. Kouneiher, S. Charron, and E. Koechlin. Motivation and cognitive control in the human prefrontal cortex. *Nature neuroscience*, 12(7):939–945, 2009.

[241] A. F. Kramer and S. Colcombe. Fitness effects on the cognitive function of older adults: a meta-analytic study—revisited. *Perspectives on Psychological Science*, 13 (2):213–217, 2018.

[242] V. Krull and L. E. Humes. Text as a supplement to speech in young and older adults. *Ear and hearing*, 37(2):164, 2016.

[243] A. M. Kueider, J. M. Parisi, A. L. Gross, and G. W. Rebok. Computerized cognitive training with older adults: a systematic review. *PloS one*, 7(7):e40588, 2012.

[244] S. W. Kuffler. Discharge patterns and functional organization of mammalian retina. *Journal of neurophysiology*, 16(1):37–68, 1953.

[245] M. Kurosawa, K. Okada, A. Sato, and S. Uchida. Extracellular release of acetylcholine, noradrenaline and serotonin increases in the cerebral cortex during walking in conscious rats. *Neuroscience letters*, 161(1):73–76, 1993.

[246] A. S. Kvitting, K. Fällman, E. Wressle, and J. Marcusson. Age-normative mmse data for older persons aged 85 to 93 in a longitudinal swedish cohort. *Journal of the American Geriatrics Society*, 67(3):534–538, 2019.

[247] B. J. Lachenmayr, S. Kojetinsky, N. Ostermaier, K. Angstwurm, P. Vivell, and M. Schaumberger. The different effects of aging on normal sensitivity in flicker and light-sense perimetry. *Investigative ophthalmology & visual science*, 35(6):2741–2748, 1994.

[248] P. Lacherez, L. Turner, R. Lester, Z. Burns, and J. M. Wood. Age-related changes in perception of movement in driving scenes. *Ophthalmic and Physiological Optics*, 34(4):445–451, 2014.

[249] D. Lakens. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and anovas. *Frontiers in psychology*, 4:863, 2013.

[250] K. Lambourne and P. Tomporowski. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain research*, 1341:12–24, 2010.

[251] K. Lambourne, M. Audiffren, and P. D. Tomporowski. Effects of acute exercise on sensory and executive processing tasks. *Med Sci Sports Exerc*, 42(7):1396–1402, 2010.

[252] A. Lampit, H. Hallock, and M. Valenzuela. Computerized cognitive training in cognitively healthy older adults: a systematic review and meta-analysis of effect modifiers. *PLoS medicine*, 11(11):e1001756, 2014.

[253] E. B. Larson, L. Wang, J. D. Bowen, W. C. McCormick, L. Teri, P. Crane, and W. Kukull. Exercise is associated with reduced risk for incident dementia among persons 65 years of age and older. *Annals of internal medicine*, 144(2):73–81, 2006.

[254] A. Lauenroth, A. E. Ioannidis, and B. Teichmann. Influence of combined physical and cognitive training on cognition: a systematic review. *BMC geriatrics*, 16(1): 1–14, 2016.

[255] P. J. Laurienti, J. H. Burdette, J. A. Maldjian, and M. T. Wallace. Enhanced multisensory integration in older adults. *Neurobiology of aging*, 27(8):1155–1163, 2006.

[256] D. Laurin, R. Verreault, J. Lindsay, K. MacPherson, and K. Rockwood. Physical activity and risk of cognitive impairment and dementia in elderly persons. *Archives of neurology*, 58(3):498–504, 2001.

[257] F.-S. Lee, L. J. Matthews, J. R. Dubno, and J. H. Mills. Longitudinal study of pure-tone thresholds in older persons. *Ear and hearing*, 26(1):1–11, 2005.

[258] I.-M. Lee. Dose-response relation between physical activity and fitness: even a little is good; more is better. *Jama*, 297(19):2137–2139, 2007.

[259] M. D. Lee and E.-J. Wagenmakers. *Bayesian cognitive modeling: A practical course.* Cambridge university press, 2014.

[260] I. Legault, J.-P. Gagné, W. Rhoualem, and P. Anderson-Gosselin. The effects of blurred vision on auditory-visual speech perception in younger and older adults. *International Journal of Audiology*, 49(12):904–911, 2010.

[261] A. Leiva, F. B. Parmentier, and P. Andrés. Aging increases distraction by auditory oddballs in visual, but not auditory tasks. *Psychological Research*, 79(3):401–410, 2015.

[262] D. Levac, H. Colquhoun, and K. K. O'Brien. Scoping studies: advancing the methodology. *Implementation science*, 5(1):1–9, 2010.

[263] M. F. Levin. Can virtual reality offer enriched environments for rehabilitation? *Expert review of neurotherapeutics*, 11(2):153–155, 2011.

[264] S. L. Levine, C. J. Brabander, A. M. Moore, A. C. Holding, and R. Koestner. Unhappy or unsatisfied: distinguishing the role of negative affect and need frustration in depressive symptoms over the academic year and during the covid-19 pandemic. *Motivation and Emotion*, 46(1):126–136, 2022.

[265] J. W. Lewis and D. C. Van Essen. Corticocortical connections of visual, sensorimotor, and multimodal processing areas in the parietal lobe of the macaque monkey. *Journal of Comparative Neurology*, 428(1):112–137, 2000.

[266] D. J. Lewkowicz. Perception of auditory–visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance*, 22(5): 1094, 1996.

[267] Y. Li, Z. Zhao, J. Cai, B. Gu, Y. Lv, and L. Zhao. The frequency-dependent aerobic exercise effects of hypothalamic gabaergic expression and cardiovascular functions in aged rats. *Frontiers in aging neuroscience*, 9:212, 2017.

[268] C. Liegeois-Chauvel, A. Musolino, J. Badier, P. Marquis, and P. Chauvel. Evoked potentials recorded from the auditory cortex in man: evaluation and topography of the middle latency components. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, 92(3):204–214, 1994.

[269] F. R. Lin, R. Thorpe, S. Gordon-Salant, and L. Ferrucci. Hearing loss prevalence and risk factors among older adults in the united states. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences*, 66(5):582–590, 2011.

[270] D. Linares and A. O. Holcombe. Differences in perceptual latency estimated from judgments of temporal order, simultaneity and duration are inconsistent. *i-Perception*, 5(6):559–571, 2014.

[271] U. Lindenberger and P. B. Baltes. Sensory functioning and intelligence in old age: a strong connection. *Psychology and aging*, 9(3):339, 1994.

[272] I. Lista and G. Sorrentino. Biological mechanisms of physical activity in preventing cognitive decline. *Cellular and molecular neurobiology*, 30(4):493–503, 2010.

[273] X. Liu and D. Yan. Ageing and hearing loss. *The Journal of Pathology: A Journal of the Pathological Society of Great Britain and Ireland*, 211(2):188–197, 2007.

[274] S. R. Lord and H. B. Menz. Visual contributions to postural stability in older adults. *Gerontology*, 46(6):306–310, 2000.

[275] S. A. Love, K. Petrini, A. Cheng, and F. E. Pollick. A psychophysical investigation of differences between synchrony and temporal order judgments. *PloS one*, 8(1), 2013.

[276] S. A. Love, K. Petrini, C. R. Pernet, M. Latinus, and F. E. Pollick. Overlapping but divergent neural correlates underpinning audiovisual synchrony and temporal order judgments. *Frontiers in human neuroscience*, 12:274, 2018.

[277] R. D. Luce et al. *Response times: Their role in inferring elementary mental organization.* Number 8. Oxford University Press on Demand, 1986.

[278] C. A. Luis, A. P. Keegan, and M. Mullan. Cross validation of the montreal cognitive assessment in community dwelling older adults residing in the southeastern us. *International Journal of Geriatric Psychiatry: A journal of the psychiatry of late life and allied sciences*, 24(2):197–201, 2009.

[279] J. Lupo and M. Barnett-Cowan. Impaired perceived timing of falls in the elderly. *Gait & posture*, 59:40–45, 2018.

[280] C. Lustig, P. Shah, R. Seidler, and P. A. Reuter-Lorenz. Aging, training, and the brain: a review and future directions. *Neuropsychology review*, 19(4):504–522, 2009.

[281] R. S. Lutz, P. Karoly, and M. A. Okun. The why and the how of goal pursuit: Self-determination, goal process cognition, and participation in physical exercise. *Psychology of Sport and Exercise*, 9(5):559–575, 2008.

[282] R. B. Lydiard. The role of gaba in anxiety disorders. *Journal of Clinical Psychiatry*, 64:21–27, 2003.

[283] E. J. Lyons, D. F. Tate, D. S. Ward, J. M. Bowling, K. M. Ribisl, and S. Kalyararaman. Energy expenditure and enjoyment during video game play: differences by game type. *Medicine and Science in Sports and Exercise*, 43(10):1987, 2011.

[284] W. J. Ma, X. Zhou, L. A. Ross, J. J. Foxe, and L. C. Parra. Lip-reading aids word recognition most in moderate noise: a bayesian explanation using high-dimensional feature space. *PloS one*, 4(3):e4638, 2009.

[285] R. J. Maddock, G. A. Casazza, M. H. Buonocore, and C. Tanase. Vigorous exercise increases brain lactate and glx (glutamate+ glutamine): a dynamic 1h-mrs study. *Neuroimage*, 57(4):1324–1330, 2011.

[286] R. J. Maddock, G. A. Casazza, D. H. Fernandez, and M. I. Maddock. Acute modulation of cortical glutamate and gaba content by physical activity. *Journal of Neuroscience*, 36(8):2449–2457, 2016.

[287] C. Maguinness, A. Setti, K. Burke, R. A. Kenny, and F. N. Newell. The effect of combined sensory and semantic components on audio-visual speech perception in older adults. *Frontiers in aging neuroscience*, 3:19, 2011.

[288] J. R. Mahoney and J. Verghese. Visual-somatosensory integration and quantitative gait performance in aging. *Frontiers in aging neuroscience*, 10:377, 2018.

[289] J. R. Mahoney and J. Verghese. Using the race model inequality to quantify behavioral multisensory integration effects. *JoVE (Journal of Visualized Experiments)*, 10 (147):e59575, 2019.

[290] J. R. Mahoney and J. Verghese. Does cognitive impairment influence visual-somatosensory integration and mobility in older adults? *The Journals of Gerontology: Series A*, 75(3):581–588, 2020.

[291] J. R. Mahoney, P. C. C. Li, M. Oh-Park, J. Verghese, and R. Holtzer. Multisensory integration across the senses in young and old adults. *Brain research*, 1426:43–53, 2011.

[292] J. R. Mahoney, J. Verghese, K. Dumas, C. Wang, and R. Holtzer. The effect of multisensory cues on attention in aging. *Brain research*, 1472:63–73, 2012.

[293] J. R. Mahoney, R. Holtzer, and J. Verghese. Visual-somatosensory integration and balance: evidence for psychophysical integrative differences in aging. *Multisensory research*, 27(1):17–42, 2014.

[294] J. R. Mahoney, K. Dumas, and R. Holtzer. Visual–somatosensory integration is linked to physical activity level in older adults. *Multisensory research*, 28(1-2):11–29, 2015.

[295] J. R. Mahoney, K. Cotton, and J. Verghese. Multisensory integration predicts balance and falls in older adults. *The Journals of Gerontology: Series A*, 74(9):1429–1435, 2019.

[296] P. Maillot, A. Perrot, and A. Hartley. Effects of interactive physical-activity video-game training on physical and cognitive function in older adults. *Psychology and aging*, 27(3):589, 2012.

[297] A. Markwick, G. Zamboni, and C. A. De Jager. Profiles of cognitive subtest impairment in the montreal cognitive assessment (moca) in a research cohort with normal mini-mental state examination (mmse) scores. *Journal of clinical and experimental neuropsychology*, 34(7):750–757, 2012.

[298] C. Mathers, A. Smith, and M. Concha. Global burden of hearing loss in the year 2000. *Global burden of Disease*, 18(4):1–30, 2000.

[299] M. J. Mayer, C. B. Kim, A. Svingos, and A. Glucs. Foveal flicker sensitivity in healthy aging eyes. i. compensating for pupil variation. *JOSA A*, 5(12):2201–2209, 1988.

[300] P. Mazzoni, R. M. Bracewell, S. Barash, and R. A. Andersen. Spatially tuned auditory responses in area lip of macaques performing delayed memory saccades to acoustic targets. *Journal of neurophysiology*, 75(3):1233–1241, 1996.

[301] D. P. McGovern, E. Roudaia, J. Stapleton, T. M. McGinnity, and F. N. Newell. The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration. *Frontiers in aging neuroscience*, 6:250, 2014.

[302] T. McMorris. History of research into the acute exercise–cognition interaction: A cognitive psychology approach. 2016.

[303] M. McSween, K. McMahon, J. Coombes, C. MacKay, A. Rodriguez, K. Erickson, and D. Copland. The immediate effects of acute aerobic exercise on cognition in healthy older adults: a systematic review. *Journal of science and medicine in sport*, 21:S95, 2018.

[304] R. Meeusen and M. Piacentini. Exercise and neurotransmission: a window to the future? *European Journal of Sport Science*, 1(1):1–12, 2001.

[305] R. Meeusen, K. Thorre, F. Chaouloff, S. Sarre, K. De Meirleir, G. Ebinger, and Y. Michotte. Effects of tryptophan and/or acute running on extracellular 5-ht and 5-hiaa levels in the hippocampus of food-deprived rats. *Brain research*, 740(1-2): 245–252, 1996.

[306] R. Meeusen, I. Smolders, S. Sarre, K. De Meirleir, H. Keizer, M. Serneels, G. Ebinger, and Y. Michotte. Endurance training effects on neurotransmitter release in rat striatum: an in vivo microdialysis study. *Acta Physiologica Scandinavica*, 159(4):335–341, 1997.

[307] P. Mégevand, S. Molholm, A. Nayak, and J. J. Foxe. Recalibration of the multisensory temporal window of integration results from changing task demands. *PloS one*, 8(8), 2013.

[308] A. Mehren, J. Özyurt, C. M. Thiel, M. Brandes, A. Lam, and A. Philipsen. Effects of acute aerobic exercise on response inhibition in adult patients with adhd. *Scientific reports*, 9(1):1–13, 2019.

[309] A. Menendez and A. Lit. Effects of test-flash and steady background luminance on simple visual reaction time (rt) and perceived simultaneity (ps). *Investigative Ophthalmology and Visual Science*, 24(5), 1983.

[310] M. A. Meredith and B. E. Stein. Interactions among converging sensory inputs in the superior colliculus. *Science*, 221(4608):389–391, 1983.

[311] M. A. Meredith and B. E. Stein. Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *Journal of neurophysiology*, 56(3):640–662, 1986.

[312] M. A. Meredith and B. E. Stein. Spatial determinants of multisensory integration in cat superior colliculus neurons. *Journal of neurophysiology*, 75(5):1843–1857, 1996.

[313] M. A. Meredith, J. W. Nemitz, and B. E. Stein. Determinants of multisensory integration in superior colliculus neurons. i. temporal factors. *Journal of Neuroscience*, 7(10):3215–3229, 1987.

[314] N. A. Merriman, C. Whyatt, A. Setti, C. Craig, and F. N. Newell. Successful balance training is associated with improved multisensory function in fall-prone older adults. *Computers in human behavior*, 45:192–203, 2015.

[315] S. P. Messier, T. D. Royer, T. E. Craven, M. L. O'Toole, R. Burns, and W. H. Ettinger. Long-term exercise and its effect on balance in older, osteoarthritic adults: results from the fitness, arthritis, and seniors trial (fast). *Journal of the American Geriatrics Society*, 48(2):131–138, 2000.

[316] L. E. Middleton, D. E. Barnes, L.-Y. Lui, and K. Yaffe. Physical activity over the life course and its association with cognitive performance and impairment in old age. *Journal of the American Geriatrics Society*, 58(7):1322–1326, 2010.

[317] S. A. Milani, M. Marsiske, L. B. Cottler, X. Chen, and C. W. Striley. Optimal cutoffs for the montreal cognitive assessment vary by race and ethnicity. *Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring*, 10(1):773–781, 2018.

[318] J. Miller. Divided attention: Evidence for coactivation with redundant signals. *Cognitive psychology*, 14(2):247–279, 1982.

[319] J. Miller. Timecourse of coactivation in bimodal divided attention. *Perception & psychophysics*, 40(5):331–343, 1986.

[320] J. Miller. Statistical facilitation and the redundant signals effect: What are race and coactivation models? *Attention, Perception, & Psychophysics*, 78(2):516–519, 2016.

[321] J. Miller and W. Schwarz. Dissociations between reaction times and temporal order judgments: a diffusion model approach. *Journal of Experimental Psychology: Human Perception and Performance*, 32(2):394, 2006.

[322] J. Mishra and A. Gazzaley. Preserved discrimination performance and neural processing during crossmodal attention in aging. *PLoS One*, 8(11):e81894, 2013.

[323] L. Mitrani, S. Shekerdjiiski, and N. Yakimoff. Mechanisms and asymmetries in visual perception of simultaneity and temporal order. *Biological cybernetics*, 54(3):159–165, 1986.

[324] M. Miyachi, K. Yamamoto, K. Ohkawara, S. Tanaka, et al. Mets in adults while playing active video games: a metabolic chamber study. *Med Sci Sports Exerc*, 42 (6):1149–1153, 2010.

[325] M. Miyazaki, S. Yamamoto, S. Uchida, and S. Kitazawa. Bayesian calibration of simultaneity in tactile temporal order judgment. *Nature neuroscience*, 9(7):875–877, 2006.

[326] S. Molholm, W. Ritter, M. M. Murray, D. C. Javitt, C. E. Schroeder, and J. J. Foxe. Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study. *Cognitive brain research*, 14(1): 115–128, 2002.

[327] S. Molholm, P. Sehatpour, A. D. Mehta, M. Shpaner, M. Gomez-Ramirez, S. Ortigue, J. P. Dyke, T. H. Schwartz, and J. J. Foxe. Audio-visual multisensory integration in superior parietal lobule revealed by human intracranial recordings. *Journal of neurophysiology*, 96(2):721–729, 2006.

[328] K. I. Molina, N. A. Ricci, S. A. de Moraes, and M. R. Perracini. Virtual reality using games for improving physical functioning in older adults: a systematic review. *Journal of neuroengineering and rehabilitation*, 11(1):1–20, 2014.

[329] D. Molloy, D. Beerschoten, M. Borrie, R. Crilly, and R. Cape. Acute effects of exercise on neuropsychological function in elderly subjects. *Journal of the American Geriatrics Society*, 36(1):29–33, 1988.

[330] J. L. Mozolic, C. E. Hugenschmidt, A. M. Peiffer, and P. J. Laurienti. Multisensory integration and aging. In *The Neural Basis of Multisensory Processing Murray MM Wallace MT (Eds)*. CRC Press/Taylor & Francis Boca Raton, FL, USA, 2012.

[331] J. L. Mozolic, C. E. Hugenschmidt, A. M. Peiffer, and P. J. Laurienti. Multisensory integration and aging. In *The Neural Bases of Multisensory Processes*, page 381–394, Boca Raton, 2012. CRC Press/Taylor & Francis.

[332] M. M. Murray, A. F. Eardley, T. Edginton, R. Oyekan, E. Smyth, and P. J. Matusz. Sensory dominance and multisensory integration as screening tools in aging. *Scientific reports*, 8(1):1–11, 2018.

[333] S. Musich, S. S. Wang, K. Hawkins, and C. Greame. The frequency and health benefits of physical activity for older adults. *Population Health Management*, 20(3): 199–207, 2017.

[334] Z. S. Nasreddine, N. A. Phillips, V. Bédirian, S. Charbonneau, V. Whitehead, I. Collin, J. L. Cummings, and H. Chertkow. The montreal cognitive assessment, moca: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, 53(4):695–699, 2005.

[335] U. nations department for economic and social affairs. *World economic situation and prospects 2020*. UN, 2020.

[336] D. C. Nieman and L. M. Wentz. The compelling link between physical activity and the body's defense system. *Journal of sport and health science*, 8(3):201–217, 2019.

[337] J.-P. Noel, M. De Niear, E. Van der Burg, and M. T. Wallace. Audiovisual simultaneity judgment and rapid recalibration throughout the lifespan. *PloS one*, 11(8): e0161698, 2016.

[338] B. Odegaard and L. Shams. The brain's tendency to bind audiovisual signals is stable but not general. *Psychological science*, 27(4):583–591, 2016.

[339] Y. Oh and S. Yang. Defining exergames & exergaming. *Proceedings of meaningful play*, 2010:21–23, 2010.

[340] F. I. F. on Aging-Related Statistics (US). Older americans 2008: Key indicators of well-being. In *Older Americans 2008: Key Indicators of Well-Being*. Federal Interagency Forum on Aging Related Statistics, 2008.

[341] G. Optale, C. Urgesi, V. Busato, S. Marin, L. Piron, K. Priftis, L. Gamberini, S. Capodieci, and A. Bordin. Controlling memory impairment in elderly adults using virtual reality memory training: a randomized controlled pilot study. *Neurorehabilitation and neural repair*, 24(4):348–357, 2010.

[342] W. H. Organization. Ageing and health described by the who, 2018. URL `https://www.who.int/news-room/fact-sheets/detail/ageing-and-health`.

[343] W. H. Organization. Vision impairment including blindness, 2021. URL `https://icd.who.int/browse11/l-m/en#/http://id.who.int/icd/entity/1103667651`.

[344] W. H. Organization. Deafness and hearing loss defined by the who, 2021. URL `https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss`.

[345] W. H. Organization. Blindness and visual impairment as defined by the who, 2021. URL `https://www.who.int/fr/news-room/fact-sheets/detail/blindness-and-visual-impairment`.

[346] W. H. Organization et al. Integrated care for older people: guidelines on community-level interventions to manage declines in intrinsic capacity. *World Health Organization*, 2017. URL `https://apps.who.int/iris/handle/10665/258981`.

[347] orld Health Organization. Physical activity definition by the who, 2020. URL `https://www.who.int/news-room/fact-sheets/detail/physical-activity`.

[348] T. U. Otto. Rse-box: an analysis and modelling package to study response times to multiple signals. *The Quantitative Methods for Psychology*, 2019.

[349] T. U. Otto and P. Mamassian. Noise and correlations in parallel perceptual decision making. *Current Biology*, 22(15):1391–1396, 2012.

[350] T. U. Otto and P. Mamassian. Multisensory decisions: the test of a race model, its logic, and power. *Multisensory Research*, 30(1):1–24, 2017.

[351] J. O'Brien, G. Ottoboni, A. Tessari, and A. Setti. One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise. *PloS one*, 12(6):e0178739, 2017.

[352] J. O'Brien, G. Ottoboni, A. Tessari, and A. Setti. Multisensory perception, verbal, visuo-spatial and motor working memory modulation after a single open-or closed-skill exercise session in children. *Journal of Cognitive Enhancement*, 5(2):141–154, 2021.

[353] J. M. O'Brien, J. S. Chan, and A. Setti. Audio-visual training in older adults: 2-interval-forced choice task improves performance. *Frontiers in neuroscience*, 14, 2020.

[354] C. O'Donovan, E. Hirsch, E. Holohan, I. McBride, R. McManus, and J. Hussey. Energy expended playing xbox kinect™ and wii™ games: a preliminary study comparing single and multiplayer modes. *Physiotherapy*, 98(3):224–229, 2012.

[355] T. M. O'Neil-Pirozzi, G. Cattaneo, J. Solana-Sánchez, J. Gomes-Osman, and A. Pascual-Leone. The importance of motivation to older adult physical and cognitive exercise program development, initiation, and adherence. *Frontiers in Aging*, page 1, 2022.

[356] M. Page, J. McKenzie, P. Bossuyt, I. Boutron, T. Hoffmann, C. Mulrow, et al. The prisma 2020 statement: an updated guideline for reporting systematic reviews. metaarxiv. 2020, 2020.

[357] R. Pagliari and L. Peyrin. Norepinephrine release in the rat frontal cortex under treadmill exercise: a study with microdialysis. *Journal of Applied Physiology*, 78(6): 2121–2130, 1995.

[358] R. Pagliari and L. Peyrin. Physical conditioning in rats influences the central and peripheral catecholamine responses to sustained exercise. *European journal of applied physiology and occupational physiology*, 71(1):41–52, 1995.

[359] C. V. Parise, C. Spence, and M. O. Ernst. When correlation implies causation in multisensory integration. *Current Biology*, 22(1):46–49, 2012.

[360] Y.-M. Park, J. A. Kanaley, J. Padilla, T. Zidon, R. J. Welly, M. J. Will, S. L. Britton, L. G. Koch, G. N. Ruegsegger, F. W. Booth, et al. Effects of intrinsic aerobic capacity and ovariectomy on voluntary wheel running and nucleus accumbens dopamine receptor gene expression. *Physiology & behavior*, 164:383–389, 2016.

[361] A. M. Peiffer, J. L. Mozolic, C. E. Hugenschmidt, and P. J. Laurienti. Age-related multisensory enhancement in a simple audiovisual detection task. *Neuroreport*, 18 (10):1077–1081, 2007.

[362] P. H. Pelicioni and S. R. Lord. Covid-19 will severely impact older people's lives, and in many more ways than you think! *Brazilian journal of physical therapy*, 2020.

[363] M. Perrone-Bertolotti, J. Kujala, J. R. Vidal, C. M. Hamame, T. Ossandon, O. Bertrand, L. Minotti, P. Kahane, K. Jerbi, and J.-P. Lachaux. How silent is silent reading? intracerebral evidence for top-down activation of temporal voice areas during reading. *Journal of Neuroscience*, 32(49):17554–17562, 2012.

[364] L. S. Pescatello, D. Riebe, and P. D. Thompson. *ACSM's guidelines for exercise testing and prescription.* Lippincott Williams & Wilkins, 2014.

[365] G. Pezzulo, F. Rigoli, and K. J. Friston. Hierarchical active inference: a theory of motivated control. *Trends in cognitive sciences*, 22(4):294–306, 2018.

[366] J. A. Phipps, T. M. Dang, A. J. Vingrys, and R. H. Guymer. Flicker perimetry losses in age-related macular degeneration. *Investigative ophthalmology & visual science*, 45(9):3355–3360, 2004.

[367] B. J. Pitts and N. Sarter. What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues. *Human factors*, 60(4):445–464, 2018.

[368] T. G. Plante, A. Aldridge, R. Bogden, and C. Hanelin. Might virtual reality promote the mood benefits of exercise? *Computers in Human Behavior*, 19(4):495–509, 2003.

[369] L. J. Podewils, E. Guallar, L. H. Kuller, L. P. Fried, O. L. Lopez, M. Carlson, and C. G. Lyketsos. Physical activity, apoe genotype, and dementia risk: findings from the cardiovascular health cognition study. *American journal of epidemiology*, 161(7): 639–651, 2005.

[370] E. Poliakoff, D. Shore, C. Lowe, and C. Spence. Visuotactile temporal order judgments in ageing. *Neuroscience letters*, 396(3):207–211, 2006.

[371] M. B. Pontifex, A. L. McGowan, M. C. Chandler, K. L. Gwizdala, A. C. Parks, K. Fenn, and K. Kamijo. A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise*, 40:1–22, 2019.

[372] E. C. Porges, A. J. Woods, R. A. Edden, N. A. Puts, A. D. Harris, H. Chen, A. M. Garcia, T. R. Seider, D. G. Lamb, J. B. Williamson, et al. Frontal gamma-aminobutyric acid concentrations are associated with cognitive performance in older adults. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, 2(1):38–44, 2017.

[373] E. C. Porges, G. Jensen, B. Foster, R. A. Edden, and N. A. Puts. The trajectory of cortical gaba across the lifespan, an individual participant data meta-analysis of edited mrs studies. *Elife*, 10:e62575, 2021.

[374] F. H. Porto, E. S. Tusch, A. M. Fox, B. R. Alperin, P. J. Holcomb, and K. R. Daffner. One of the most well-established age-related changes in neural activity disappears after controlling for visual acuity. *NeuroImage*, 130:115–122, 2016.

[375] A. R. Powers, A. R. Hillock, and M. T. Wallace. Perceptual training narrows the temporal window of multisensory binding. *Journal of Neuroscience*, 29(39):12265–12274, 2009.

[376] A. R. Powers, M. A. Hevey, and M. T. Wallace. Neural correlates of multisensory perceptual learning. *Journal of Neuroscience*, 32(18):6263–6274, 2012.

[377] A. R. Powers III, A. Hillock-Dunn, and M. T. Wallace. Generalization of multisensory perceptual learning. *Scientific reports*, 6(1):1–9, 2016.

[378] S. Puschmann, P. Sandmann, A. Bendixen, and C. M. Thiel. Age-related hearing loss increases cross-modal distractibility. *Hearing research*, 316:28–36, 2014.

[379] D. H. Raab. Division of psychology: Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, 24(5 Series II):574–590, 1962.

[380] D. Rahnev, A. Koizumi, L. Y. McCurdy, M. D'Esposito, and H. Lau. Confidence leak in perceptual decision making. *Psychological science*, 26(11):1664–1680, 2015.

[381] R. Ramkhalawansingh, B. Keshavarz, B. Haycock, S. Shahab, and J. L. Campos. Age differences in visual-auditory self-motion perception during a simulated driving task. *Frontiers in psychology*, 7:595, 2016.

[382] P. R. Rapp and W. C. Heindel. Memory systems in normal and pathological aging. *Current opinion in neurology*, 7(4):294–298, 1994.

[383] N. Raz, U. Lindenberger, K. M. Rodrigue, K. M. Kennedy, D. Head, A. Williamson, C. Dahle, D. Gerstorf, and J. D. Acker. Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cerebral cortex*, 15(11): 1676–1689, 2005.

[384] M. Reiner, C. Niermann, D. Jekauc, and A. Woll. Long-term health benefits of physical activity–a systematic review of longitudinal studies. *BMC public health*, 13 (1):1–9, 2013.

[385] Y. Ren, W. Yang, Q. Wu, F. Wu, S. Takahashi, E. Yoshimichi, and J. Wu. Study of audiovisual asynchrony signal processing: Robot recognition system of different ages. In *2016 IEEE International Conference on Mechatronics and Automation*, pages 2320–2325. IEEE, 2016.

[386] Y. Ren, W. Yang, K. Nakahashi, S. Takahashi, and J. Wu. Audiovisual integration delayed by stimulus onset asynchrony between auditory and visual stimuli in older adults. *Perception*, 46(2):205–218, 2017.

[387] Y. Ren, Y. Ren, W. Yang, X. Tang, F. Wu, Q. Wu, S. Takahashi, Y. Ejima, and J. Wu. Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration. *International Journal of Psychophysiology*, 124: 1–11, 2018.

[388] Y.-N. Ren, W. Yang, S. Takahashi, K. Nakahashi, and J. Wu. Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention. In *2015 IEEE International Conference on Mechatronics and Automation (ICMA)*, pages 511–516. IEEE, 2015.

[389] P. A. G. Resources. Trending topic: Physical activity guidelines, 2022. URL `https://www.acsm.org/read-research/trending-topics-resource-pages/physical-activity-guidelines#:~:text=ACSMandCDCrecommendationsstate,onthreedaysperweek`.

[390] I. Rhyu, J. Boklewski, B. Ferguson, K. Lee, H. Lange, J. Bytheway, J. Lamb, K. McCormick, N. Williams, J. Cameron, et al. Exercise training associated with increased cortical vascularization in adult female cynomologus monkeys. In *Abstr Soc Neurosci*, volume 920, 2003.

[391] D. Rizzolo, G. P. Zipp, D. Stiskal, S. Simpkins, et al. Stress management strategies for students: The immediate effects of yoga, humor, and reading on stress. *Journal of College Teaching & Learning (TLC)*, 6(8), 2009.

[392] K. S. Rockland and H. Ojima. Multisensory convergence in calcarine visual areas in macaque monkey. *International Journal of Psychophysiology*, 50(1-2):19–26, 2003.

[393] L. A. Ross, D. Saint-Amour, V. M. Leavitt, D. C. Javitt, and J. J. Foxe. Do you see what i am saying? exploring visual enhancement of speech comprehension in noisy environments. *Cerebral cortex*, 17(5):1147–1153, 2007.

[394] E. Roudaia, A. B. Sekuler, P. J. Bennett, and R. W. Sekuler. Aging and audio-visual and multi-cue integration in motion. *Frontiers in psychology*, 4:267, 2013.

[395] E. Roudaia, F. J. Calabro, L. M. Vaina, and F. N. Newell. Aging impairs audiovisual facilitation of object motion within self-motion. *Multisensory research*, 31(3-4):251–272, 2018.

[396] J. Roufs. Dynamic properties of vision—v: Perception lag and reaction time in relation to flicker and flash thresholds. *Vision research*, 14(9):853–869, 1974.

[397] M. R. Rueda, M. K. Rothbart, B. D. McCandliss, L. Saccomanno, and M. I. Posner. Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences*, 102(41):14931–14936, 2005.

[398] J. Rutschmann and R. Link. Perception of temporal order of stimuli differing in sense mode and simple reaction time. *Perceptual and Motor Skills*, 18(2):345–352, 1964.

[399] J. S Chan, J. Kaiser, M. Brandl, S. Matura, D. Prvulovic, M. J Hogan, and M. J Naumer. Expanded temporal binding windows in people with mild cognitive impairment. *Current Alzheimer Research*, 12(1):61–68, 2015.

[400] T. A. Salthouse. The processing-speed theory of adult age differences in cognition. *Psychological review*, 103(3):403, 1996.

[401] T. A. Salthouse, H. E. Hancock, E. J. Meinz, and D. Z. Hambrick. Interrelations of age, visual acuity, and cognitive functioning. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 51(6):P317–330, 1996.

[402] T. A. Salthouse, D. Z. Hambrick, and K. E. McGuthry. Shared age-related influences on cognitive and noncognitive variables. *Psychology and Aging*, 13(3):486, 1998.

[403] A. Sanders. Towards a model of stress and human performance. *Acta psychologica*, 53(1):61–97, 1983.

[404] M. C. Sanders, N.-Y. N. Chang, M. M. Hiss, R. M. Uchanski, and T. E. Hullar. Temporal binding of auditory and rotational stimuli. *Experimental brain research*, 210(3):539–547, 2011.

[405] B. M. Sandroff, R. W. Motl, W. R. Reed, A. K. Barbey, R. H. Benedict, and J. DeLuca. Integrative cns plasticity with exercise in ms: the primers (processing, integration of multisensory exercise-related stimuli) conceptual framework. *Neurorehabilitation and neural repair*, 32(10):847–862, 2018.

[406] A. Sanford. Effects of changes in the intensity of white noise on simultaneity judgements and simple reaction time. *The Quarterly Journal of Experimental Psychology*, 23(3):296–303, 1971.

[407] A. Sanford. Attention bias and the relation of perception lag to simple reaction time. *Journal of Experimental Psychology*, 102(3):443, 1974.

[408] A. Schlack, S. J. Sterbing-D'Angelo, K. Hartung, K.-P. Hoffmann, and F. Bremmer. Multisensory space representations in the macaque ventral intraparietal area. *Journal of Neuroscience*, 25(18):4616–4625, 2005.

[409] C. E. Schroeder and J. Foxe. Multisensory contributions to low-level,'unisensory'processing. *Current opinion in neurobiology*, 15(4):454–458, 2005.

[410] C. E. Schroeder, A. D. Mehta, and S. J. Givre. A spatiotemporal profile of visual system activation revealed by current source density analysis in the awake macaque. *Cerebral cortex (New York, NY: 1991)*, 8(7):575–592, 1998.

[411] D. H. Schunk and M. K. DiBenedetto. Motivation and social cognitive theory. *Contemporary Educational Psychology*, 60:101832, 2020.

[412] G. Segovia, A. Porras, A. Del Arco, and F. Mora. Glutamatergic neurotransmission in aging: a critical perspective. *Mechanisms of ageing and development*, 122(1):1–29, 2001.

[413] K. Sekiyama, T. Soshi, and S. Sakamoto. Enhanced audiovisual integration with aging in speech perception: a heightened mcgurk effect in older adults. *Frontiers in Psychology*, 5:323, 2014.

[414] R. Sekuler, S. N. Watamaniuk, and R. Blake. Motion perception. *Stevens' Handbook of Experimental Psychology*, 2002.

[415] A. Setti, K. E. Burke, R. A. Kenny, and F. N. Newell. Is inefficient multisensory processing associated with falls in older people? *Experimental brain research*, 209 (3):375–384, 2011.

[416] A. Setti, S. Finnigan, R. Sobolewski, L. McLaren, I. H. Robertson, R. B. Reilly, R. A. Kenny, and F. N. Newell. Audiovisual temporal discrimination is less efficient with aging: an event-related potential study. *Neuroreport*, 22(11):554–558, 2011.

[417] A. Setti, K. E. Burke, R. A. Kenny, and F. N. Newell. Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes. *Frontiers in psychology*, 4:575, 2013.

[418] A. Setti, J. Stapleton, D. Leahy, C. Walsh, R. A. Kenny, and F. N. Newell. Improving the efficiency of multisensory integration in older adults: audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion. *Neuropsychologia*, 61:259–268, 2014.

[419] C. E. Sexton, J. F. Betts, N. Demnitz, H. Dawes, K. P. Ebmeier, and H. Johansen-Berg. A systematic review of mri studies examining the relationship between physical fitness and activity and the white matter of the ageing brain. *Neuroimage*, 131:81–90, 2016.

[420] L. Shams, Y. Kamitani, and S. Shimojo. What you see is what you hear. *Nature*, 408(6814):788–788, 2000.

[421] L. Shams, Y. Kamitani, and S. Shimojo. Visual illusion induced by sound. *Cognitive Brain Research*, 14(1):147–152, 2002.

[422] L. Shams, W. J. Ma, and U. Beierholm. Sound-induced flash illusion as an optimal percept. *Neuroreport*, 16(17):1923–1927, 2005.

[423] T. T. Shigeta, T. P. Morris, D. H. Henry, A. Kucyi, P. Bex, A. F. Kramer, and C. H. Hillman. Acute exercise effects on inhibitory control and the pupillary response in young adults. *International Journal of Psychophysiology*, 170:218–228, 2021.

[424] B. A. Sibley and J. L. Etnier. The relationship between physical activity and cognition in children: a meta-analysis. *Pediatric exercise science*, 15(3):243–256, 2003.

[425] S. Sinnett, S. Soto-Faraco, and C. Spence. The co-occurrence of multisensory competition and facilitation. *Acta psychologica*, 128(1):153–161, 2008.

[426] G. S. Siqueira, P. d. M. Hagemann, D. d. S. Coelho, F. H. D. Santos, and P. H. Bertolucci. Can moca and mmse be interchangeable cognitive screening tools? a systematic review. *The Gerontologist*, 59(6):e743–e763, 2019.

[427] N. Skjæret, A. Nawaz, T. Morat, D. Schoene, J. L. Helbostad, and B. Vereijken. Exercise and rehabilitation delivered through exergames in older adults: An integrative review of technologies, safety and efficacy. *International journal of medical informatics*, 85(1):1–16, 2016.

[428] M. S. Sommers, N. Tye-Murray, and B. Spehar. Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults. *Ear and hearing*, 26(3):263–275, 2005.

[429] W. E. Sonntag, C. D. Lynch, P. T. Cooney, and P. M. Hutchins. Decreases in cerebral microvasculature with age are associated with the decline in growth hormone and insulin-like growth factor 1. *Endocrinology*, 138(8):3515–3520, 1997.

[430] W. Sparrow, E. J. Bradshaw, E. Lamoureux, and O. Tirosh. Ageing effects on the attention demands of walking. *Human movement science*, 21(5-6):961–972, 2002.

[431] P. D. Spear. Neural bases of visual deficits during aging. *Vision research*, 33(18): 2589–2609, 1993.

[432] B. P. Spehar, N. Tye-Murray, and M. S. Sommers. Intra-versus intermodal integration in young and older adults. *The Journal of the Acoustical Society of America*, 123(5): 2858–2866, 2008.

[433] C. Spence. Crossmodal spatial attention. *Annals of the New York Academy of Sciences*, 1191(1):182–200, 2010.

[434] C. Spence and V. Santangelo. Capturing spatial attention with multisensory cues: A review. *Hearing research*, 258(1-2):134–142, 2009.

[435] C. Spence and S. Squire. Multisensory integration: maintaining the perception of synchrony. *Current Biology*, 13(13):R519–R521, 2003.

[436] W. W. Spirduso, L. W. Poon, and W. E. Chodzko-Zajko. Exercise and its mediating effects on cognition. In *Advanced Research Workshop, Jun, 2003, Austin Lakeway Inn and Resort, Austin, TX, US*. Human Kinetics, 2008.

[437] M. Stawicki, P. Majdak, and D. Başkent. Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals. *Multisensory research*, 32(8):745–770, 2019.

[438] R. Steele and K. Linsley. Relieving in-patient boredom in general hospitals: the evidence for intervention and practical ideas. *BJPsych Advances*, 21(1):63–70, 2015.

[439] B. E. Stein and M. A. Meredith. The merging of the senses. In *Multisensory Integration: The Merging of the Senses*. The MIT Press, 1993.

[440] B. E. Stein and T. R. Stanford. Multisensory integration: current issues from the perspective of the single neuron. *Nature Reviews Neuroscience*, 9(4):255–266, 2008.

[441] B. E. Stein, B. Magalhães-Castro, and L. Kruger. Superior colliculus: visuotopic-somatotopic overlap. *Science*, 189(4198):224–226, 1975.

[442] B. E. Stein, W. S. Huneycutt, and M. A. Meredith. Neurons and behavior: the same rules of multisensory integration apply. *Brain research*, 448(2):355–358, 1988.

[443] B. E. Stein, T. R. Stanford, and B. A. Rowland. The neural basis of multisensory integration in the midbrain: its organization and maturation. *Hearing research*, 258 (1-2):4–15, 2009.

[444] B. E. Stein, T. R. Stanford, and B. A. Rowland. Development of multisensory integration from the perspective of the individual neuron. *Nature Reviews Neuroscience*, 15(8):520–535, 2014.

[445] S. Sternberg, R. L. Knoll, et al. The perception of temporal order: Fundamental issues and a general model. *Attention and performance IV*, pages 629–685, 1973.

[446] R. A. Stevenson, M. M. Wilson, A. R. Powers, and M. T. Wallace. The effects of visual training on multisensory temporal processing. *Experimental brain research*, 225(4):479–489, 2013.

[447] R. A. Stevenson, M. Segers, S. Ferber, M. D. Barense, S. Camarata, and M. T. Wallace. Keeping time in the brain: Autism spectrum disorder and audiovisual temporal processing. *Autism Research*, 9(7):720–738, 2016.

[448] R. A. Stevenson, S. H. Baum, J. Krueger, P. A. Newhouse, and M. T. Wallace. Links between temporal acuity and multisensory integration across life span. *Journal of Experimental Psychology: Human Perception and Performance*, 44(1):106, 2018.

[449] R. Stojan and C. Voelcker-Rehage. A systematic review on the cognitive benefits and neurophysiological correlates of exergaming in healthy older adults. *Journal of clinical medicine*, 8(5):734, 2019.

[450] M. Stones and D. Dawe. Acute exercise facilitates semantically cued memory in nursing home residents. *Journal of the American Geriatrics Society*, 41(5):531–534, 1993.

[451] G. Stothart and N. Kazanina. Auditory perception in the aging brain: the role of inhibition and facilitation in early processing. *Neurobiology of aging*, 47:23–34, 2016.

[452] W. Stummer, K. Weber, B. Tranmer, A. Baethmann, and O. Kempski. Reduced mortality and brain damage after locomotor activity in gerbil forebrain ischemia. *Stroke*, 25(9):1862–1869, 1994.

[453] W. H. Sumby and I. Pollack. Visual contribution to speech intelligibility in noise. *The journal of the acoustical society of america*, 26(2):212–215, 1954.

[454] Y. Sun, X. Liu, B. Li, C. Sava-Segal, A. Wang, and M. Zhang. Effects of repetition suppression on sound induced flash illusion with aging. *Frontiers in psychology*, 11: 216, 2020.

[455] J. Szudek, A. Ostevik, P. Dziegielewski, J. Robinson-Anagor, N. Gomaa, B. Hodgetts, A. Ho, C. Mathers, A. Smith, M. Concha, et al. Can uhear me now? validation of an ipod-based hearing loss screening test. *Journal of Otolaryngology-Head and Neck Surgery*, 41(1):S78, 2012.

[456] R. Taitelbaum-Swead and L. Fostick. Auditory and visual information in speech perception: A developmental perspective. *Clinical linguistics & phonetics*, 30(7): 531–545, 2016.

[457] H. Takayama, N. Ogawa, M. Yamamoto, M. Asanuma, H. Hirata, and Z. Ota. Age-related changes in cerebrospinal fluid γ-aminobutyric acid concentration. *Clinical Chemistry and Laboratory Medicine*, 30(5):271–274, 1992.

[458] D. Talsma, A. Kok, and K. R. Ridderinkhof. Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: effects on event-related brain potentials and performance data. *International Journal of Psychophysiology*, 62(2): 249–261, 2006.

[459] D. Taylor. Physical activity is medicine for older adults. *Postgraduate medical journal*, 90(1059):26–32, 2014.

[460] L. M. Taylor, R. Maddison, L. A. Pfaeffli, J. C. Rawstorn, N. Gant, and N. M. Kerse. Activity and energy expenditure in older people playing active video games. *Archives of physical medicine and rehabilitation*, 93(12):2281–2286, 2012.

[461] H.-L. Teuber. Alterations of perception after brain injury. In *Brain and conscious experience*, pages 182–216. Springer, 1965.

[462] L. Thaler, A. C. Schütz, M. A. Goodale, and K. R. Gegenfurtner. What is the best fixation target? the effect of target shape on stability of fixational eye movements. *Vision research*, 76:31–42, 2013.

[463] J. W. Todd. *Reaction to multiple stimuli.* New era printing Company, 1912.

[464] T. N. Tombaugh and N. J. McIntyre. The mini-mental state examination: a comprehensive review. *Journal of the American Geriatrics Society*, 40(9):922–935, 1992.

[465] P. Toril, J. M. Reales, and S. Ballesteros. Video game training enhances cognition of older adults: a meta-analytic study. *Psychology and aging*, 29(3):706, 2014.

[466] A. Treisman. Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 353(1373): 1295–1306, 1998.

[467] S. G. Trost, R. R. Pate, J. F. Sallis, P. S. Freedson, W. C. Taylor, M. Dowda, J. Sirard, et al. Age and gender differences in objectively measured physical activity in youth. *Medicine and science in sports and exercise*, 34(2):350–355, 2002.

[468] N. Tye-Murray, M. Sommers, and B. Spehar. Auditory and visual lexical neighborhoods in audiovisual speech perception. *Trends in Amplification*, 11(4):233–241, 2007.

[469] N. Tye-Murray, M. Sommers, B. Spehar, J. Myerson, and S. Hale. Aging, audiovisual integration, and the principle of inverse effectiveness. *Ear and hearing*, 31(5):636, 2010.

[470] N. Tye-Murray, B. Spehar, J. Myerson, M. S. Sommers, and S. Hale. Crossmodal enhancement of speech detection in young and older adults: Does signal content matter? *Ear and hearing*, 32(5):650, 2011.

[471] N. Tye-Murray, B. Spehar, J. Myerson, S. Hale, and M. Sommers. Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration. *Psychology and aging*, 31(4):380, 2016.

[472] R. Ulrich, G. Rinkenauer, and J. Miller. Effects of stimulus duration and intensity on simple reaction time and response force. *Journal of Experimental Psychology: Human Perception and Performance*, 24(3):915, 1998.

[473] R. L. Van Eijk, A. Kohlrausch, J. F. Juola, and S. van de Par. Audiovisual synchrony and temporal order judgments: effects of experimental method and stimulus type. *Perception & psychophysics*, 70(6):955–968, 2008.

[474] H. Van Praag. Neurogenesis and exercise: past and future directions. *Neuromolecular medicine*, 10(2):128–140, 2008.

[475] H. Van Praag, B. R. Christie, T. J. Sejnowski, and F. H. Gage. Running enhances neurogenesis, learning, and long-term potentiation in mice. *Proceedings of the National Academy of Sciences*, 96(23):13427–13431, 1999.

[476] A. Vatakis, J. Navarra, S. Soto-Faraco, and C. Spence. Audiovisual temporal adaptation of speech: temporal order versus simultaneity judgments. *Experimental brain research*, 185(3):521–529, 2008.

[477] S. Vaynman, Z. Ying, and F. Gomez-Pinilla. Hippocampal bdnf mediates the efficacy of exercise on synaptic plasticity and cognition. *European Journal of neuroscience*, 20(10):2580–2590, 2004.

[478] P. Verhaeghen and T. A. Salthouse. Meta-analyses of age–cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological bulletin*, 122(3):231, 1997.

[479] L. Verheijden Klompstra, T. Jaarsma, and A. Strömberg. Exergaming in older adults: a scoping review and implementation potential for patients with heart failure. *European Journal of Cardiovascular Nursing*, 13(5):388–398, 2014.

[480] E. D. Vidoni, D. K. Johnson, J. K. Morris, A. Van Sciver, C. S. Greer, S. A. Billinger, J. E. Donnelly, and J. M. Burns. Dose-response of aerobic exercise on cognition: a community-based, pilot randomized controlled trial. *PloS one*, 10(7):e0131647, 2015.

[481] V. Virsu, P. Lahti-Nuuttila, and M. Laasonen. Crossmodal temporal processing acuity impairment aggravates with age in developmental dyslexia. *Neuroscience letters*, 336(3):151–154, 2003.

[482] M. W. Voss, K. I. Erickson, R. S. Prakash, L. Chaddock, J. S. Kim, H. Alves, A. Szabo, S. M. Phillips, T. R. Wójcicki, E. L. Mailey, et al. Neurobiological markers of exercise-related brain plasticity in older adults. *Brain, behavior, and immunity*, 28:90–99, 2013.

[483] J. Vroomen and M. Keetels. Perception of intersensory synchrony: a tutorial review. *Attention, Perception, & Psychophysics*, 72(4):871–884, 2010.

[484] E.-J. Wagenmakers. A practical solution to the pervasive problems of p values. *Psychonomic bulletin & review*, 14(5):779–804, 2007.

[485] M. T. Wallace, L. K. Wilkinson, and B. E. Stein. Representation and integration of multiple sensory inputs in primate superior colliculus. *Journal of neurophysiology*, 76(2):1246–1266, 1996.

[486] M. T. Wallace, G. Roberson, W. D. Hairston, B. E. Stein, J. W. Vaughan, and J. A. Schirillo. Unifying multisensory signals across time and space. *Experimental Brain Research*, 158(2):252–258, 2004.

[487] A. Walling and G. Dickson. Hearing loss in older adults. *American family physician*, 85(12):1150–1156, 2012.

[488] B. Wang, P. Li, D. Li, Y. Niu, T. Yan, T. Li, R. Cao, P. Yan, Y. Guo, W. Yang, et al. Increased functional brain network efficiency during audiovisual temporal asynchrony integration task in aging. *Frontiers in aging neuroscience*, 10:316, 2018.

[489] L. Wang, W. Wang, T. Yan, J. Song, W. Yang, B. Wang, R. Go, Q. Huang, and J. Wu. Beta-band functional connectivity influences audiovisual integration in older age: an eeg study. *Frontiers in aging neuroscience*, 9:239, 2017.

[490] F. Waszak and A. Gorea. A new look at the relationship between perceptual and motor responses. *Visual Cognition*, 11(8):947–963, 2004.

[491] J. Weuve, J. H. Kang, J. E. Manson, M. M. Breteler, J. H. Ware, and F. Grodstein. Physical activity, including walking, and cognitive function in older women. *Jama*, 292(12):1454–1461, 2004.

[492] A. H. Winneke and N. A. Phillips. Does audiovisual speech offer a fountain of youth for old ears? an event-related brain potential study of age differences in audiovisual speech perception. *Psychology and aging*, 26(2):427, 2011.

[493] A. Wise and M. Barnett-Cowan. Perceived simultaneity and temporal order of audiovisual events following concussion. *Frontiers in human neuroscience*, 12:139, 2018.

[494] J. M. Wood. Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human factors*, 44(3):482–494, 2002.

[495] R. Y. Wood, K. K. Giuliano, C. U. Bignell, and W. W. Pritham. Assessing cognitive ability in research: use of mmse with minority populations and elderly adults with low education levels. *Journal of Gerontological Nursing*, 32(4):45–54, 2006.

[496] J. Wu, J. Yang, Y. Yu, Q. Li, N. Nakamura, Y. Shen, Y. Ohta, S. Yu, and K. Abe. Delayed audiovisual integration of patients with mild cognitive impairment and alzheimer's disease compared with normal aged controls. *Journal of Alzheimer's Disease*, 32(2):317–328, 2012.

[497] J. Wu, W. Yang, Y. Gao, and T. Kimura. Age-related multisensory integration elicited by peripherally presented audiovisual stimuli. *Neuroreport*, 23(10):616–620, 2012.

[498] K. Yaffe, D. Barnes, M. Nevitt, L.-Y. Lui, and K. Covinsky. A prospective study of physical activity and cognitive decline in elderly women: women who walk. *Archives of internal medicine*, 161(14):1703–1708, 2001.

[499] H. Yanagisawa, I. Dan, D. Tsuzuki, M. Kato, M. Okamoto, Y. Kyutoku, and H. Soya. Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with stroop test. *Neuroimage*, 50(4):1702–1710, 2010.

[500] W. Yang, A. Guo, Y. Li, J. Qiu, S. Li, S. Yin, J. Chen, and Y. Ren. Audio-visual spatiotemporal perceptual training enhances the p300 component in healthy older adults. *Frontiers in psychology*, 9:2537, 2018.

[501] B. Yao, P. Belin, and C. Scheepers. Silent reading of direct versus indirect speech activates voice-selective areas in the auditory cortex. *Journal of cognitive neuroscience*, 23(10):3146–3152, 2011.

[502] H.-Y. Yen and H.-L. Chiu. Virtual reality exergames for improving older adults' cognition and depression: A systematic review and meta-analysis of randomized control trials. *Journal of the American Medical Directors Association*, 2021.

[503] Y. Yi and D. M. Merfeld. A quantitative confidence signal detection model: 1. fitting psychometric functions. *Journal of Neurophysiology*, 115(4):1932–1945, 2016.

[504] G. Yogev-Seligmann, N. Giladi, L. Gruendlinger, and J. M. Hausdorff. The contribution of postural control and bilateral coordination to the impact of dual tasking on gait. *Experimental brain research*, 226(1):81–93, 2013.

[505] D. Young, P. A. Lawlor, P. Leone, M. Dragunow, and M. J. During. Environmental enrichment inhibits spontaneous apoptosis, prevents seizures and is neuroprotective. *Nature medicine*, 5(4):448–453, 1999.

[506] B. Yueh, N. Shapiro, C. H. MacLean, and P. G. Shekelle. Screening and management of adult hearing loss in primary care: scientific review. *Jama*, 289(15):1976–1985, 2003.

[507] L. Zając-Lamparska, M. Wiłkość-Dębczyńska, A. Wojciechowski, M. Podhorecka, A. Polak-Szabela, Ł. Warchoł, K. Kędziora-Kornatowska, A. Araszkiewicz, and P. Izdebski. Effects of virtual reality-based cognitive training in older adults living without and with mild dementia: A pretest–posttest design pilot study. *BMC research notes*, 12(1):1–8, 2019.

[508] M. Zampini, D. I. Shore, and C. Spence. Multisensory temporal order judgments: the role of hemispheric redundancy. *International Journal of Psychophysiology*, 50 (1-2):165–180, 2003.

[509] M. Zampini, S. Guest, D. I. Shore, and C. Spence. Audio-visual simultaneity judgments. *Perception & psychophysics*, 67(3):531–544, 2005.

[510] X. Zheng, S. Takatsu, R. Ishikawa, and H. Hasegawa. Moderate intensity, exercise-induced catecholamine release in the preoptic area and anterior hypothalamus in rats is enhanced in a warm environment. *Journal of thermal biology*, 71:123–127, 2018.

[511] W. Zhu. Should, and how can, exercise be done during a coronavirus outbreak? an interview with dr. jeffrey a. woods. *Journal of sport and health science*, 9(2):105, 2020.

[512] X. Zhu, S. Yin, M. Lang, R. He, and J. Li. The more the better? a meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults. *Ageing Research Reviews*, 31:67–79, 2016.

[513] Z. Zou, B. K. Chau, K.-H. Ting, and C. C. Chan. Aging effect on audiovisual integrative processing in spatial discrimination task. *Frontiers in aging neuroscience*, 9:374, 2017.

Appendix A

Supplementary Scoping Review Tables

A.1 Tables

The tables listed below are supplementary to the ones provided in chapter 5.

Table 1: Classification of the severity of visual impairment

Table A.1: This table provides information regarding the classification of the severity of vision impairment based on the definition provide by the International Classification of Disease 11th Revision (ICD-11) for Mortality and Morbidity Statistics (WHO, 2018b).

Category	**Worse than:**	**Equal to or better than:**
No vision impairment		6/12; 5/10 (0.5); 20/40; LogMAR: 0.30
Mild vision impairment	6/12; 5/10 (0.5); 20/40; LogMAR: 0.30	6/18; 3/10 (0.3); 20/70; LogMAR: 0.50
Moderate vision impairment	6/18; 3/10 (0.3); 20/70; LogMAR: 0.50	6/60; 1/10 (0.1); 20/200; LogMAR: 1.00
Severe vision impairment	6/60; 1/10 (0.1); 20/200; LogMAR: 1.00	3/60; 1/20 (0.05); 20/400; LogMAR: 1.30
Blindness	3/60; 1/20 (0.05); 20/400; LogMAR: 1.30	1/60; 1/50 (0.02); 5/300 (20/1200); LogMAR: 1.80; or counts fingers (CF) at metre
Blindness	1/60; 1/50 (0.02); 5/300 (20/1200); LogMAR: 1.80	Light perception
Blindness	No light perception	

Table 2: Country of origin of studies included in this scoping review

Table A.2: This table provides details regarding where the studies were produced. Note that the country of origin was determined by the affiliation of the all the authors listed on each manuscript. The percentage is calculated by using the number of studies included in this scoping review. Note, that some studies were produced in collaboration between countries. USA = United States of America, UK = United Kingdom.

Country	**Number of Studies**	**Percentage of sample (%)**
United States of America	24	28.24
Ireland	12	14.12
Canada	10	11.76
China	8	9.41
United Kingdom	7	8.42
Australia	6	7.06
Japan	6	7.06
Spain	5	5.88
Netherlands	3	3.53
France	2	2.35
Switzerland	1	1.18
Israel	1	1.18
Belgium	1	1.18
Germany	1	1.18
Austria	1	1.18
New Zealand	1	1.18
Italy	1	1.18

Table 3: Inclusion scores used for MMSE and MoCA

Title	Location	Aim of study	Task type/behavioural outcomes
Age-related changes in auditory and visual interactions in temporal rate perception [61]	Australia and UK	To compare the effect of rate asynchrony on perceived rate, as well as the effect of rate synchrony on discrimination rate in young and older adults.	Rate asynchrony on perceived rate and on rate discrimination for auditory flutter presented with visual flicker; integration of asynchronous flicker and flutter rates, integration of synchronous flicker and flutter rates.
Age-related differences in inhibitory control predict audiovisual speech perception [125]	USA	To understand the role of cognitive mechanisms in multimodal speech perception and how this process may elucidate the changes in speech perception that accompany the aging process.	Audiovisual speech recall task; percent correct, visual enhancement, error analysis.
Age-related hearing loss increases cross-modal distractibility [378]	Germany	To compare cross-modal distractibility between a group of elderly participants with a moderate symmetrical high-frequency hearing loss and age-matched normal hearing older and young adults.	Cross-modal distraction paradigm; mean response time (RT), error rate, change in mean RT, change in error rate.
Age-related multisensory enhancement in a simple audiovisual detection task [361]	USA	To determine whether older adults show greater multisensory gain than younger adults on a simple response time (RT) task.	Multisensory processing as assessed through simple RT task to suprathreshold auditory, visual, and audiovisual stimuli; mean RT, race model (cumulative probability, probability difference).
Age-related multisensory integration elicited by peripherally presented audiovisual stimuli [497]	Japan	To determine whether multisensory integration of elderly would be delayed or weaker than that of younger adults.	audiovisual discrimination task; hit rate, mean response time (RT), race model [cumulative distribution functions (CDFs)/cumulative difference, probability difference].

Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception [207]	Ireland	To investigate the impact of unisensory function upon multisensory integration in aging. To distinguish the role of acuity, contrast sensitivity, and temporal abilities in both vision and audition on multisensory integration within a large sample size of adults age 50+ to understand how the Sound Induced Flash Illusion (SIFI) is affected by sensory decline. They explored the relationship between SIFI susceptibility and visual gain, age, and visual gain mediated by unisensory measures of vision and audition.	SIFI as a measure of audiovisual integration; susceptibility to the illusion (fewer correct responses).
Ageing effects on the attention demands of walking [430]	Australia and New Zealand	To determine whether normal unobstructed walking has an attention cost and whether the attention demands of walking would vary as a function of the difficulty or 'challenge' posed by the gait task.	Attention demands of walking were determined using an auditory-visual probe response time (RT); mean auditory RT, mean visual RT, mean audiovisual RT.
Aging and audio-visual and multi-cue integration in motion [394]	Canada, Ireland, and USA	To assess age related changes in integration of inter- and intra-modal cues for visual motion and to examine how age affects occlusion's impact on the bi-stable bouncing-steam percept. Further, they aimed determine whiter the differences between young and older adults are due to the reduction in retinal illuminance that accompanies aging.	Investigated age-related changes in the integration of inter- and intra-modal cues using the bounce-stream percept; proportion of bouncing and streaming responses.

Aging Effect on Audiovisual Integrative Processing in Spatial Discrimination Task [513]	Hong Kong	To investigate how aging modulates audiovisual integration, using a spatial discrimination task and through recording Event-Related Potential (ERPs) (specifically P2).	Spatial discrimination task; mean response time (RT), accuracy rate, inverse efficiency score.
Aging Impairs Audiovisual Facilitation of Object Motion Within Self-Motion [395]	Ireland and USA	To determine whether older adults can use dynamic auditory information to enhance the detection of visual object motion in the context of self-motion.	Perception of object motion within self-motion using congruent audiovisual cues compared to visual cues alone; sensitivity (d'), median response time (RT), accuracy (proportion correct).
Aging increases distraction by auditory oddballs in visual, but not auditory tasks [261]	Spain and Australia	To investigate the effect of aging on the ability to ignore distractors (oddball task) as a function of whether distracters and targets are presented in the same (auditory-only) or in different sensory (cross-modal) modalities.	Multimodal (audio-visual) and unimodal (audio-audio) oddball tasks; proportion of correct responses, and mean response time (RT).
Aging, audiovisual integration and the principle of inverse effectiveness [469]	USA	To compare the ability of young and older adults to benefit from audiovisual speech relative unimodal speech.	Speech perception as measured through the Build-a-sentence test and the City University of New York (CUNY) sentence test; mean percentage correct, mean integration enhancement, mean auditory enhancement.
Audio-Visual Spatiotemporal Perceptual Training Enhances the P300 Component in Healthy Older Adults [500]	China	To determine whether audiovisual perceptual training could induce 'far-transfer' effects in other forms of untrained cognitive processing that older adults were not directly trained in.	Audiovisual spatiotemporal training paradigm and an auditory oddball paradigm; mean accuracy.

Audiovisual binding for speech perception in noise and in aging [165]	France	To determine if increased acoustic noise increases the amount of fusion and if increased visual noise would decrease McGurk illusion. Also, to determine if binding evaluates the level of noise within each sensory channel while controlling the weight of each modality in the fusion process.	McGurk effect measured through a syllable monitoring task where participants were asked to monitor for ’ba’ or ’da’ and press a key as rapidly as possible on a keyboard to indicate detection; mean response time (RT), misses, and proportion of ’ba’ responses.
Audiovisual Integration Delayed by Stimulus Onset Asynchrony Between Auditory and Visual Stimuli in Older Adults [386]	Japan	To determine how stimulus onset asynchronies between auditory and visual stimuli modulate audiovisual integration in young and older adults.	audio/visual discrimination task; mean response time (RT), hit rate, and race model violation (cumulative distribution function, difference probability).
Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan [337]	USA	To explore the changes in audiovisual simultaneity judgment, the ability to rapidly recalibrate to multisensory asynchrony, and the relation between them across the lifespan.	Simultaneity judgement task for complex (audiovisual speech) and simple (beep/flash) stimuli; synchrony detection, temporal window of simultaneity (TWS), point of subjective simultaneity (PSS), rapid recalibration of the the TWS and PSS.
Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise [181]	USA	To determine whether older and young adults perform similarly on an audiovisual speech detection task with low or high noise. They also aimed determine whether older adults rely on cognitive resources to process multisensory information.	Audiovisual speech integration and recall examined using McGurk stimuli; mean proportion correct, visual enhancement.

Audiovisual temporal discrimination is less efficient with aging: an event-related potential study [416]	Ireland	To compare cerebral function associated with audiovisual Temporal order judgment (TOJ) processing in young and older adults using event-related potentials (ERPs).	Audiovisual temporal discrimination assessed through the TOJ; mean accuracy.
Auditory and visual information in speech perception: A developmental perspective [456]	Israel	They aimed to test audiovisual speech perception across the life span, while (1) employing a wide range of age groups, (2) using a research paradigm that enables calculation of each modality's contribution to audiovisual integration, (3) studying the developmental effect of context on audiovisual integration, and (4) examining audiovisual speech perception in Hebrew, a language with comparatively limited number of vowels and relatively late development of reading, in order to further understand its specific/universal nature.	Audiovisual speech perception task using meaningful and nonsense words; accuracy rate, auditory and visual enhancement.

Auditory and visual lexical neighbourhoods in audiovisual speech perception [468]	USA	To test three hypotheses: to determine if a word that has few words in the overlapping regions of the audio and visual neighbourhoods will have a greater likelihood of being recognized correctly in the audiovisual condition than a words that has many words, in adverse listening conditions, (2) whether the density of the acoustic and visual lexical neighbourhoods will predict how well words will be recognized in an audiovisual condition, and (3) whether acoustic lexical density will be predictive of auditory performance but not of visual, whereas visual lexical density will be predictive of visual performance but not auditory.	Audiovisual speech perception through the manipulation of lexical neighbourhoods; percent word correct.
Auditory perception in the aging brain: the role of inhibition and facilitation in early processing [451]	UK	To determine whether the patterns of age-related change observed in auditory processing extend to audiovisual speech processing. They examined the influence of ’relevant’ versus ’distracting’ visual info.	Audiovisual speech integration examined using McGurk stimuli; perceiving the illusion and correctly identifying the syllables presented (accuracy).

Auditory-visual speech perception and aging [92]	USA	To assess whether the most significant contribution to audiovisual integration of speech comes from the individual unimodal systems regardless of age or if it's more related to higher-order cognitive function. Further, to determine if integration of auditory and visual speech cues in conflicting conditions (such as those observed in the McGurk effect) is unrelated to lipreading performance regardless of age (or if there is top-down processing in the bimodal perception of speech before phonetic identification).	Integration of place and voicing information using the McGurk effect; percentage of key words correctly identified in all the conditions, percentage of syllables identified.
Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults [428]	USA	To examine the effects of age on the ability to benefit from combining auditory and visual speech information after minimizing differences in unimodal performance. Additionally, to investigate age differences in auditory enhancement and visual enhancement for consonants, words, and sentences. They also aimed to assess whether any observed age effects on auditory enhancement and visual enhancement would be modulated by the amount of lexical and semantic info available.	Speech detection (consonants, words, and sentences); percent correct, visual enhancement, auditory enhancement.

Beta-Band Functional Connectivity Influences Audiovisual Integration in Older Age: An EEG Study [489]	China	To investigate the functional connectivity in different oscillatory frequency bands during audiovisual integration in young and older adults.	Target detection response time (RT) task for visual, audio, and audiovisual stimuli; race model [cumulative distribution function (CDFs), probability difference curve].
Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration [387]	China	To determine how audiovisual temporal integration processing varies with aging and how the audiovisual interaction pattern was different between audio-leading and audio-lagging visual conditions.	Studied the temporal asynchrony between audio and visual stimuli in an audio/visual discrimination task; mean response times (RT), hit rate, false alarm, sensitivity measures (d'), and response criteria (c).
Cross-modal enhancement of speech detection in young and older adults: does signal content matter? [470]	USA	To determine whether aging modified, either quantitatively (low-contrast clip of the talker's face) or qualitatively (Lissajous figure), the effect of signal content on cross-modal enhancement.	Speech detection in noise; speech detection thresholds.
Dissociable Effects of Aging and Mild Cognitive Impairment on Bottom-Up Audiovisual Integration [151]	USA	To investigate changes in audiovisual speech integration that accompany healthy younger and older adults, compared to patients with mild cognitive impairments and the earliest influence of bottom-up and top-down processes mediating audiovisual integration in these populations.	Audiovisual speech integration examined using McGurk-type stimuli; accuracy rate, visual bias (McGurk effect), and perceptual goodness ratings.

Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? [20]	Canada	To determine how the information content of a masker (noise, babble, speech), as well as the listener's age and/or linguistic competence might affect the degree of release from masking provided by additional visual speech information.	Speech recognition task; percent correct, slopes at 50% threshold, 50% thresholds.
Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception [492]	Canada	To determine the extent to which performance and electrophysiological patterns differ between healthy young and older adults during audiovisual speech perception in noisy environments.	Audiovisual speech perception and discrimination task; accuracy, response time (RT), cumulative distribution functions (cumulative probability), auditory and visual enhancement.
Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus [90]	Spain	To evaluate the effect of aging on task performance and to evaluate the effect of involuntary capture of attention provoked by the auditory novel stimuli and standard stimuli.	Auditory-visual distraction-attention task and an auditory passive oddball task and a visual active three-stimulus task; mean response time (RT), and percentage of hits.

Effects of aging on audio-visual speech integration [211]	Belgium and France	To determine whether integration abilities of older adults are preserved compared to those of young adults (related to speech perception) and the impact of aging and audiovisual integration of speech in noise by studying the impact of degrading a visual speech cue.	Audiovisual speech through the use of a syllable identification task with audio, visual, audiovisual congruent and incongruent (McGurk) conditions; susceptibility to McGurk effect, speech identification score.
Effects of Repetition Suppression on Sound Induced Flash Illusion With Aging [454]	China and the USA	To add related stimuli of the auditory modality prior to the presentation of audiovisual stimuli to investigate the effects of repetition suppression before audiovisual stimuli on Sound Induced Flash Illusion (SIFI).	SIFI with repeated auditory stimuli prior to the appearance of audiovisual stimuli to explore the effect of repetition suppression; susceptibility to the illusion (fewer correct responses broken down by fission and fusion).
Enhanced audiovisual integration with aging in speech perception: a heightened McGurk effect in older adults [413]	Japan	To compare the McGurk effect in young and older adults by comparing their accuracy and speed in unisensory speech perception. The primary purpose was to determine if young-olds with normal hearing use visual information more than younger adults. Further, they aimed to test the visual priming hypothesis - that visual contribution will be larger for those who process visual speech faster than auditory speech compared with those who process visual and auditory speech at about the same speed.	Audiovisual speech perception task using McGurk-type stimuli; mean accuracy, visual influence (McGurk effect), mean response time (RT).
Enhanced multisensory integration in older adults [255]	USA	To evaluate multisensory integration in the elderly using response time (RT) measures in a redundant-target discrimination task.	Two-alternative forced-choice discrimination task; mean RT, mean accuracy, log-transformed RT, race model (cumulative probability, probability difference).

Impaired timing of audiovisual events in the elderly [43]	Canada	To determine age differences between young and older adults in terms of their temporal binding window (TBW) and point of subjective simultaneity (PSS) and the relation among simultaneity judgment (SJ), temporal order judgment (TOJ), and stream/bounce tasks.	Temporal processing associated with binding of audiovisual cues measured through the SJ, TOJ, and the stream/bounce illusion; TBW, PSS, synchrony judgment.
Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion [418]	Ireland	To train temporal discrimination in older adults and to improve their ability to discriminate the temporal order of inputs across two different modalities, vision and audition, and to show that this improvement generalises to a related, but not trained multisensory integration task.	Temporal order judgment (TOJ) and susceptibility to a multisensory integration task (sound-induced flash illusion; SIFI); frequency of correct responses for the TOJ task, temporal window of integration, proportion of correct responses for the SIFI, sensitivity (d') in detecting flashes with beeps (susceptibility to SIFI).
Increased Functional Brain Network Efficiency During Audiovisual Temporal Asynchrony Integration Task in Aging [488]	China and Japan	To better understand the functional connectivity and brain network efficiencies during audiovisual temporal asynchrony integration in older adults and younger adults.	Auditory and target visual discrimination task; hit race, false alarm rate, race model violations (cumulative distribution function, probability difference).

Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study [200]	Ireland	To assess whether ageing is associated with changes in multisensory processing, especially susceptibility to Sound Induced Flash Illusion (SIFI).	SIFI as a measure of audiovisual temporal integration; susceptibility to the illusion (fewer correct responses).
Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory-visual distraction-attention task [91]	Spain	The aim is to identify correct-related negativity (CRN), pre-response frontal positivity (preRFP), postRFP, and parietalRFP amplitudes in young, middle aged, and older adults in order to determine whether the sequence in which these components appear is the same across the age groups. Further, they aimed to evaluate the effects of attentional capture caused by irrelevant auditory novel stimuli as well as its interaction with aging.	audiovisual distraction-attention task. Included a passive auditory oddball task and a visually active three-stimulus task; mean response time (RT), hits.
Intra-versus intermodal integration in young and older adults [432]	USA	To determine whether there is overlap in the processes mediating inter- and intra-modal integration abilities and to determine whether and how some integrative abilities are affected by age and hearing loss.	Speech recognition task; mean percent word correct, monotic and dichotic scores, integration enhancement.

Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants [103]	Spain	To compare the distracting effects of novel and deviant stimuli on three different age groups: young, middle aged, and older adults. They looked at the effects of aging on various event-related potential (ERP) components and on response time (RT) in response to Go visual stimulus. The also investigated at the effect of involuntary capture of attention on the RTs measured in response to the Go visual stimuli, in each age group.	audiovisual distraction-attention task. Included a passive auditory oddball task and an active Go/No-go three-stimuli visual oddball task; RTs.
Is inefficient multisensory processing associated with falls in older people? [415]	Ireland	To assess the efficiency with which multisensory integration occurs as a function of aging and the role of multisensory integration and falling risk in older adults. Tested audiovisual integration efficiency in older with and without a history of falling to assess whether the incidence of falling in older adults might be related to a general impairment in multisensory processing.	General multisensory efficiency investigated using the sound induced flash illusion (SIFI); mean percentage of correct responses, proportion of correct responses at varying stimulus onset asynchronies.
Links between temporal acuity and multisensory integration across lifespan [448]	Canada and USA	To determine how temporal acuity plays a role in integrative abilities throughout the lifespan.	Temporal acuity and multisensory integration were tested both within and across modalities using the simultaneity Judgment (SJ), temporal order judgment (TOJ) tasks and a phoneme/McGurk illusion task; synchrony/asynchrony judgments, temporal binding window, accuracy, McGurk susceptibility.

Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration [471]	USA	To determine whether a separate integration stage is needed to explain age and individual differences in audiovisual speech recognition. Further, aimed to determine whether unimodal performance could account for the audiovisual speech benefit, even in the face of age-related declines in lipreading abilities. Additionally, they examined the effects of the clarity of the visual speech signal on the audiovisual speech advantage.	Visual and audiovisual speech recognition task; recognition accuracy (percent of words correct).
Multisensory integration across the senses in young and old adults [291]	USA	To directly compare the effect of multisensory integration across three multisensory pairing (audiovisual, audio-somatosensory, visual-somatosensory) and determine whether multisensory integration varies as a function of age.	Effects of multisensory cues on response time (RT); mean RT, cumulative probability, race model.
Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly [115]	Netherlands	To determine whether the temporal ventriloquist effect and the development of sensitivity of temporal order in auditory, visual, and audiovisual domains changes with age, using the temporal order judgment (TOJ) task.	Audio, visual, and audiovisual temporal order was measured. Additionally, multisensory integration was measured using the 'temporal ventriloquism' phenomenon; just noticeable difference (JND), temporal ventriloquist effect.

Multisensory Integration, Aging, and the Sound-Induced Flash Illusion [120]	USA	To determine age-related differences in perceptual multisensory integration and the role of attention in age-related differences in multisensory integration using the sound-induced flash illusion (Experiment 1) and the go/no-go task.	Multisensory perceptual processing as assessed using the sound-induced flash illusion and the role of attention using the go-no-go task; mean perceived number of flashes, mean perceived number of beeps, susceptibility to the illusion, accuracy for correctly withheld responses (go/no-go), false alarms (go/no-go).
Older adults expend more listening effort than young adults recognizing audiovisual speech in noise [184]	Canada	To quantify and compare the amount of listening effort that young and older normal-hearing adults with normal or corrected to normal vision expend when speech is presented in background noise. Further, they compared the results of Experiment 1 (auditory only) with experiment 2 (audiovisual) to determine the influence that the addition of visual cues have on listening effort.	speech recognition task; proportional dual task cost (pDTC), response time (RT), and accuracy.
Older adults sacrifice response speed to preserve multisensory integration performance [222]	UK	To determine how aging impacts the underlying mechanisms that govern multisensory decision making in both speeded and unspeeded contexts.	Sound localization task, where participants indicated the perceived sound location, common - source judgement where participants indicated whether the auditory and visual signals originated from the same location; mean response time (RT), proportion correct, localization (probability of ventriloquist effect) and common-source judgment (probability of same source) responses, and Bayesian outcomes (e.g., sensory noise).

Older age results in difficulties separating auditory and visual signals in time [80]	Australia	To determine the impact of aging on audiovisual synchrony perception.	Simultaneity Judgment (SJ) with different sound-lead and sound-lay asynchrony detection thresholds; detection threshold, audiovisual synchrony widow widths, audiovisual asynchrony detection thresholds, asynchrony detection.
One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise [351]	Ireland and Italy	To assess the effects of one bout of exercise which could either be classified as 'open skill' or 'closed skill' in older adults and compare it with the effects of one session of a sedentary activity. Processes tested were multisensory perception and immediate memory.	Audiovisual perception as measured by the sound induced flash illusion (SIFI); proportion correct (accuracy), and sensitivity changes (d' score - as a measure of susceptibility to the SIFI).
Preserved discrimination performance and neural processing during crossmodal attention in aging [322]	USA	To investigate the impact of attention on cross-modal performance accuracy and response times (RTs) in aging, simultaneous with the underlying neurophysiology of these interactions as measured by ERPs.	effect of attention on cross-modal discrimination performance; hits, false alarm rates, accuracy, discrimination index (d'), mean RT.

Recognition of asynchronous auditory-visual speech by younger and older listeners: A preliminary study [183]	USA	To assess the separate effects of age and hearing loss on speech recognition at a range of audiovisual asynchronies to determine if older adults and those with hearing impairment are more adversely affected than younger listeners with normal hearing under conditions of auditory and visual temporal misalignment of speech signals. Further, the study assessed recognition performance for synchronous and asynchronous stimuli of different durations (sentences and isolated words) to identify possible sources of discrepancy in the effect of age observed in previous studies.	Speech recognition and audiovisual asynchrony detection judgment was assessed for sentences and words in audiovisual modalities with varying degrees of auditory lead and lag; recognition accuracy, detection of asynchrony.
Reduced audiovisual recalibration in the elderly [81]	Australia	To determine whether older adults exhibit altered adaptation to audiovisual synchrony compared to younger adults.	Audiovisual synchrony perception (simultaneity judgment, SJ); synchrony perception, synchrony window (asynchrony discrimination sensitivity), adaptation (recalibration) effect.

Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data [458]	Netherlands	To investigate whether differences in the capacity of the attentional system stay focused on task-relevant stimuli items differ between younger and older adults. They aimed to investigate whether the processes involved in focusing spatial selective attention are affected by age, and if so, to what degree. They aimed to determine whether older adults' ability to focus attention would change when presented with increasing noise in the environment. Further, they aimed to determine whether non-spatial attention would be more susceptible to the aging process.	Spatial and non-spatial selective attention task; mean response time (RT), hit rate, false alarms.
Sensory dominance and multisensory integration as screening tools in aging [332]	Switzerland and UK	To assess differences in unisensory and multisensory processing across healthy young and older adults as well as in adults with mild cognitive impairment.	Detection Response Time (RT); mean RT, sensory dominance, auditory gain on RTs, multisensory gain, race model violation (CDFs, difference probability, and area under the curve).
Simultaneity and Temporal Order Judgments Are Coded Differently and Change With Age : An Event-Related Potential Study [36]	Canada	To investigate the behavioural [temporal binding window (TBW), point of subjective simultaneity (PSS)] as well as electrophysiological differences that exist between the Simultaneity Judgment (SJ) and Temporal Order Judgment (TOJ) tasks and between young and older adults.	SJ and TOJ; TBW and PSS.

Spatio-temporal patterns of event-related potentials related to audiovisual synchrony judgments in older adults [82]	Australia	To compare neural correlates for audiovisual synchrony judgement using electroencephalography (EEG) in young and older adults. Study also determined if there were differences in the neural mechanisms used to encode audiovisual synchrony judgements, accounting for age differences in unisensory processing.	Simultaneity Judgment (SJ); proportion of synchronous and asynchronous responses, and detection of visual and auditory stimuli.
Study of audiovisual asynchrony signal processing: Robot recognition system of different ages [385]	Japan and China	To compare performance on the response time (RT) task between young and older adults to determine if visual enhancement observed between the two groups is comparable.	audiovisual discrimination task; hit rate, mean RT, false alarm rate, response enhancement (%).
Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes [417]	Ireland	To determine whether audiovisual interactions in speech depend on the semantic content of the spoken message utilizing the McGurk effect in young and older adults.	Speech perception assessed using the McGurk illusion; percent responses provided, percent of correct responses, percent of McGurk infused responses.

Task-Specific, Age Related Effects in the Cross-Modal Identification and Localisation of Objects [32]	Ireland	To assess unisensory and multisensory object and spatial processing in children, adolescents, young adults, and older adults using auditory and visual stimuli. Further, they wanted to determine if age-differences emerged across object identification and object localisation tasks. They tested whether multisensory inputs enhanced either object localisation performance relative to unisensory input alone, and whether this enhancement was evident in all age groups or emerged only in late childhood. Further, they tested whether incongruent audiovisual stimuli affected object identification and object localisation performance equally across all ages.	audiovisual object identification task and audiovisual object localization task; mean accuracy scores, mean reaction times (RTs) to correct responses, cumulative probability distributions of RTs to correct responses.
Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention [388]	Japan and China	To determine whether audiovisual facilitation decreases as temporal disparity enlarges in older adults.	Audio/visual discrimination task; mean response times (RTs), hit rate, and race model violation.
Temporal metrics of multisensory processing change in the elderly [37]	Canada and USA	To assess the relation between tasks that are most commonly used to measure audiovisual integration [Simultaneity Judgment (SJ), Temporal Order Judgment (TOJ), Response time (RT) tasks] in young and older adults.	SJ, TOJ, and detection RT; temporal binding window (TBW), point of subjective simultaneity (PSS), mean RTs to auditory, visual, and audiovisual stimuli, mean RT, and race model violations [cumulative distribution functions (CDFs) and difference probability, area under the curve].

Text as a Supplement to Speech in Young and Older Adults [242]	USA	The primary objective was to evaluate the benefit of using text as a supplement to speech understanding in noise.	Speech recognition task; auditory and visual enhancement, text accuracy, and auditory and text bias.
The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging [14]	UK and Spain	To test the prefrontal neuronal loss hypothesis of aging using an audiovisual distraction task based on the oddball paradigm to measure the ability of young and older adults to filter irrelevant information.	Audiovisual distraction task based on the oddball paradigm; mean response time (RT), mean proportion of correct response, alertness.
The effect of combined sensory and semantic components on audio-visual speech perception in older adults [287]	Ireland	To explore the interaction between the cognitive and perceptual processes involved in speech perception and to examine how aging affects these processes.	Audiovisual speech perception by manipulating the reliability and semantics of cues; mean percent correct, mean percent recall, multisensory enhancement.
The effects of blurred vision on auditory visual speech perception in younger and older adults [260]	Canada	To investigate the effect of reduced visual acuity on audiovisual speech recognition for sentences presented in a background noise. In addition, cohort of young and older adults were tested to investigate whether the effects of blurring differ as a function of aging.	Audiovisual speech perception was investigated by reducing visual acuity; mean percent correct, mean percent visual enhancement.
The influence of Aging on Audiovisual Temporal Order Judgements [152]	Canada	To determine age-related differences in audiovisual temporal perception (Experiment 1) and to replicate the design of a previous study (Experiment 2) to determine how spatial factors impact temporal perception.	Temporal order judgment (TOJ) where the audio and visual stimuli were presented from the same perceived location and where they were perceived from different locations; just noticeable difference (JND) and point of subjective simultaneity (PSS).

The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration [301]	Ireland and UK	To determine whether older adults are equally susceptible to fission and fusion illusion and how they compare to younger adults.	Sound Induced Flash Illusion (SIFI) as a measure of audiovisual temporal integration; proportion of incorrect responses, perceptual sensitivity (d'), response bias (c).
Using race model violation to explore multisensory responses in older adults: Enhanced multisensory integration or slower unisensory processing? [106]	UK	To investigate whether enhanced multisensory integration in older adults was due to a greater number of older adults who showed race model violation and/or whether enhancement of multisensory integration was accentuated in those older adults who show race model violation. Another aim of the study was to address the issue of ceiling unisensory response (because older adults are slower than younger adults, they may show a greater magnitude of integration due to having a greater 'room for improvement' from their unisensory response times (RTs).	Detection RT task ; mean RT to auditory, visual, and audiovisual (tactile also included, but not of interest) cues, race model violations [cumulative distribution functions (CDFs), difference probability].
Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals [437]	Netherlands and Austria	To assess whether using a modified ventriloquist paradigm (using speech and simple auditory stimuli) would provide a useful tool that is simple to use to investigate audiovisual integration in young and older adults.	Ventriloquist effect using auditory only signal, audiovisual (synchronous and asynchronous) to determine the MAAs (minimum audible angle); MAA was compared with and without visual input.

What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues [367]	USA	To establish if people can process more than two nonredundant cues that appear concurrently in visual, auditory, and tactile modalities and to investigate how aging and concurrent task demands modulate this multimodal info processing ability.	Detection Response Time (RT) task where participants detected and responded to pairs of visual, auditory or triplets of visual, auditory and tactile stimuli (tactile not of interest); mean response time and accuracy (error rate).

Table A.3: This tables provides details, including title, country of origination, the aim, as well as the types of tasks used and the behavioural outcomes measures obtained from the studies included in this scoping review. Please note that the numbers are associated with the bibliography

Table 4: Description of the specific behavioural outcomes of interest

Table A.4: This table provides information regarding the behavioural outcomes of interest. Note that inclusion in one category does not preclude inclusion from another one.

Behavioural outcomes of interest	**Number of studies**
Accuracy or proportion correct, or percent correct	42
Mean or median response time (RT)	32
Race model as a measure of enhancement [may include any or all of: cumulative distribution, difference probability, Area Under the Curve (AUC)]	13
Enhancement (auditory and/or visual for speech perception tasks)	11
Hit rate	10
Temporal Binding Window or Temporal Window of Integration or Just noticeable Difference (TBW/TWI/JND)	10
Synchrony or asynchrony perception	9
Susceptibility to the Sound Induced Flash Illusion (SIFI)	8
False alarm rate	8
Susceptibility to McGurk	7
Sensitivity measure or perceptual sensitivity (e.g., d')	6
Point of Subjective Simultaneity (PSS)	6
Speech recognition thresholds	2
Integration of synchronous and asynchronous flicker and flutter rates	2
Perceived sound location and causal structure	2
Recalibration of the point of subjective simultaneity and the temporal window of simultaneity	2
Misses/errors	2
Response bias	1
Minimum audible angle (MAA)	1
Slopes at 50% thresholds	1
Inverse effectiveness score	1
Perceptual goodness ratings	1
Dual task cost	1
Proportion of stream/bounce responses	1
Bayesian outcomes (sensory noise)	1
Auditory and text bias	1
Common source judgement response	1

Table 5: Description of the inclusion criteria

Inclusion Criteria	Number of studies	Percentage (%)
△ Normal hearing (self-reported or measured)	69	95.83
• Normal vision (self-reported or measured; acuity and/or contrast sensitivity)	66	91.67
☐ No neurological condition/cognitive disorder (tested using MMSE or MoCA or self-reported)	55	76.39
• Normal vision based on visual acuity cut-off score	37	51.39
☐ Normal score on the Mini-Mental State Examination (MMSE)	34	47.22
☐∇ No relevant medical/psychiatric condition (including: AD, PD, stroke, epilepsy, neuropathy, seizures, transient ischemic disorder, trauma, unconsciousness, dizziness, depression, working memory impairment, executive memory impairment)	23	31.94
• Objectively measured normal contrast sensitivity score	19	26.39
☐ Normal score on Montreal Cognitive Assessment (MoCA)	13	18.06
☐ No severe head injuries (including TBI)	10	13.89
τ Naïve participants	10	13.89
△ No hearing disorders	9	12.50
△ No hearing aid use (either in general or during the study)	7	9.72
• No vision disorders	7	9.72
τ No Substance Abuse	6	8.33
∇ Didn't have any disease/were in good health	6	8.33
τ Vocabulary test (WAIS vocabulary test, verbal IQ, WAIS-22, Mill-Hill), WAIS-V	6	8.33
∇ Balance disorders/ mobility disfunction/fall risk	4	5.56
τ Accuracy met threshold	4	5.56
τ Education (e.g., matching with young adults, at least 12 years of education, missing)	3	4.17
• Not colour blind	3	4.17
• Not legally blind	2	2.78
∇ Didn't have a compromised sense of touch	2	2.78

∇ No cardiac condition	2	2.78
∇ No motor sensory deficit	2	2.78
τ Not being too slow	2	2.78
τ If sex wasn't missing in database	1	1.39
τ Unable to comply with instructions	1	1.39
τ No musical training (3+ months)	1	1.39
∇ Didn't have diabetes	1	1.39
□ Didn't meet MCI based on Q-MCI	1	1.39
∇ Didn't have any learning disabilities	1	1.39
△ No excessive noise exposure	1	1.39
□ Normal score on a dementia screening test	1	1.39
τ No language disorders	1	1.39
∇ Normal blood pressure	1	1.39

Table A.5: This table provides details regarding various inclusion criteria that were utilized by the studies included in this scoping review. The percentage is calculated by using the number of studies included in this scoping review that accounted for each criterion. Note: MMSE = Mini-Mental State Examination, MoCA = Montreal Cognitive Assessment, AD = Alzheimer's disease, PD = Parkinson's disease, WAIS = Wechsler Adult Intelligence Scale, IQ = Intelligence Quotient. Note that various symbols are used below to help classify the inclusion criteria in 5 cateogories; ● = vision criteria, △ = auditory criteria, □ = cognitive/neurological criteria, ∇ = health-related criteria, τ = miscellaneous

Table 6: This table provides details regarding the inclusion criteria for auditory and visual acuity

Title	Criteria used to measure auditory acuity	If auditory acuity was self-reported, what questions were asked	Criteria used to measure visual acuity	If visual acuity was self-reported, what questions used
Age-related changes in auditory and visual interactions in temporal rate perception [61]	Yes: normal hearing was defined as thresholds of $\leq$ 25 dB for pure tone average for 500,1000, 2000, 4000 Hz.	Questions were not stated	Yes: participants were required to have visual acuity of of 6/7.5 or better in both eyes; achieved with a spectacle prescription with spherical error less than 5 dioptres and astigmatism less than two dioptres.	Questions were not stated
Age-related differences in inhibitory control predict audiovisual speech perception [125]	Yes: pure-tone air-conduction audiogram measuring thresholds of <20 dB HL for octave frequencies from 250 - 4000 Hz; pure tone average obtained for each ear for all participants.	Questions were not stated	Didn't measure in the lab	Questions were not stated

Age-related hearing loss increases cross-modal distractibility [378]	Yes: pure tone audiogram test with normal hearing defined as hearing loss of <25 dB in both low (125-1500 Hz) and high frequency (2000-8000 Hz).	Questions were not stated	Didn't measure in the lab	Questions were not stated
Age-related multisensory enhancement in a simple audiovisual detection task [361]	Yes: Screened for hearing loss (50 dB) at 1000-2000 Hz.	Questions were not stated	Yes: excluded if vision loss was worse than 20/40.	Questions were not stated
Age-related multisensory integration elicited by peripherally presented audiovisual stimuli [497]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception [207]	Didn't measure in the lab	Is your hearing (with or without a hearing appliance): excellent, very good, good, fair, poor? Or don't know (if don't know they excluded)	Visual acuity measured using early treatment diabetic retinopathy study (ETDRS) LogMAR chart AND contrast sensitivity also assessed	Is your vision: excellent, very good, good, fair, poor or are you registered as legally blind?
Ageing effects on the attention demands of walking [430]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Aging and audio-visual and multi-cue integration in motion [394]	Yes: older adults completed a short hearing test to determine either they could successfully hear the sound stimuli. 10 sounds were played, and participants were asked to press the spacebar as soon as they heard the sound.	Questions were not stated	Yes: near and far visual acuity screened using Snellen acuity. All participants had Snellen acuity of 20/30 or better and Pelli-Robson contrast sensitivity measure also revealed good sensitivity.	Questions were not stated
Aging Effect on Audiovisual Integrative Processing in Spatial Discrimination Task [513]	Participants needed to be able to differentiate the audial stimuli.	Questions were not stated	Standard logarithmic visual acuity chart test with acuity >0.8.	Questions were not stated
Aging Impairs Audiovisual Facilitation of Object Motion Within Self-Motion [395]	Yes: older adults were screened with the Hughson Westlake pure tone audiometry tests and those classified as having hearing impairment in at least one ear were not recruited.	Questions were not stated	Yes: all participants were screened to have at least 6/9 or better Snellen acuity and normal contrast sensitivity (M = 1.99 log contrast) on Pelli-Robson contrast sensitivity test.	Questions were not stated
Aging increases distraction by auditory oddballs in visual, but not auditory tasks [261]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Aging, audiovisual integration and the principle of inverse effectiveness [469]	Yes: participants' hearing acuity was determined by averaging the pure-tone thresholds (PTAs) for 0.5, 1.0, and 2.0 kHz. The PTA for the better ear was used as the indicator of hearing acuity. Further, participants' speech discrimination was assessed using percent words correct with the W-22-word lists presented at 35dB above their PTA. No differences found between young and older adults.	Questions were not provided but participants were asked over the phone if they had any uncorrected hearing problems.	Yes: all participants were screened to have at least 20/40 visual acuity using the Snellen eye chart and normal contrast sensitivity of 1.8 or better using the Pelli-Robson contrast sensitivity chart.	Questions were not provided but participants were asked over the phone if they had any serious vision problems.
Audio-Visual Spatiotemporal Perceptual Training Enhances the P300 Component in Healthy Older Adults [500]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Audiovisual binding for speech perception in noise and in aging [165]	Yes: measured for older adults (in Experiment 2 only): audiometric thresholds obtained at octave intervals from 250-8000 Hz; average threshold $\leq$ 25 dB HL (500-2000 Hz) and 35-40 dB in higher frequencies.	Yes: no questions mentioned but used the speech, spatial, and qualities of hearing scale (self-reported) questionnaire to assess how effectively auditory information is being processed in various everyday events.	Didn't measure in the lab	Questions were not stated
Audiovisual Integration Delayed by Stimulus Onset Asynchrony Between Auditory and Visual Stimuli in Older Adults [386]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan [337]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise [181]	Yes: audiometric thresholds for 250-4000 Hz frequencies. older adults with no hearing loss up to 2000 Hz (20 dB HL or better) were accepted with the condition that they could not have more than moderate hearing loss at 4000 Hz (35 dB HL or better) and hearing loss difference between the two ears could never exceed 10 dB.	Questions were not stated	Yes: both near and far visual acuities were tested. The participants had to demonstrate vision of 20/40 or better for both eyes. younger adults had near visual acuity of M = 20/16 and older adults had near visual acuity of M = 20/20. Younger adults had far visual acuity of 20/20 while older adults had far visual acuity of 20/20. Participants were also tested on visual contrast acuity and had to demonstrate normal contrast vision on a low acuity test.	Questions were not stated
Audiovisual temporal discrimination is less efficient with aging: an event-related potential study [416]	Yes: Hughson-Westlake audiometer. No further info provided; seems like this was done only for older adults.	Questions were not stated	Yes: visual acuity was assessed using the LogMAR scale (M = .08) and contrast sensitivity measured through the Pelli-Robson chart (M = 1.70).	Questions were not stated

Auditory and visual information in speech perception: A developmental perspective [456]	Yes: young adults (20-30 yrs) had pure tone air conduction thresholds less than 15 dB HL bilaterally for frequencies from 250 to 4000 Hz. While older adults (65-80 yrs) were screened for age normal hearing at 500, 1000, 2000 and 4000 Hz.	Questions were not stated	Didn't measure in the lab	Questions were not stated
Auditory and visual lexical neighbourhoods in audiovisual speech perception [468]	Yes: all older adults were screened for hearing acuity via pure tone audiometer. Only older adults with a pure tone average (PTA) between 30 and 55 dB HL (tested at 500, 1000, and 2000 Hz) were included in the normal hearing group. Participants with inter-octave slopes greater than 15 dB at frequencies 500 and 4000 Hz were screened out.	Questionnaire where participants indicated that they had good or excellent hearing; but questions not provided	Yes: only those participants with visual acuity or corrected acuity equal to or better than 20/40 using the standard Snellen eye chart and contrast sensitivity better than 1.8 as assessed with the Pelli-Robison contrast sensitivity chart were included.	Questions were not stated

Auditory perception in the aging brain: the role of inhibition and facilitation in early processing [451]	Yes: participants' hearing thresholds were assessed using a Bekesy threshold procedure.	Questions were not stated	Didn't measure in the lab	Questions were not stated
Auditory-visual speech perception and aging [92]	Yes: hearing thresholds were measured at octave intervals of 500 - 8000 Hz bilaterally. HLs were considered normal if thresholds were better than 20 dB HL bilaterally at all testing frequencies. Older adults had hearing thresholds of $\leq$ 35 dB HL for the frequencies from 500-3000 Hz. At 6000 and/or 8000 HZ, all participants except 2 of them, showed some degree of hearing loss.	Questions were not stated	Yes: both visual acuity and contrast sensitivity were measured. Snellen chart placed at a distance of 20 feet was used and visual acuity was considered normal if participants achieved a score of 20/25. The Pelli-Robson chart set at a distance of 3 meters was used to determine contrast sensitivity. Contrast sensitivity measure of 1.80 was considered normal.	Questions were not stated

Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults [428]	Yes: pure-tone air conduction thresholds were obtained from 250-4000 Hz. Participants whose threshold exceeded 20 dB HL were excluded. Participants with asymmetric HL operationalized as greater than 10 dB threshold difference between the two ears at any of the test frequencies were excluded.	Questions were not stated	Yes: visual acuity was tested and those with scores higher than 20/40 on the Snellen eye chart were excluded. Pelli-Robson contrast sensitivity test was used and those who scored higher than 1.8 were excluded.	Questions were not stated
Beta-Band Functional Connectivity Influences Audiovisual Integration in Older Age: An EEG Study [489]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration [387]	yes: using a RION audiometer; criteria not specified just that all participants had normal hearing.	Questions were not stated	Yes: measured using a Japanese eye chart; no criteria specified, just that all participants had normal vision.	Questions were not stated

Cross-modal enhancement of speech detection in young and older adults: does signal content matter? [470]	Yes: pure-tone testing for both young and older adults where all participants had pure tone average thresholds of <30 dB (based on threshold for 500, 1000, and 2000 Hz).	Questions were not stated	Yes: both young and older adults had normal or corrected-to-normal visual acuity of 20/30 or better (assessed using a Snellen chart).	Questions were not stated
Dissociable Effects of Aging and Mild Cognitive Impairment on Bottom-Up Audiovisual Integration [151]	Yes: participants needed to obtain overall accuracy of 75% and 80% in the audio-alone and congruent conditions; otherwise, they were excluded.	Questions were not stated	Didn't measure in the lab	Questions were not stated
Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? [20]	Yes: pure-tone air conduction thresholds where participants were required to have pure-tone air-conduction thresholds of 25 dB HL or lower between 0.25 and 3 KHz in both ears.	Questions were not stated	Yes: measured near acuity and contrast sensitivity using LogMar acuity and functional acuity contrast test (FACT). All participants were required to have near acuity of 20/32 or better in both eyes.	Questions were not stated

Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception [492]	Yes: auditory acuity was measured using pure tone averages (PTA). Average hearing threshold for frequencies of 500, 1000, and 2000 Hz were measured. older adults had PTA of 12.7 and younger adults had PTA of 6.2. Only participants with PTA below 20 dB and PTA differences between the left and right ear of 10 dB or less were included.	Questions were not stated	Yes: visual contrast sensitivity was screened using the MARS letter contrast sensitivity test where older adults had a MARS score of 1.6 and younger adults had a MARS score of 1.7. Both groups had age-appropriate and clinically normal sensitivity scores.	Questions were not stated
Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus [90]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Effects of aging on audio-visual speech integration [211]	Yes: pure-tone thresholds for 250-4000Hz were tested, where participants had no hearing loss up to 2000 Hz (20 dB HL or better) and no more than mild hearing loss at 4000 Hz (35 dB HL or better).	Questions were not stated	Didn't measure in the lab	Questions were not stated
Effects of Repetition Suppression on Sound Induced Flash Illusion With Aging [454]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Enhanced audio-visual integration with aging in speech perception: a heightened McGurk effect in older adults [413]	Yes: participants were screened for normal hearing where the threshold was set to $\leq$ 25 dB HL, averaged over 500, 1000, 2000, 4000 Hz.	Questions were not stated	Didn't measure in the lab	Questions were not stated

Enhanced multisensory integration in older adults [255]	Yes: participants who could hear 1000-2000 Hz at an intensity of 40 dB using an audioscope or at an intensity of 55 dB using a digital audiometer were included.	Questions were not stated	Yes: modified Snellen visual acuity examination was performed for each eye (with corrective lenses if necessary), and each subject had to perform at 20/40 or better. Colour blindness was also tested using the concise edition of Ishihara's test for colour-blindness (a score of ≤ 7 was used as an exclusion criteria).	Questions were not stated
Impaired timing of audiovisual events in the elderly [43]	Didn't measure in the lab	Self-report if they have normal to corrected-to-normal vision (yes/no).	Didn't measure in the lab	Self-report if they have normal to corrected-to-normal vision (yes/no).
Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion [418]	Didn't measure in the lab	Questions were not stated	Yes: Visual acuity was measured using LogMar, and contrast sensitivity was measured using the Pelli-Robson chart. Control group LogMAR (M = 0.0036) and training group (M = 0.005). Contrast sensitivity: control (M = 1.68) and training group (M = 1.77).	Questions were not stated

Increased Functional Brain Network Efficiency During Audiovisual Temporal Asynchrony Integration Task in Aging [488]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study [200]	Didn't measure in the lab	Is your hearing with or without a hearing appliance: excellent, very good, good, fair, poor?	Didn't measure in the lab	Is your vision: excellent, very good, good, fair, poor or are you registered as legally blind?
Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory-visual distraction-attention task [91]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Intra-versus inter-modal integration in young and older adults [432]	Yes: participants were screened to include only those with pure tone average threshold values at 500, 1000, and 2000Hz at or below 55 dB HL in each ear (includes hearing impaired older adults). Younger adult PTA: 4.9 dB, older adults considered to have normal hearing PTA: M = 15.1 (normal if PTAs were at or below 25 dB). Participants with inter-octave slopes greater than 15 dB at frequencies between 500 and 4000 Hz were screened out.	Questions were not stated	Yes: participants were also screened to include those with visual acuity equal to or better than 20/40 using the standard Snellen chart and contrast sensitivity better than 1.8 as assessed with the Pelli-Robison contrast sensitivity chart.	Questions were not stated
Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants [103]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Is inefficient multisensory processing associated with falls in older people? [415]	Yes: frequencies of 1000-2000-3000 Hz were tested using the Hughson-Westlake test. Healthy older adults achieved a mean score of 17 dB at these frequencies.	Questions were not stated	Yes: visual acuity and contrast sensitivity measured using the LogMar test and Pelli-Robson contrast test respectively. The mean LogMar score was 0.05 and the mean contrast score was 1.73 in healthy older adults.	Questions were not stated
Links between temporal acuity and multisensory integration across lifespan [448]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration [471]	Yes: pure tone average test where normal hearing was measured at 500, 1000, 2000 Hz in the better ear and participants were screened to include only those with age-appropriate hearing ($\leq$ 25 for 66-80 year olds). Speech recognition was assessed using a 50 word list from the W-22 in each ear level of 35 dB.	Questions were not stated	Yes: near visual acuity screened and those with acuities of 20/40 or better on the Eger Near Point Equivalent Card were included. Contrast sensitivity was assessed using Pelli-Robsons contrast sensitivity chart.	Questions were not stated

Multisensory integration across the senses in young and old adults [291]	Yes: a computerized tone-emitting otoscope that delivered lateral and bilateral 20, 25, 40 dB tones at 500, 1000, 2000, and 4000 Hz was employed to assess hearing loss. The cut-off or averages were not reported - just state participants were excluded if they had severe hearing disturbances.	self-administered hearing handicap inventory for the elderly (HHIE-S) questionnaire; this is meant to measure the degree of social and emotional handicap from hearing loss - scores on the HHIE-S range from 0 (no handicap) to 40 (maximum handicap).	Yes: all participants had normal or corrected to normal visual acuity (better or equal to 20/40) as measured by a Snellen eye chart.	Questions were not stated
Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly [115]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Multisensory Integration, Aging, and the Sound-Induced Flash Illusion [120]	Yes: a custom hearing test where participants had to get 8 trials in a row correct of number of beeps presented in order to be eligible for the study.	Questions were not stated	Yes: all participants demonstrated equal to or better than 0.40 LogMAR visual acuity, and equal to or better than 1.00 contrast sensitivity.	Questions were not stated

Older adults expend more listening effort than young adults recognizing audiovisual speech in noise [184]	Yes: hearing sensitivity was assessd and defined as $\leq$ 25 dB HL at octave frequencies between 0.25 and 2.0 KHz as well as at 3 KHz in both ears.	Questions were not stated	Yes: vision was assessed using the Sloan letters chart at a distance of 3 meters where normal or corrected to normal vision was defined as 6/12 or better on the chart.	Questions were not stated
Older adults sacrifice response speed to preserve multisensory integration performance [222]	Yes: a spatial hearing performance test where participants were presented with white noise bursts on right or left side of the screen and participants pressed a button to indicate the side.	Questions were not stated	Yes: a basic visual spatial perception test where participants were presented with visual stim on right or left side of the screen and participants pressed a button to indicate the side.	Questions were not stated
Older age results in difficulties separating auditory and visual signals in time [80]	Yes: normal hearing defined as having audiometric thresholds less than 35 dB HL at 4KHz and less than 25 dB HL at all other frequencies (.25, .5, 1. and 2 KHz).	Questions were not stated	Yes: normal or corrected to normal visual acuity defined as $\geq$ 6/7.5).	Questions were not stated

One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise [351]	Didn't measure in the lab	Is your hearing (with or without a hearing appliance): excellent, very good, good, fair, poor? Or don't know (excluded if they didn't know).	Didn't measure in the lab	Is your vision: excellent, very good, good, fair, poor? Or don't know (excluded if they didn't know).
Preserved discrimination performance and neural processing during cross-modal attention in aging [322]	Yes: hearing tested in both ears in the 250 Hz - 6 kHz frequency range as estimated by an audiometer application called Uhear. Individuals with poorer hearing sensitivities than in the 'mild loss' range as per Uhear results, were excluded from the study, thus controlling for presbycusis.	Participants completed a 12 multiple choice questionnaire to document no hearing problems in daily life situations.	Yes: Snellen chart was used to screen for normal vision; no other info provided.	Questions were not stated
Recognition of asynchronous auditory-visual speech by younger and older listeners: A preliminary study [183]	Yes: pure-tone detection thresholds $\leq$ 20 dB hearing level (HL) from 250 to 4000 Hz.	Questions were not stated	Didn't measure in the lab	Questions were not stated

Reduced audiovisual recalibration in the elderly [81]	Yes: audiometer with headphones where normal hearing was defined as having audiometric thresholds of less than 35 dB at 4KHz and less than 25 dB at all other frequency (.25, .5, 1, 2 kHz).	Questions were not stated	Yes: having normal or corrected to normal vision of 6/7.5 or better.	Questions were not stated
Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data [458]	Yes: all participants were screened to have good hearing as assessed through an on-site examination by an expert; no further details provided.	Questions were not stated	Yes: all participants had normal or corrected to normal visual acuity as measured by a Snellen eye chart; no further details provided.	Questions were not stated
Sensory dominance and multisensory integration as screening tools in aging [332]	Yes: participants performance on the detection task on the auditory trials was evaluated and those with $< 90\%$ accuracy were excluded.	Questions were not stated	Didn’t measure in the lab	Questions were not stated

Simultaneity and Temporal Order Judgments Are Coded Differently and Change With Age : An Event-Related Potential Study [36]	Didn't measure in the lab	Self-reported if they had normal to corrected-to-normal hearing (yes/no).	Didn't measure in the lab	Self-reported if they had normal to corrected-to-normal vision (yes/no).
Spatio-temporal patterns of event-related potentials related to audio-visual synchrony judgments in older adults [82]	Yes: no more than 35 dB HL at 4KHz and no more than 25 dB HL at 0.25, 0.5, 1, and 2 KHz.	Questions were not stated	Yes: normal or corrected to normal visual acuity ($\geq 6/7.5$), spherical and cylindrical correction between ± 5D and ± 2D respectively and no ocular disease.	Questions were not stated
Study of audiovisual asynchrony signal processing: Robot recognition system of different ages [385]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes [417]	Yes: Hughson Westlake test with Kamplex BA 25 screening audiometer to assess whether or not hearing was within normal range for age (3000-4000 Hz was 16.5dB in left ear and 15 dB in right ear); young adults self-reported.	Questions were not stated	Yes: LogMAR testing to assess normal or corrected to normal vision (logMAR mean = 0.05); young adults self-reported only.	Questions were not stated

Task-Specific, Age Related Effects in the Cross-Modal Identification and Localisation of Objects [32]	Didn't measure in the lab	Questions were not stated	Yes: a score of 0.2 or lower was considered normal; near LogMAR (0.09), far LogMAR (0.03), and Pelli-Robson contrast (1.98) tests conducted only for older adults.	Questions were not stated
Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention [388]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated
Temporal metrics of multisensory processing change in the elderly [37]	Didn't measure in the lab	Self-reported if they had normal to corrected-to-normal hearing (yes/no).	Didn't measure in the lab	Self-reported if they had normal to corrected-to-normal vision (yes/no).
Text as a Supplement to Speech in Young and Older Adults [242]	Yes: younger adults: air-conduction thresholds 15 dB HL at 250 - 8000 Hz; Older Adults: 25 dB HL through 4000 Hz.	Questions were not stated	Didn't measure in the lab	Questions were not stated
The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging [14]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

The effect of combined sensory and semantic components on audio-visual speech perception in older adults [287]	Yes: hearing was assessed using the Hughson Westlake audiometer test and older adults needed to fall within the normal range to participate.	Questions were not stated	Yes: visual acuity measured using the LogMAR test where the mean LogMAR score for older adults was 0.03.	Questions were not stated
The effects of blurred vision on auditory visual speech perception in younger and older adults [260]	Yes: hearing sensitivity was tested between 250 Hz - 3000 Hz and all participants had normal hearing sensitivity of ≤ 25 dB at those frequencies in both ears.	Questions were not stated	Yes: visual acuity was measured using the Snellen chart positioned at a distance of 1 m from the participant. All participants had normal or corrected to normal 6/6 visual binocular acuity. older adults were recruited from school of optometry and had normal results on the following tests as well: refraction, visual field, retinoscopy, binocular fusion, lens examination, and blood pressure.	Questions were not stated

The influence of Aging on Audio-visual Temporal Order Judgements [152]	Didn't measure in the lab	Questions were not stated	Yes: snellen acuity for near and far distnaces was assessed. All participants had normal or corrected-to-normal near (older: M = .98; younger adults: M = 1.46) and far (older: M = .97; younger adults: M = 1.38) acuities.	Questions were not stated
The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration [301]	Yes: Hughson Westlake test with Kamplex BA 25 screening audiometer to assess whether or not hearing was within normal range for age.	Questions were not stated	Yes: acuity for near and far ranges measured in older adults using the SLOAN two sided ETDRS near vision and the 4 m 200 series revised ETDRS charts. Contrast sensitivity measured using Pelli-Robson contrast sensitivity test.	Questions were not stated
Using race model violation to explore multisensory responses in older adults: Enhanced multisensory integration or slower unisensory processing? [106]	Yes: pure-tone audiometry where participants were required to be able to hear 1000-2000 Hz at an intensity of 40 dB HL in either ear.	Questions were not stated	Yes: all participants demonstrated equal to or better than 6/12 (20/40) visual acuity, with or without correction as assessed through the Snellen chart.	Questions were not stated

Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals [437]	Yes: thresholds lower than or equal to 25 dB HL at the audiometric test frequencies of .25, .5, 1, 2, and 4 KHz for both ears - measured with a standard clinical audiometry procedure. None of the older adults showed hearing threshold deficits larger than 20 dB, thus they were all within normal hearing limits.	Questions were not stated	Yes: participants were asked to identify the visual 'catch stimulus' in a 3x3 grid where the other 8 stimuli were in the 'normal' condition. Participants were seated at a 1.5m distance and had to do this task correctly three times before being able to participate.	Questions were not stated
What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues [367]	Didn't measure in the lab	Questions were not stated	Didn't measure in the lab	Questions were not stated

Table A.6: This table provides details regarding the methods used to assess auditory and visual acuity in the studies included in this scoping review. It lists the criteria each study used to assess auditory and visual acuity (if it was provided) and the questions utilized for self-reported assessment for both the auditory and visual acuity as well. Please note that the numbers are associated with the bibliography found in the scoping review. Articles are sorted alphabetically and are located in the bibliography in the manuscript.

Table 7: Important behavioural results

Title	Important Results
Age-related changes in auditory and visual interactions in temporal rate perception [61]	Reliability based weighting of temporal rate is preserved in older adults as they are able to resolve intersensory conflict in perceived rate through partial integration of asynchronous auditory and visual temporal rates. However, older adults are not able to benefit from audiovisual rate synchrony like younger adults when discriminating changes in temporal rate. In everyday conditions where age-related changes in audition are not controlled, older adults will rely more on vision to achieve a coherent percept of asynchronous rates by using their preserved ability to weight sensory information.
Age-related differences in inhibitory control predict audiovisual speech perception [125]	Younger adults exhibited better inhibitory control and higher identification of words performance compared to older adults. A significant relation was found between identification of hard words and the stroop interference task for older adults which did not exist for younger adults. These results indicate that both hearing and cognition contribute to age-related differences in audiovisual speech perception.
Age-related hearing loss increases cross-modal distractibility [378]	While healthy older adults performed comparably to younger adults, older adults with moderate high-frequency hearing loss, showed greater error rates when confronted with distracting cross-modal stimulation. Further analysis showed that cross-modal visual distractibility in the auditory task increased with the degree of high-frequency hearing loss.
Age-related multisensory enhancement in a simple audiovisual detection task [361]	Older adults showed faster RTs to multisensory (audio-visual) compared to younger adults. Further, older adults showed significantly greater multisensory enhancement compared to younger adults.
Age-related multisensory integration elicited by peripherally presented audiovisual stimuli[497]	The time window of audiovisual facilitation was longer and more delayed in older adults compared to younger adults when the stimuli were presented peripherally. Older adults responded more slowly, however they responded faster with AV stimuli. These results indicate that peripheral resolution decreases with age.

Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception [207]	SIFI susceptibility increases with age and is influenced, not accounted for by age-related changes in unsensory abilities. SIFI is mediated by visual acuity and self-reported hearing, where better scores on these measures predicted reduced and stronger SIFI susceptibility respectively. The relation between age and SIFI remained significant even when mediators were accounted for.
Ageing effects on the attention demands of walking [430]	Mean no-walk-baseline RTs for auditory and visual cues were not different between younger and older adults. RTs increased for for both younger and older adults in all walking conditions relative to baseline, indicating the attentional cost of walking. Older adults had similar RTs to the auditory but not the visual and audiovisual walking conditions compared to younger adults.
Aging and audio-visual and multi-cue integration in motion [394]	Older adults were less likely to perceive bouncing when a sharp sound was presented with the coincidence of the two disks compared to younger adults. Further, when an occluder was presented for a longer period of time, it promoted the perception of streaming in both younger and older adults, however, a brief occluder only promoted the perception of a bounce in younger adults. These results did not result from differences in hearing or retinal illuminance.
Aging Effect on Audiovisual Integrative Processing in Spatial Discrimination Task [513]	Younger adults showed faster RTs in all the conditions (audio, visual, and audiovisual). However, older adults showed a greater extent of improvement in the multisensory condition compared to younger adults. Older participants relied more on the visual modality to achieve greater ability for stimulus evaluation, which improved their performance.
Aging Impairs Audiovisual Facilitation of Object Motion Within Self-Motion [395]	Younger adults had higher target detection accuracy in the audiovisual compared to visual condition at the slowest speed level. Older participants showed no improvement in the target detection accuracy in the presence of the sound (audiovisual condition) at any of the speeds (slow or faster). Further, older adults showed significantly poorer target detection accuracy at all speeds compared to younger adults.
Aging increases distraction by auditory oddballs in visual, but not auditory tasks [261]	Longer RTs were found for the deviant compared to the standard sounds for both younger and older adults. A distraction effects were observed in the cross-modal task but not in the unimodal task in older adults suggesting that aging might affect the processes involved in switching attention across modalities.

Aging, audiovisual integration and the principle of inverse effectiveness [469]	Neither auditory nor integration enhancement increased when signal clarity in the auditory and visual channels of audiovisual speech was decreased. However, with easy visual stimuli in the audiovisual condition, the integration enhancement measure for older adults was comparable to younger adults. Under the hard visual stimuli conditions, integration enhancement for older adults was significantly lower than younger adults. These results do not support the principle of inverse effectiveness for audiovisual speech recognition.
Audio-Visual Spatiotemporal Perceptual Training Enhances the P300 Component in Healthy Older Adults [500]	Accuracy of audiovisual perception improved after training for both young and older adults as accuracy on the audio-visual perceptual test was significantly higher after training than before and there was no significant difference between the pretest and post-test for the control group.
Audiovisual binding for speech perception in noise and in aging [165]	Audiovisual fusion is not automatic and instead is controlled by an audiovisual binding process prior to fusion. The binding process evaluates both the coherence of and the reliability of the auditory and visual channels and wights the unisensory evidence accordingly. Incoherent context leads to unbinding, or a reduction in the amount of fusion. Older adults show more unbinding than younger adults.
Audiovisual Integration Delayed by Stimulus Onset Asynchrony Between Auditory and Visual Stimuli in Older Adults [386]	Younger adults exhibited faster RTs compared to older adults. Enhanced audiovisual integration was greatest when auditory and visual stimuli were presented simultaneously but the enhancement decreased with the expansion of the SOAs (i.e., the stimuli were presented further apart; $>$ 50 ms). Older adults showed significantly delayed onset for the window of integration and peak latency in all conditions.
Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan [337]	They found that the temporal window of simultaneity (TWS) develops over an extended period of time, where it appears to mature earlier for simple (flash-beep) stimuli compared to more complex (speech) stimuli. The TWS reached maturity at around 17 years of age for simple, and around 31 for speech stimuli. They also found that the TWS followed a U-shaped pattern as a function of age for flash-beep stimuli, with the window appearing the widest for youngest participant which continued to narrow until 50 years of age and then began to widen again until a significant difference emerged at age 64.

Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise [181]	Older adults had worse performance scores than younger adults. However, older adults demonstrated the same level of visual enhancement compared to younger adults under the normal audiovisual conditions. Blurring the visual speech did not impact the performance of younger adults but left the older adults with almost no enhancement effect. These results suggest that sensory-level and not cognitive level changes impact older adults as no relation was found between age and context.
Audiovisual temporal discrimination is less efficient with aging: an event-related potential study [416]	Participants were more accurate at the SOA of 270 ms as compared to the 70 ms SOA. No effect of age was found for the accuracy at the SOA of 70 ms however, older adults were less accurate at the SOA of 270 ms compared to younger adults. There was also a trend for greater accuracy when the auditory stimulus preceded the visual stimulus.
Auditory and visual information in speech perception: A developmental perspective [456]	Speech perception accuracy patterns were similar between auditory and audiovisual modalities, resulting in an inverse U-shape, with the worst performance in those aged 4-5 and 65-80. Speech perception in the visual modality showed that older adults performed similarly to younger adults and that 4-5 and 8-9 year olds were less accurate. Auditory and visual enhancement was greater in meaningful than non meaningful words. There was an increased auditory enhancement from childhood to 20-30 year olds, but this decreased with older participants (65+).
Auditory and visual lexical neighbourhoods in audiovisual speech perception [468]	Words with sparse visual neighbourhoods were recognized more accurately compared to words with dense neighbourhoods in the vision-only. Older adults with hearing impairment recognized fewer words compared to older adults with normal hearing and younger adults in the visual-only condition. No significant difference found between the three groups for the auditory-only condition. Auditory- and visual-neighbourhoods were predictive of audiovisual performance such that words that had fewer overlapping regions were more likely to be recognized in the audiovisual condition.
Auditory perception in the aging brain: the role of inhibition and facilitation in early processing [451]	There was no significant difference between younger and older adults in the number of McGurk /da/ illusions perceived or the number of congruent /ba/ or /ga/ syllables correctly identified.

Auditory-visual speech perception and aging [92]	Older adults perform similarly to younger adults at integrating auditory and visual information for speech perception at the syllable level. All participants did however display visual bias but younger adults with normal hearing showed the least bias. When integration failed, young adults with normal hearing chose the auditory alternative whereas older adults as well as younger adults with modified auditory thresholds, chose the visual alternatives. Indicating that when integration fails, participants select an alternative response from the modality that has the least ambiguous signal; for older adults this is the visual input while it's the auditory input for younger adults.
Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults [428]	Older adults perform similarly to younger adults at integrating auditory and visual information for speech perception at the syllable level. All participants did however display visual bias but younger adults with normal hearing showed the least bias. When integration failed, young adults with normal hearing chose the auditory alternative whereas older adults as well as younger adults with modified auditory thresholds, chose the visual alternatives. Indicating that when integration fails, participants select an alternative response from the modality that has the least ambiguous signal; for older adults this is the visual input while it's the auditory input for younger adults.
Beta-Band Functional Connectivity Influences Audiovisual Integration in Older Age: An EEG Study [489]	RTs to the audiovisual stimuli were faster than RTs to visual or auditory stimuli in both younger and older adults. Older adults had a longer window of integration and were more delayed in facilitation compared to younger adults. The peak time of the probability difference curve showed that younger adults had an earlier peak than older adults in all conditions.
Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration [387]	Younger adults had faster RTs compared to older adults and RTs were faster when auditory and visual cues were presented simultaneously. Older adults had lower perceptual sensitivity to visual stimuli compared to the other stimuli.

Cross-modal enhancement of speech detection in young and older adults: does signal content matter? [470]	Older adults showed cross-modal enhancement only when the signal when the visual signal was unaltered and clear compared to younger adults who showed cross-modal enhancement for all signal types (unaltered, low-contrast, and Lissajous figure). The Lissajous figure did not produce cross-modal enhancement in older adults. These results suggest that signal content effect cross-modal enhancement of speech detection.
Dissociable Effects of Aging and Mild Cognitive Impairment on Bottom-Up Audiovisual Integration [151]	Young adults, healthy older adults, and those with MCI accurately identified auditory speech under congruent audiovisual conditions and displayed high levels of visual bias under strong bottom-up condition (i.e., visual component is more reliable than the auditory component). Under weak bottom-up incongruent conditions, healthy older adults showed enhanced visual bias whereas those with MCI showed reduced visual bias compared to younger adults.
Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? [20]	The audiovisual advantage is greater for maskers with a higher informational content than for those without information content. Further, there is no evidence to indicate that age and linguistic competence of the listener have an impact on the listener's ability to use visual information to improve speech recognition in background noise.
Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception [492]	Both younger and older adults were more accurate and had faster RTs when responding to audiovisual speech compared to audio-only or visual-only condition. Older adults had slower RTs compared to younger adults on all conditions however, race model violations did not differ between younger and older adults. These results indicate that the ability to integrate auditory and visual speech cues remains intact in older adults.
Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus [90]	RTs were longer in older adults compared to middle-aged and younger adults. The distraction effect was not greater in aging, may be explained by inter-individual differences among participants. RTs were longer in the novel condition compared to the standard condition.

Effects of aging on audio-visual speech integration [211]	Older adults had preserved lipreading abilities when the visual input was clear but not when it was degraded. If the visual cues were clear, then the audiovisual gain observed in younger and older adults was not different. However, if the visual cues were unclear (i.e., degraded), the audiovisual gain was reduced but only for the stationary noise condition (versus modulated noise) in older adults compared to younger adults. Further, when the visual input was degraded, older adults awarded more weight to the auditory input compared to younger adults. These results suggest that older adults are able to compensate for the loss of lipreading abilities using the available auditory information.
Effects of Repetition Suppression on Sound Induced Flash Illusion With Aging [454]	SIFI is regulated by repetition suppression (RS). The RS effect on the SIFI is larger in older adults compared to younger adults. Decreased perceptual sensitivity based on auditory RS can weaken the SIFI effect in multisensory integration and because older adults are more susceptible to RS, they perceive the SIFI effect weakly under auditory RS.
Enhanced audiovisual integration with aging in speech perception: a heightened McGurk effect in older adults [413]	Older adults used more visual speech information than younger adults and were more susceptible to the McGurk effect when tested with stimuli containing equivalently intelligible auditory speech. Older adults were found to have slower RTs compared to younger adults for both the audiovisual and auditory condition but not the visual only condition. Further, no correlations were however found between hearing thresholds and longer auditory RTs, indicating that the two factors are dissociable. These results suggest that the enhanced visual influence seen in older adults is likely associated with an aging-related delay in auditory processing.
Enhanced multisensory integration in older adults [255]	RTs to audiovisual condition were faster than the audio-only and visual-only conditions. Presentation of audiovisual cues speeded the responses for both younger and older adults but older adults showed a greater facilitation. Further the multisensory condition was able to restore performance of older adults to the levels comparable to the fastest unisensory channel in younger adults. Results indicate that presenting information through multiple channels may provide a compensatory strategy to overcome unisensory deficits.

Impaired timing of audiovisual events in the elderly [43]	Older adults had wider temporal binding windows compared to younger adults for the TOJ and stream/bounce tasks but performance on the SJ task was indistinguishable between the two groups. These results suggest that age-related changes in multisensory integration are task specific and not a general trait of aging.
Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion [418]	Older adults maintain plasticity in their audiovisual perceptual discrimination abilities. Further, temporal discrimination training can impact other perceptual processes that are not directly trained as improvements in the temporal order judgment were associated with a reduction in susceptibility to the SIFI. The size of the temporal window of integration was predictive of subsequent susceptibility to the illusion.
Increased Functional Brain Network Efficiency During Audiovisual Temporal Asynchrony Integration Task in Aging [488]	The average hit rates of older adults was 95.2 and 93.7% for younger adults. RTs to audiovisual stimuli were faster than RTs to auditory or visual stimuli. The difference curve revealed that older adults had a longer peak time than younger adults in all conditions.
Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study [200]	Higher susceptibility to the SIFI was predicted by older age, female sex, and a lower score on the Montreal Cognitive Assessment (MoCA). Longer SOAs resulted in the older adults (75+) being more susceptible to the illusion compared to 50-64 year olds.
Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory-visual distraction-attention task [91]	Older adults had significantly longer RTs compared to middle aged and younger adults. Further, RTs were significantly longer in the novel condition than in the standard condition. Percentage of hits were significantly higher in the standard compared to the novel condition.
Intra-versus intermodal integration in young and older adults [432]	Intra-modal (auditory-auditory) and inter-modal (audio-visual) integration was largely similar between younger and older adults (both with and without hearing loss). Intra- and inter-modal integration were not correlated suggesting that there are distinct mechanisms for inter- and intra-modal integration processes.

Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants [103]	Older adults had significantly longer RTs compared to middle aged and younger adults. All three age-groups showed longer RTs when the visual stimulus was preceded by novel relative as compared to deviant and standard auditory stimuli. These results suggest a distracting effect that is provoked by novel stimuli.
Is inefficient multisensory processing associated with falls in older people? [415]	Older adults (fallers and non-fallers) were as susceptible to the illusion at a short delay (i.e., 70 ms) as younger adults. Older adults, however, older adults (fallers and non-fallers) were more susceptible to the illusion at longer SOAs compared to younger adults. Fallers however, continued to show susceptibility to the illusion even at the longest delays between auditory and visual cues (i.e., 270 ms). Older adults were significantly less accurate than younger adults at longer SOAs (i.e., 150, 190 & 270 ms) compared to 30 or 70 ms.
Links between temporal acuity and multisensory integration across lifespan [448]	Temporal acuity (both within and across modalities) as well as the ability to integrate multisensory speech information decline with healthy aging. They found that although temporal processing abilities were highly predictive of multisensory integration in younger adults, this was not the case in older adults. Indeed, temporal acuity did not predict integration at the individual level within the aging population.
Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration [471]	Speech recognition became worse in both visual-only as well as audiovisual conditions with age but performance was worse in the visual-only condition. The benefit of combining audio-visual cues observed are entirely driven by age-related changes in unimodal visual and auditory speech recognition. Auditory and visual enhancement - visual enhancement was negatively correlated with age, while auditory enhancement was positively correlated with age.
Multisensory integration across the senses in young and old adults [291]	RTs to the multisensory conditions (audiovisual, audio-somatosensory, and visual-somatosensory) were faster than unimodal conditions in both younger and older adults and were fastest for conditions containing somatosensory cues. Older adults had slower RTs for all conditions compared to younger adults but demonstrated greater RT facilitation when processing visual-somatosensory cues.

Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly [115]	Sensitivity to auditory, visual, and audiovisual temporal order declined from the age of 50 and onwards. However, there were no declines in multisensory integration (temporal ventriloquist effect), indeed older adults showed enhanced MSI to audiovisual stimuli. Older adults had a larger JND than the younger adults. Older adults were also less sensitive to the temporal order than the younger ones.
Multisensory Integration, Aging, and the Sound-Induced Flash Illusion [120]	On the sound-induced flash illusion, older adults demonstrated greater multisensory integration and thus a greater susceptibility to the sound-induced flash illusion as there was a greater influence of the beeps when judging the number of flashes during the illusory trials. In the go/no-go task, where the effect of attention on the sound-induced flash illusion was examined, increased integration was found once again for older adults. Further, they found that the strength of the illusion was modulated by attention as there was a decrease in the strength of the illusion when the go/no-go task was in the visual domain, but an increase when the go/no-go task was in the auditory-domain (this did not vary by age).
Older adults expend more listening effort than young adults recognizing audiovisual speech in noise [184]	Older adults expend more listening effort compared to younger adults for both audio-only and audiovisual speech cues. Further, older adults exerted more effort on audiovisual speech compared to audio-only speech recognition. These results suggest that although visual cues can improve speech recognition, they can also place an extra demand on processing resources.
Older adults sacrifice response speed to preserve multisensory integration performance [222]	Older and younger adults were comparable in their final localization and common source judgment responses under speeded and unspeeded conditions. Older adults showed the same audiovisual binding tendency as younger adults. However, older adults showed noisier auditory representation and they set a higher decisional threshold, trading off speed for accuracy. Results suggest that older adults preserve audiovisual localization performance, despite noisier sensory representation, by sacrificing response speed. Older adults and younger adults showed similar binding tendencies like the predictions of the Bayesian models.

Older age results in difficulties separating auditory and visual signals in time [80]	Older adults are overall less able to discriminate timing differences between auditory and visual stimuli compared to younger adults. Further, older adults required a longer physical asynchrony between the auditory and visual cues to perceive the stimuli as asynchronous, especially for low frequency sounds as compared to high frequency sounds. The impact of age on audiovisual synchrony cannot be explained by declines in unisensory sensitivity alone as stimuli were presented suprathreshold (and near-threshold) for each participant.
One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise [351]	No significant differences found for sensitivity, detecting 2 real flashes when presented with 2 beep as opposed to 2 illusory flashes, between those in open, closed, and control group prior to the 'intervention' (i.e., exercise or sedentary activity). Improvements in sensitivity to the audiovisual perceptual task (SIFI) was observed post exercise in the open skill group only.
Preserved discrimination performance and neural processing during crossmodal attention in aging [322]	Older adults had slower RTs compared to younger adults and had a greater false alarm rate. Distributed attention generated faster response times for semantically congruent audiovisual stimuli without compromising accuracy relative to focused visual attention. Further, distributed attention improved discrimination accuracy relative to focused visual attention. These results suggest that audiovisual processing and its interaction with attention is preserved with aging.
Recognition of asynchronous auditory-visual speech by younger and older listeners: A preliminary study [183]	Older adults, whether with normal hearing or those with hearing impairment, exhibited poorer performance in the auditory-lead speech conditions relative to visual-lead conditions compared to younger adults whose recognition performance was stable across audio- and visual-lead conditions. Younger adults accurately identified the speech stimuli better than older adults. Processing speed was found to contribute to speech recognition for synchronous or asynchronous audiovisual conditions.
Reduced audiovisual recalibration in the elderly [81]	Older adults recalibrated their sound-lag thresholds to a lesser extent when exposed to the same asynchrony adaptation as younger adults. There were no adaptation effects for sound-lead pairs. Older adults had wider audiovisual synchrony windows compared to younger adults but there was no relation between adaptation effect and window width. These results suggest that recalibration responses in older adults differ from that of younger adults.

Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data [458]	No significant differences were found between younger and older adults on the spatial selection task. However, older adults made more errors on the more complex audiovisual non-spatial attention task. Indicating that performance of older adults worsens with increasingly complex stimulus context.
Sensory dominance and multisensory integration as screening tools in aging [332]	The pattern of sensory dominance shifts from visual-dominant to auditory-dominant (i.e., detecting sounds faster than light) in cognitively impaired compared to healthy older adults. Further, while healthy older adults demonstrated overall enhanced multisensory benefits compared to younger adults, no similar advantage was observed for older individuals with mild cognitive impairment. Healthy older adults generally had slower reaction times than younger adults.
Simultaneity and Temporal Order Judgments Are Coded Differently and Change With Age : An Event-Related Potential Study [36]	Older adults had wider temporal binding windows compared to younger adults for both the Simultaneity Judgment (SJ) and Temporal Order Judgment (TOJ) tasks but they were not significantly wider.
Spatio-temporal patterns of event-related potentials related to audiovisual synchrony judgments in older adults [82]	Both younger and older adults had unisensory and auditory identification thresholds over 92%. The older adults perceived significantly fewer sound-lead pairs as synchronous; not other differences were found between the two groups (for synchronous or sound-lag perception). In younger adults, the varying position of the visual stimulus did not alter audiovisual synchrony, which was not found in older adults.
Study of audiovisual asynchrony signal processing: Robot recognition system of different ages [385]	Older adults had longer RTs compared to younger adults for all conditions. Both younger and older adults responded faster to the synchronous audiovisual stimuli as compared to when they were presented asynchronously or independently of one another. Further, the results suggest that visual gain was influenced by temporal disparity between auditory and visual stimuli.

Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes [417]	Audiovisual integration of incongruent audiovisual words was higher in older adults compared to younger adults whereas the recognition of auditory-only or visual-only presented words was the same across the groups. In the visual only conditions, younger participants responded to 72% of the trials, compared to older adults who responded to 59% of the trials, which reflects that older adults may have difficulty with lip reading compared to younger adults.
Task-Specific, Age Related Effects in the Cross-Modal Identification and Localisation of Objects [32]	Children as well as older adults were less accurate at localizing objects compared to adolescents and younger adults. A greater cost in accuracy was found for the audio-visual congruent compared to audio-visual incongruent conditions for older adults, children, and adolescents compared to younger adults. As no benefits were found for congruent audiovisual targets compared to visual-only targets in either the identification or localization tasks, this suggests that visual information is dominant when identifying or localizing audio-visual stimuli.
Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention [388]	RTs to the audiovisual condition were significantly faster than the unimodal conditions and when the auditory stimulus was presented 100 ms prior to the visual stimulus and vice versa. Enhanced audiovisual integration was greatest when auditory and visual stimuli were presented simultaneously. Significant enhancement disappears when temporal gaps (i.e., 100 ms) between auditory and visual stimuli were utilized.
Temporal metrics of multisensory processing change in the elderly [37]	Older adults exhibit slower response times, violate the race model more, and have wider temporal binding windows as measured through the Response Time (RT), Simultaneity Judgment (SJ), and Temporal Order Judgment (TOJ) tasks. Further, a significant positive relation between the magnitude of race model violation in younger adults is found as a function of the point of subjective simultaneity (PSS) obtained from the TOJ task which isn't found for the SJ task or for older adults. Results confirm that audiovisual temporal processing change with age, that distinct processes are likely involved in simultaneity and temporal order perception, and processing between race model violation and TOJ is impaired in the elderly.

Text as a Supplement to Speech in Young and Older Adults [242]	Supplementing degraded speech with partially accurate text improves speech understanding in noise in both younger and older adults compared to auditory- and text-only conditions. Cognition was a key predictor for general speech-text integration ability suggesting that cognitive ability modulates the benefits observed.
The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging [14]	Older adults had longer RTs compared to younger adults. Older adults were more distracted by irrelevant novel sounds compared to younger adults. However, both older and younger adults were equally able to use the presentation of sound as a warning cue to prepare for upcoming stimuli. These results support the frontal hypothesis which states that there is an early and selective deterioration of frontal attentional networks of the brain.
The effect of combined sensory and semantic components on audio-visual speech perception in older adults [287]	Older adults showed a greater cost in recall of meaningless audiovisual speech under the blur condition compared to the 'no blur' condition when compared to younger adults.
The effects of blurred vision on auditory visual speech perception in younger and older adults [260]	The addition of visual speech cues improved speech-perception relative to auditory-alone condition and this was the case even when the visual cues were blurred to simulate a visual acuity of 6/60 as speech recognition scores were still higher than those obtained for the audio-only condition. Speech recognition in the audiovisual condition became worse with increased blurring. However, these results indicate that speech recognition is enhanced even when visual acuity isn't optimal.
The influence of Aging on Audiovisual Temporal Order Judgements [152]	No significant differences were found between younger and older adults on audiovisual temporal processing. Further, no effect of stimulus location was found, indicating that performance was not dependent on whether auditory and visual stimuli were presented from the same or different locations. Theses results indicate that audiovisual temporal sensitivity does not decline with age. The point of subjective simultaneity (PSS) values were positive in both groups for the temporal order task, indicated that the visual stimulus preceded the auditory stimulus in order to be perceived as simultaneous.

The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration [301]	Older adults were more susceptible to the illusion at longer SOAs under fission conditions compared to younger adults. Performance was similar between younger and older adults under the conditions known to produce fusion illusion. These results suggest that these two illusions may be mediated by distinct neural mechanisms.
Using race model violation to explore multisensory responses in older adults: Enhanced multisensory integration or slower unisensory processing? [106]	Older adults exhibited enhanced integration, but only when accounting for individual differences in unimodal (audio, visual, tactile) RT distributions. Slower unisensory RTs were associated with a greater degree of race model violations suggesting that greater race model violations may reflect a greater opportunity to observe RT improvement due to slower unisensory responses.
Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals [437]	The illusion effect, as measured through the minimum audible angle (MAA) and head-related transfer functions (HRTFs), was observed with synchronous and asynchronous visual stimulus but only with tone and not speech. In line with previous literature, no significant differences age differences were found between young and older adults.
What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues [367]	Older adults took longer to respond and had higher error rates in response to cues (auditory alone, visual alone, and tactile alone)/cue combinations. Older adults were more likely to miss tactile cues when the three modalities were combined. The results showed that individuals are more likely to miss information if more than two concurrent non-redundant signals are presented. Accuracy significantly decreased as the number of signals increased, especially in the older adult group.

Table A.7: This table provides a summary of the main results reported for young and older adults reported in each paper included in this scoping review. Note that some studies only tested older adults and thus no results are reported regarding younger adults for those particular studies. Articles are sorted alphabetically and are located in the bibliography in the manuscript.

Table 8: Description of the types of auditory and visual stimuli utilized by each study included in this scoping review

Title	Type of stimuli presented (visual)	Type of stimuli presented (auditory)
Age-related changes in auditory and visual interactions in temporal rate perception [61]	A flickering light of 0.7°diameter LED that sinusoidally varied in luminance over time about a mean of 438 cd/m^2. Visual stimuli was presented for 500 ms.	A fluttering sound was presented by sinusoidally modulating a intensity of 65 dB 500 Hz pure tone. Auditory stimulus was presented for 500 ms.
Age-related differences in inhibitory control predict audiovisual speech perception [125]	Female speaker pronounced words with high and low lexical difficulty. Her head and shoulders were visible.	Female speaker pronounced words with high and low lexical difficulty. Signal-to-babble ratio set to -1 dB across all participants to prevent ceiling performance.
Age-related hearing loss increases cross-modal distractibility [378]	Moving dot pattern was presented centrally within a square of 7 cm edge length. Single dots had a diameter of 0.2 cm and moved with a constant velocity of 3.2 cm/s in horizontal or vertical direction. Dots were represented in black on a gray background. The visual stimuli were presented for 500 ms.	Frequency modulated tones had a duration of 500 ms, in which they either increased or decreased in frequency at a constant rate of 2 octaves/second. Frequency range was 500-1000 Hz. 33 out of 38 participants chose a loudness level of 72 Phon.
Age-related multisensory enhancement in a simple audiovisual detection task [361]	Two green emitting diodes were illuminated at eye level.	Broadband white noise was presented from 4 speakers. Volume was adjusted to be easily discernible for each participant ($\sim$ 68 dB).
Age-related multisensory integration elicited by peripherally presented audiovisual stimuli [497]	Target stimuli = Red and white block of 5.2 cm x 5.2 cm with a subtending visual angle of 5°. The stimuli were presented for 150 ms on a black background. Non-target stimulus = black and white block.	Target stimulus = white noise. Non-target stimulus = sinusoidal tone of 60 dB SPL at 1000 Hz. Both presented for 150 ms (5 ms of rise/fall time).

Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception [207]	White disks projected against a black background subtending a visual angle of 1.5°and luminance of 32fl, positioned 5 cm below the fixation cross for 16 ms.	Beeps = 80 dB at 3500 Hz for 10 ms, 1 ms ramp.
Ageing effects on the attention demands of walking [430]	A red letter 'R' presented on a computer screen.	Built-in computer 'chime'.
Aging and audio-visual and multi-cue integration in motion [394]	Two disks (radius = 1.5°) appeared at ± 9°horizontal eccentricity and 3 above fixation and moved toward each other. Mean luminance of the display was 37.5 cd/m2 (in Experiment 2, this was changed to 4.24 cd/m^2) with a 1280 x 1024 resolution. Luminance was manipulated, in the ambiguous condition, the two disks had the same luminance with -0.7 contrast with the background. In the unambiguous condition, the two disks had -0.85 and -0.55 contrast with the background respectively.	In some conditions, a synthesized click of 90 dBC and 70 ms sounded as the disks were coinciding. Auditory stimuli presented through speakers, 33 degrees to the left and right of the subject's mid-sagittal plane. Frequency of response was 44-20 kHz, ± 10 dB.
Aging Effect on Audiovisual Integrative Processing in Spatial Discrimination Task [513]	An arrow (blurred by Gaussian noise) that appeared within the foveal region and had an internal edge of 0.7°, external edge of 1.7°, and center point of 1.2°in the visual field. Visual stimulus was presented for 500 ms.	The auditory stimuli used were the sounds produced by 'bat ears'. 4 sounds produced between 30-55 dB at 2600-4900 Hz. Auditory 'bat-ears' stimuli were presented for 1000 ms. In the spatial task however, auditory stimuli were presented for 500 ms alongside visual stimuli.

Aging Impairs Audiovisual Facilitation of Object Motion Within Self-Motion [395]	Nine textured purple spheres (mean luminance of 28 cd/m^2) presented against a black background (mean luminance of 0.3 cd/m^2). The spheres were distributed inside a virtual rectangular prism measuring 25 cm wide x 25 cm high x 60 cm deep. Objects had a mean diameter of 1.58°, but their size scaled with distance. For 1 second, eight spheres moved outward, simulating self-motion. The ninth sphere moved according to the sum of the scene motion vector and an independent motion vector either in the same or opposite direction relative to the scene.	a moving sound was either looming or receding, congruent with the direction of the target motion. The sound was a broadband noise filtered between 0.3 and 12 kHz. Sound motion was simulated by increasing or decreasing the sound amplitude by $\sim$ 10 dB SPL, from a starting sound level of $\sim$ 65 dB SPL.
Aging increases distraction by auditory oddballs in visual, but not auditory tasks [261]	Digits 1-6 presented at the center of the computer screen in white colour against a black background. Each stimulus was presented at a visual angle of 4.4°.	Digits 1-6 spoken in a female voice. The duration for each digit was 400 ms. Two additional sounds were used: one consisting of a 150 ms sine-wave tone of a frequency of 600 Hz, the other of a 150 ms burst of white noise. All sounds were presented at an intensity of 75 dB SPL.
Aging, audiovisual integration and the principle of inverse effectiveness [469]	Head and shoulders of a female speaker. The talker sat in front of a neutral background.	All auditory stimuli included six-talker babble presented at $\sim$ 62 dB SPL (the signal was increased or decreased in amplitude to create the various signal to noise ratios).
Audio-Visual Spatiotemporal Perceptual Training Enhances the P300 Component in Healthy Older Adults [500]	White ring on a black background with an outer diameter of 7 cm and inner diameter of 6 cm with a subtending visual angle of 6°presented on a black background. Duration of each stimulus was 15 ms.	Sinusoidal tone = 65 dB at 2000 Hz with a linear rise and fall times of 5 ms. Duration of each stimulus was 15 ms.
Audiovisual binding for speech perception in noise and in aging [165]	Target stimulus = video of 'ba' or 'ga'. Context stimulus = videos of random sentences or 'za', 'va', 'ja' and 'ma'.	Target stimulus = audio of 'ba'. Context stimulus = audio of 'za', 'va', 'ja', and 'ma'.

Audiovisual Integration Delayed by Stimulus Onset Asynchrony Between Auditory and Visual Stimuli in Older Adults [386]	Target stimulus: black and white checkboard image containing two black dots in white checkers. Non-target stimulus: a black and white checkerboard image (no dots). The stimuli were presented in the lower left or right quadrant at 12°for 150 ms on a black background.	Target: 1000 Hz white noise. Non-target: 1000 Hz sinusoidal tone. The auditory stimuli were presented randomly to the left or right ear through earphones at 60 dB SPL for 150 ms.
Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan [337]	Flash: white ring circumscribing a fixation cross on a black background. The visual angle was 17.3°and it was presented for 10 ms. Speech stimuli: syallable utterances of 'ba' and 'ga' from a female speaker were presented. The visual angle was 17.3°with a 400 x 400 pixel resolution and it was presented for for 2 s.	Auditory beep: 3500 Hz pure tone with a duration of 13 ms. Speech stimuli: syllable utterances of 'ba' and 'ga' from a female speaker were presented. Overall duration was 2 s.
Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise [181]	The lower half of the male speaker's face was displayed in grayscale as either blurry or not blurry. The display was approximately 14°of visual angle.	The words said by the male speaker were presented. The background 12-talker babble was added as a background noise at 65 dBA and the speech signal was 15 dB quieter than the babble levels.
Audiovisual temporal discrimination is less efficient with aging: an event-related potential study [416]	White disk with a diameter subtending a visual angle of 1.3°and a luminance of 49 cd/m^2. The visual stimulus was presented for 16 ms against a black background.	Beeps = 70 dB at 3.5 kHz for 10 ms (with 1 ms rise and fall times). Presented through headphones.
Auditory and visual information in speech perception: A developmental perspective [456]	The face of a female speaker appeared on the entire screen uttering the words.	Words pronounced by a female speaker were presented through headphones at 70 dB SPL.
Auditory and visual lexical neighbourhoods in audiovisual speech perception [468]	A female actor's face and shoulders are presented as she articulated words. Stimuli were presented on a 17-inch screen in full screen mode.	A female actor articulated words. 6-talker babble was presented and the stimulus level was held at 60 dB SPL.

Auditory perception in the aging brain: the role of inhibition and facilitation in early processing [451]	Female speaker pronouncing the syllables ’ba’ and ’ga’. The entire video with the females head and shoulders showing against a black background was 1280 ms long.	Auditory pronunciations of ’ba’ and ’ga’ were presented approximately 60 dB SPL above the individual’s hearing threshold. The puretone stimuli were 1000 Hz, presented at 60 dB SPL (not adjusted for the participant’s hearing thresholds), and presented for 200 ms.
Auditory-visual speech perception and aging [92]	Two speakers (1 male and 1 female) recorded words and syllables. They were seated 1.5 m from the camera against a neutral gray background and their face and shoulders could be seen.	Two speakers (1 male and 1 female) said words and syllables. Auditory information for the sentences, syllables, and videos were digitized at a sampling rate of 11 kHz.
Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults [428]	Male talker produced the consonants, words, and sentences and participants saw the head and shoulders of the speaker.	Male talker produced the consonants, words, and sentences. The signal level remained at 60 dB SPL for the audio and audiovisual conditions.
Beta-Band Functional Connectivity Influences Audiovisual Integration in Older Age: An EEG Study [489]	Target stimulus: red and white block, non-target stimulus: black and white block of 5.2 cm x 5.2 cm with a subtending visual angle of 5°. The stimulus was presented for 150 ms.	Target stimulus = white noise, non-target stimulus = sinusoidal tone of 60 dB SPL at 1000 Hz for 150 ms (5 ms of rise/fall time).
Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration [387]	0 or 2 dots contained within a checkerboard and participants were instructed to detect the image with the 2 dots and ignore the image without the dots (standard stimulus). The stimuli were presented on the lower left or right quadrant of a black background for 150 ms. Stimuli were presented 5°angle below the fixation cross (12°visual angle to the left or right of centre).	Target stimulus = white noise, Standard stimulus = 60 dB SPL at 1000 Hz for 150 ms (10 ms of rise/fall cosine gate).

Cross-modal enhancement of speech detection in young and older adults: does signal content matter? [470]	In two of the three audiovisual conditions, the visual stimulus was a 2.2 second video clip showing the head and shoulder of a woman speaking 'ba'. The stimulus was presented with contrast reduced by 98% in the poor audiovisual condition and unaltered for the audiovisual good condition. For the last audiovisual condition, the stimuli was a Lissajous figure, where the participants saw a mouth like shape that appeared to open and close rapidly within the speech segment.	The screen remained a neutral gray while the auditory stimuli were presented. Speech shaped noise was presented at 62 dB SPL-A.
Dissociable Effects of Aging and Mild Cognitive Impairment on Bottom-Up Audiovisual Integration [151]	Video of speaker's face and the top of her shoulders. The speaker uttered each one syllable word three times. Stimulus duration was between 5 and 5.5 s.	Audio of words presented at a loudness of 60-70 dBA across the stimuli.
Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? [20]	Sentences were accompanied with a video of a talker presented at a natural size. The sentences were presented against one of three maskers: two talker-anomalous speech, 12-talker babble, or speech spectrum noise. The speech masker was a 315 s long track.	Sentences were presented against one of three maskers: two talker-anomalous speech, 12-talker babble, or speech spectrum noise. The speech masker was a 315 s long track. The target sentences were 55 dBA.
Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception [492]	Spoken object names, where half were natural objects and the rest were artificial or manmade. A female speaker's head, face, and neck were revealed as she uttered the object names. The video subtended a visual angle of 8.3°x 8.3°.	Auditory stimuli were presented binuarally at 55dB SPL for an average of 617 ms (range from 417 to 860 ms).

Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus [90]	Numbers (33%), letters (33%), or trinagles (34%). Visual stimuli were presented for 200 ms. Visual angle: 1.7°x 3.3°. degrees of arc on a 19" flat screen monitor.	Three types of sounds: 70% standard stimuli (tone bursts of 1000 Hz), 15% deviant stimuli (tone bursts of 2000 Hz), and 15% novel stimuli (different each time, e.g., glass crashing, phone ringing, etc.). All auditory stimuli were presented at an intensity of 75 dB SPL. Stimuli were presented for 150 ms.
Effects of aging on audiovisual speech integration [211]	Vowel-consonant vowel syllables. Videotape of a male speaker saying the syllables acted as the visual stimuli. He was filmed from the bottom of his nose to the chin. 21 x 21 cm videos were displayed centered on a 15-inch display.	Vowel-consonant vowel syllables. Audio files of a male speaker saying the syllables acted as the auditory stimuli. For the audio only condition, a neutral image of the speaker was presented along with the auditory stimulus. Noise was added to signal at a fixed SNR of $\sim$ 23 dB.
Effects of Repetition Suppression on Sound Induced Flash Illusion With Aging [454]	Flash: white disks on black background with a radius view of 2°, presented at a 5°below the fixation point, presented for 17 ms.	75dB, frequency: 3.5 KHz, presented for 7 ms.
Enhanced audiovisual integration with aging in speech perception: a heightened McGurk effect in older adults [413]	'ba', 'da', and 'ga' uttered by three speakers (2 males, 1 female). The entire video had a 640 x 840 pixel resolution and was 2300 ms in duration.	'ba', 'da', and 'ga' uttered by three speakers (2 males, 1 female). The duration of auditory cues was 290 ms on average. Speech was always presented at 65 dB SPL while the noise level was presented at 54 dB for experiment 2 (band noise of 300-12000 Hz).
Enhanced multisensory integration in older adults [255]	Either a red or blue-filled circle that subtended 7.7°of visual angle, presented on a black background. Each visual stimulus was 250 ms in duration.	Verbalizations of either the word red or blue and were 350 ms in duration. The volume of thes stimulus was adjusted to a comfortable and easily discriminable level for each subject ($\sim$ 75 dB).
Impaired timing of audiovisual events in the elderly [43]	White circle (49.3 cd/m^2) against a black background (0.3 cd/m^2) subtending a visual angle of 1°, appeared 4°below the fixation cross (visual angle = 0.5°) for 17 ms.	Beeps = 71.7 dB at 1850 Hz for 7 ms.

Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion [418]	White disk with a diameter subtending a visual angle of 1.5°and a luminance of 3/154 fl. The visual stimulus was presented for 12 ms.	A beep of 3500 Hz was presented for 10 ms (1 ms ramp). The beep was presented at 79 dB.
Increased Functional Brain Network Efficiency During Audiovisual Temporal Asynchrony Integration Task in Aging [488]	Target stimulus: black and white checkerboard image containing two black dots. Non-target stimulus: a black and white checkerboard image (no dots). The stimuli were presented for 150 ms on a black background.	Target: white noise. Non-target: 1000 Hz sinusoidal tone. The auditory stimuli were presented at 60 dB SPL for 150 ms.
Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study [200]	Flash: white disk subtending a visual angle of 1.5°and luminance of approximately 32 foot Lambert, projected on to a black background 5 cm below the central fixation point for 16 ms.	Beeps = 80 dB at 3500 Hz for 10 ms, 1 ms ramp.
Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory-visual distraction-attention task [91]	Numbers (33%), letters (33%), or triangles (34%). Visual stimuli were presented for 200 ms.	Three types of sounds: 70% standard stimuli (tone bursts of 1000 Hz), 15% deviant stimuli (tone bursts of 2000 Hz), and 15% novel stimuli (different each time, e.g., glass crashing, phone ringing, etc.). All auditory stimuli were presented at an intensity of 75 dB SPL. Stimuli were presented for 150 ms.
Intra-versus intermodal integration in young and older adults [432]	CUNY sentences were used for the visual only condition. The Iowa Sentence Test was used for the audiovisual condition, where participants saw a new speaker for each trial.	Sentence pronunciation was presented at 50 dB SPL for younger, and 70 dB SPL for older adults. through headphones. For the Iowa Sentence Test, participants heard a new speaker for each trials.

Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants [103]	Numbers (33%), letters (33%), or triangles (34%). Visual stimuli were presented for 200 ms.	Three types of sounds: 70% standard stimuli (tone bursts of 1000 Hz), 15% deviant stimuli (tone bursts of 2000 Hz), and 15% novel stimuli (different each time, e.g., glass crashing, phone ringing, etc.). All auditory stimuli were presented at an intensity of 75 dB SPL. Stimuli were presented for 150 ms.
Is inefficient multisensory processing associated with falls in older people? [415]	Flash: white disks on black background with a radius view of 1.5°(luminance of 31.54 fl), presented at a 5°below the fixation point, presented for 12 ms.	Brief burst of 3500 Hz presented for 10 ms (with 1 ms ramp) at 79 dB.
Links between temporal acuity and multisensory integration across lifespan [448]	Unisenosry timing task: two white circles were presented on a black background, above and below a fixation cross for 10 ms. Audiovisual timing tasks: a single flash of light was presented for 10 ms. Audiovisual speech perception and integration: a female vocalist said single-phoneme speech tokens of ’ba’ and ’ga’ that were visually represented.	All auditory stimuli were presented through Phillips noise-cancelling SBC HN-110 headphones at 72 dB. For the unisensory and audiovisual timing tasks, the stimuli were presented for 10 ms. For the unisensory temporal order judgment (TOJ) task, stimuli consisted of high or low-pitch pairs of beeps presented at 1000 or 500 Hz respectively. In the the audiovisual simultaneity judgment (SJ) and TOJ tasks, the beeps were only presented at 500 Hz. Audiovisual speech perception and integration: a female vocalist said single-phoneme speech tokens of ’ba’ and ’ga’.
Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration [471]	List of target words were shown on the screen. A female speaker recorded all the words in front of a neutral background.	Participants heard the words where the speech was presented in 68 dB SPL six-talker babble.
Multisensory integration across the senses in young and old adults [291]	Black asterisks, 0.64 cm in diameter and with a luminosity of 253.99 cd/m^2, were presented for 100 ms.	1000 Hz tones, 100 ms in duration, 75 dB in intensity with a 5 ms/rise and fall presented via headphones.

Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly [115]	Visual Temporal Order Judgment (TOJ) stimuli: two white (100 cd/m^2) squares (diameter of 1.5 cm) were presented against a dark background (0.05 cd/m^2) background in two gray placeholders (diameter of 3.5 cm). The squares were presented 2.4°above and below the central fixation cross. Audiovisual TOJ stimuli: one visual stimulus with the same dimensions as described above.	Auditory Temporal Order Judgment (TOJ) stimuli: two 20 ms, 1000 Hz tones presented at 75 dB through headphones. Audiovisual TOJ stimuli: one 7 ms stereo sound burst at 75 dB, presented through headphones.
Multisensory Integration, Aging, and the Sound-Induced Flash Illusion [120]	Sound-induced flash illusion: 1-3 flashes of a uniform white disk that were 0.75°in visual angle and were presented at 127.97 cd/m^2. The flashes were presented for 70 ms 12°below the fixation cross (0.33°). Go-no-go task: same as those in the SIFI except that the disk increased in size on 12% of the trials to 1.5°to indicate indicate that subjects should not respond to them	Sound-induced flash illusion: auditory beeps were 3.5 kHz sine wave tones that were presented at 74.2 dB for 10 ms. Go-no-go: same as the stimuli used above except the standard frequency for the beeps during the go and control trials was 4.5 kHz and the frequency of 12% of the trials was decreased by 2.5 kHz to indicate that participants should not respond to them."
Older adults expend more listening effort than young adults recognizing audiovisual speech in noise [184]	A woman's head and shoulders were visible as she stated sentences. Participants were asked to touch the screen to indicate the words she had said; target words appeared with a horizontal visual angle ranging from 1.18°-2.53°and a vertical visual angle of 0.25°- 0.38°.	Audio of words presented at a loudness of 60 dBA for experiment 1 and 52 dBA for experiment 2.
Older adults sacrifice response speed to preserve multisensory integration performance [222]	15 white dots (88 cd/m^2) against a dark gray (4 cd/m^2) background with each dot having a visual angle in diameter of 0.44°, presented for 50 ms.	Burst of white noise for 50 ms at 75 dB SPL with a ramp on/off over 5ms was presented through individual speakers that were concealed behind the screen.

Older age results in difficulties separating auditory and visual signals in time [80]	Vertically striped Gabor of 3 c/deg.	Pure tone pip presented for 10 ms with 2.5 ms onset and offset. The auditory stimulus was either 0.5 or 4 kHz that was presented binuarally through headphones over a pure tone mask (75 dB) of the same frequency.
One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise [351]	White disks projected against a black background subtending a visual angle of 1.5°, positioned 5 cm below the fixation cross for 16 ms.	Beeps = 3500 Hz for 10 ms, 1 ms ramp.
Preserved discrimination performance and neural processing during cross-modal attention in aging [322]	Words presented as black text in a gray square sized 4.8°on the fovea. Visual stimuli were presented for 100 ms.	Words were spoken by a male speaker and presented at 65 dB SPL using insert earphones. Auditory stimuli were presented for 250 ms.
Recognition of asynchronous auditory-visual speech by younger and older listeners: A preliminary study [183]	Videos of speakers saying sentences, multisyllabic words, and monosyllabic words. Mean duration for sentences was 2128.30 ms, for multisyllabic words was 410.92 ms, and 327.63 ms for monosyllabic words. Presented on a television monitor.	Audio was from the speaker saying sentences. The sound was presented at 85 dB sound pressure level (SPL).
Reduced audiovisual recalibration in the elderly [81]	Vertically striped Gabor of 3 c/deg at 85% contrast. Visual stimuli were presented for one monitor frame (frame rate: 100 Hz, 1024 × 768 pixels).	Pure tone pip presented for 10 ms with 2.5 ms onset and offset. The auditory stimulus was 500 Hz of 20 dB, presented binuarally through headphones over a pure tone mask (75 dB, 100 ms onset and offset ramp) of the same frequency.

Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data [458]	Experiment 1: Standard stimuli: white squares subtending a visual angle of about 2.3°, presented with equal probability on the left or right side of a visual display at an angle of 15°from the center of fixation. Presented for 50 ms. Target stimuli: fewer trials that were 200 ms in duration were also presented. Experiment 2: the stimuli were presented centrally.	Experiment 1: sine waves with a frequency of 1000 Hz at 65 dBA were presented for 50 ms with a 10 ms linear rise and fall time and were also presented with equal probability to the left or right speakers. Experiment 2: the auditory stimuli were presented simultaneously through both speakers. The auditory stimuli consisted of sine waves with a frequency of 900 Hz for the low-pitched tones and 2000 Hz for the high-pitched tones were presented at 65 dBA with linear fall and rise times of 10 ms. The stimuli were presented for 50 ms.
Sensory dominance and multisensory integration as screening tools in aging [332]	Black circle subtending 7.9°and presented centrally against a white background. The duration of the stimulus was 100 ms.	Sinusoidal tone = presented at 1000 Hz. The volume presentation was individually adjusted to a comfortable level before the task; mean dB: 71.8 ± 8.2 dB. The duration of the stimulus was 100 ms.
Simultaneity and Temporal Order Judgments Are Coded Differently and Change With Age : An Event-Related Potential Study [36]	White circle against a black background (0.3 cd/m^2) subtending a visual angle of 0.4° (49.3 cd/m^2), appeared 2°below the fixation cross (visual angle = 0.5°) for 17 ms.	Beeps = 71.7 dB at 1850 Hz for 7 ms.
Spatio-temporal patterns of event-related potentials related to audiovisual synchrony judgments in older adults [82]	Vertically striped Gabor of 3 c/deg at 85% contrast. Visual stimuli were presented for 10 ms.	Pure tone pip of 500 Hz presented for 10 ms at 75 dB.

Study of audiovisual asynchrony signal processing: Robot recognition system of different ages [385]	2 dots contained within a checkerboard as well as a checkerboard without dots. The stimuli were presented on the lower left or right quadrant of a black background for 150 ms. Stimuli were presented 5°angle below the fixation cross (12°visual angle to the left or right of centre). The visual stimulus was presented on a black background.	Target stimulus = white noise, Standard stimulus = 60 dB SPL at 1000 Hz sinusoidal tone presented for 150 ms (5 ms of rise/fall cosine gate).
Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes [417]	Visual stimulus was a video presented by a female speaker pronouncing a single word. 33 words recovered. Female speaker pronounced words.	Female speaker pronounced words at 75 dB.
Task-Specific, Age Related Effects in the Cross-Modal Identification and Localisation of Objects [32]	4 images (dog, cat, horse, and a pig), each subtending a visual angle of 5.8°horizontally and 4.85°vertically were presented for 380 ms. Each image was presented at an approximate visual angle of 8.69°.	4 sounds corresponding to each animal (cat, dog, horse and pig) were chosen, presented in 4 different location of speakers, at 75 dB SPL. and were presented for 380 ms.
Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention [388]	Target stimulus: black and white checkerboard image containing two black dots. Non-target stimulus: a black and white checkerboard image (no dots). The stimuli were presented for 150 ms on a black background.	Target: white noise. Non-target: 1000 Hz sinusoidal tone. The auditory stimuli were presented at 60 dB SPL for 150 ms.
Temporal metrics of multisensory processing change in the elderly [37]	White circle against a black background (0.3 cd/m^2) subtending a visual angle of 0.4°(49.3 cd/m^2), appeared 2°below the fixation cross (visual angle = 0.5°) for 17 ms.	Beeps = 71.7 dB at 1850 Hz for 7 ms.
Text as a Supplement to Speech in Young and Older Adults [242]	Speech text was presented. For the audiovisual (AV) condition, the text duration was the same as the audio duration (ms).	Sentence pronunciation was presented alongside with white noise. Stimuli were presented to the test ear at 85 dB SPL. These stimuli were presented for 250 ms.

The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging [14]	Digits 1-8 presented at the center of the computer screen in white colour against a black background for 200 ms. Each stimulus was presented at a visual angle of 2.6°.	Standard sound: 600 Hz sinewave tone of 200 ms duration (including 10 ms rise/fall times); 90% of the trials were standard trials. Novel sound: different experimental sounds (e.g., drill, hammer, rain, door, etc.). Each sound was presented for 200 ms (including 10 ms rise and fall times). All sounds were presented through the speakers at 75 dB SPL.
The effect of combined sensory and semantic components on audio-visual speech perception in older adults [287]	A female actor's face and shoulders can be seen as she articulates sentences. Each video clip ranged from 2.9 to 4.1 s, with a mean duration of 3.4 s. The images in the video clip subtended 17" horizontally and 12" vertically. Visual cues were either blurred or not.	A female actor articulated sentences. Each clip ranged from 2.9 to 4.1 s, with a mean duration of 3.4 s. No blur was added to the auditory cues.
The effects of blurred vision on auditory visual speech perception in younger and older adults [260]	Sentences spoken by a female audiologist whose head and shoulders could be seen. The luminance of the display was 29 cd/m^2. Further test words were positioned slightly above the monitor and they subtended 2°of visual angle. Visual stimulus was presented normally, with some blurring (visual acuity of 6/30) or severe blurring (visual acuity of 6/30).	The signal (57 dBA) and pink noise (69 dBA) were presented at the same time. Before each testing session a free-field acoustic calibration was completed to ensure that the acoustic speech and noise were presented at intended sound level.
The influence of Aging on Audiovisual Temporal Order Judgements [152]	Gaussian-damped, 1 cycle/degree, horizontal grating set to a contrast of 0.8. One standard deviation of the Gaussian envelope subtended 0.23°of visual angle. The duration of the stimulus was 10 ms, however the actual duration was 2-3 ms.	Auditory stimulus consisted of 10 cycles of a 1kHz tone with a intensity of 76 dB SPL.

The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration [301]	Hard-edged annulus presented at maximum luminance and displayed for 17 ms. The inner and outer edges of the annulus extended 8.5°and 10°from the center of the screen respectively.	Auditory tone with a frequency of 3500 Hz, a sound pressure level of 65 dB. The auditory stimulus was presented for 10 ms through Sennheisser HD 202 headphones.
Using race model violation to explore multisensory responses in older adults: Enhanced multisensory integration or slower unisensory processing? [106]	Single red LED flash (3700 cd/m^2) positioned 20 cm below the central line of sight at a 28°angle. Presented for 50 ms.	Tone = 95 dB SPL at 1300 Hz for 50 ms.
Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals [437]	Yellow circle on black background presented in the centre of the screen, whose diameter was modulated and it ranged between 10 - 15 mm. A black square was placed above the yellow circle and it ranged in size between 0 - 3 mm.	Two types of auditory stimuli used: (1) pure-tone: 60 dB at 0.5 kHz for 200-ms and (2) speech - meaningful consonant-vowel-consonant dutch words; 60 dB, 3kHz, 700-1000 ms.
What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues [367]	Blue light emitting diode (LED) with a frequency of approximately 450 Hz located in the participant's peripheral vision, at an angle of 35°below the center of the computer monitor.	Monotone beeps = loudness range of 0 dB - 88 dB at 350 Hz.

Table A.8: This tables provides details, including title, country of origination, the aim, as well as the types of tasks used and the behavioural outcomes measures obtained from the studies included in this scoping review. Please note that the numbers are associated with the bibliography

Table 9: Further details regarding the stimuli presented, the viewing distance, and whether or not a control condition was included

Title	Viewing distance	Whether the stimuli were suprathreshold	Whether the stimuli were threshold level	No explicit information provided about whether stimuli were threshold or suprathreshold level	If a unisensory control condition was included
Age-related changes in auditory and visual interactions in temporal rate perception [61]	0.8 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Age-related differences in inhibitory control predict audiovisual speech perception [125]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Age-related hearing loss increases cross-modal distractibility [378]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Age-related multisensory enhancement in a simple audiovisual detection task [361]	0.75 m	yes	n/a	n/a	Audio and visual only conditions served as controls for the audiovisual conditions

Age-related multisensory integration elicited by peripherally presented audiovisual stimuli [497]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception [207]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Ageing effects on the attention demands of walking [430]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Aging and audiovisual and multi-cue integration in motion [394]	0.57 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Aging Effect on Audiovisual Integrative Processing in Spatial Discrimination Task [513]	Distance between the listener's eyes and screen = 0.8 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Aging Impairs Audiovisual Facilitation of Object Motion Within Self-Motion [395]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Aging increases distraction by auditory oddballs in visual, but not auditory tasks [261]	0.5 m	n/a	n/a	yes	Auditory-auditory condition served as a control for the audiovisual condition
Aging, audiovisual integration and the principle of inverse effectiveness [469]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Audio-Visual Spatiotemporal Perceptual Training Enhances the P300 Component in Healthy Older Adults [500]	0.7 m	n/a	n/a	yes	Auditory only oddball condition used to assess the effects of the audiovisual training paradigm
Audiovisual binding for speech perception in noise and in aging [165]	Did not report	n/a	n/a	yes	No control condition

Audiovisual Integration Delayed by Stimulus Onset Asynchrony Between Auditory and Visual Stimuli in Older Adults [386]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan [337]	0.6 m	n/a	n/a	yes	No control condition
Audiovisual speech in older and younger adults: integrating a distorted visual signal with speech in noise [181]	20 inches	n/a	n/a	yes	Audio only condition served as a control for the audiovisual condition
Audiovisual temporal discrimination is less efficient with aging: an event-related potential study [416]	0.57 m	n/a	n/a	yes	No control condition
Auditory and visual information in speech perception: A developmental perspective [456]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Auditory and visual lexical neighbourhoods in audiovisual speech perception [468]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Auditory perception in the aging brain: the role of inhibition and facilitation in early processing [451]	0.5 m	The auditory speech was suprathreshold	The puretones were threshold level	yes	Auditory only stimuli were included as control for the audiovisual condition
Auditory-visual speech perception and aging [92]	1.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Auditory-visual speech perception and auditory-visual enhancement in normal-hearing younger and older adults [428]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Beta-Band Functional Connectivity Influences Audiovisual Integration in Older Age: An EEG Study [489]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration [387]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Cross-modal enhancement of speech detection in young and older adults: does signal content matter? [470]	0.5 m	n/a	n/a	yes	Audio only condition served as a control for the audiovisual condition
Dissociable Effects of Aging and Mild Cognitive Impairment on Bottom-Up Audiovisual Integration [151]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Do age and linguistic background alter the audiovisual advantage when listening to speech in the presence of energetic and informational masking? [20]	Distance beween the listener's head and each one of the speakers = 1.69 m	n/a	n/a	yes	Audio only condition served as a control for the audiovisual condition

Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception [492]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus [90]	1 m	n/a	n/a	yes	No control condition
Effects of aging on audio-visual speech integration [211]	0.7 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Effects of Repetition Suppression on Sound Induced Flash Illusion With Aging [454]	Did not report	n/a	n/a	yes	No control condition

Enhanced audio-visual integration with aging in speech perception: a heightened McGurk effect in older adults [413]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Enhanced multisensory integration in older adults [255]	24 inches	n/a	Volume was adjusted to comfortable and easily discriminable level of each subject	n/a	Audio and visual only conditions served as controls for the audiovisual conditions
Impaired timing of audiovisual events in the elderly [43]	0.57 m	n/a	n/a	yes	No control condition
Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion [418]	0.7 m	n/a	n/a	yes	None for the Temporal Order Judgment (TOJ), but Audio and visual only conditions served as controls for the audiovisual condition for the Sound Induced Flash Illusion (SIFI)

Increased Functional Brain Network Efficiency During Audiovisual Temporal Asynchrony Integration Task in Aging [488]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study [200]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory-visual distraction-attention task [91]	1 m	n/a	n/a	yes	No control condition
Intra-versus intermodal integration in young and older adults [432]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Involuntary capture and voluntary reorienting of attention decline in middle-aged and old participants [103]	1 m	n/a	n/a	yes	No control condition
Is inefficient multisensory processing associated with falls in older people? [415]	0.57 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Links between temporal acuity and multisensory integration across lifespan [448]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration [471]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Multisensory integration across the senses in young and old adults [291]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly [115]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Multisensory Integration, Aging, and the Sound-Induced Flash Illusion [120]	0.94 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Older adults expend more listening effort than young adults recognizing audiovisual speech in noise [184]	0.7 m	n/a	n/a	yes	Audio only condition served as a control for the audiovisual condition
Older adults sacrifice response speed to preserve multisensory integration performance [222]	1.3 m	n/a	n/a	yes	No control condition
Older age results in difficulties separating auditory and visual signals in time [80]	1 m	yes	yes	n/a	Audio and visual only conditions served as controls for the audiovisual conditions

One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise [351]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Preserved discrimination performance and neural processing during cross-modal attention in aging [322]	0.8 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Recognition of asynchronous auditory-visual speech by younger and older listeners: A preliminary study [183]	1.5 m	n/a	n/a	yes	No control condition
Reduced audiovisual recalibration in the elderly [81]	1 m	n/a	n/a	yes	No control condition

Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: Effects on event-related brain potentials and performance data [458]	0.56 m	n/a	n/a	yes	Visual only condition served as a control for the audiovisual conditions
Sensory dominance and multisensory integration as screening tools in aging [332]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Simultaneity and Temporal Order Judgments Are Coded Differently and Change With Age : An Event-Related Potential Study [36]	0.57 m	n/a	n/a	yes	No control condition
Spatio-temporal patterns of event-related potentials related to audiovisual synchrony judgments in older adults [82]	0.5 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Study of audiovisual asynchrony signal processing: Robot recognition system of different ages [385]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes [417]	0.57 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions
Task-Specific, Age Related Effects in the Cross-Modal Identification and Localisation of Objects [32]	0.52 m	Yes, the stimuli were suprathreshold	n/a	n/a	Audio and visual only conditions served as controls for the audiovisual conditions
Temporal gap between visual and auditory stimuli lessen audiovisual integration in aging under cross-modal attention [388]	0.6 m	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Temporal metrics of multisensory processing change in the elderly [37]	0.57 m	n/a	n/a	yes	For the audiovisual response time task only, there were unisensory control conditions (audio-only and visual-only) that served as comparisons
Text as a Supplement to Speech in Young and Older Adults [242]	Did not report	Yes, the auditory stimuli were suprathreshold	n/a	n/a	Audio and visual only conditions served as controls for the audiovisual conditions
The effect of age on involuntary capture of attention by irrelevant sounds: a test of the frontal hypothesis of aging [14]	0.5 m	n/a	n/a	yes	No control condition
The effect of combined sensory and semantic components on audio-visual speech perception in older adults [287]	0.57 m	yes	n/a	n/a	No control condition

The effects of blurred vision on auditory visual speech perception in younger and older adults [260]	1 m when viewing the monitor but 1.5 m when viewing the words placed slightly above the monitor	n/a	n/a	yes	Audio only condition served as a control for the audiovisual condition
The influence of Aging on Audio-visual Temporal Order Judgements [152]	1.14 m	n/a	n/a	yes	No control condition
The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration [301]	0.57 m	n/a	n/a	yes	Visual only condition served as a control for the audiovisual conditions
Using race model violation to explore multisensory responses in older adults: Enhanced multisensory integration or slower unisensory processing? [106]	Did not report	n/a	n/a	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals [437]	1 m	Measured at sensation level	Measured at sensation level	n/a	Unisensory control: No visual condition with auditory stimuli only and multisensory control: catch trials were included in the audiovisual condition, to ensure that participants didn't have their eyes closed
What you don't notice can harm you: age-related differences in detecting concurrent visual, auditory, and tactile cues [367]	0.762 m	Cross-modal matching was performed prior to start of the experiment to ensure that the visual, auditory (and tactile) cues were equal in terms of stimulus intensity. No further information about thresholds.	Cross-modal matching was performed prior to start of the experiment to ensure that the visual, auditory (and tactile) cues were equal in terms of stimulus intensity. No further information about thresholds.	yes	Audio and visual only conditions served as controls for the audiovisual conditions

Table A.9: This table provides further information including whether or not studies reported the threshold level of the stimuli or not, the viewing distance at which stimuli were presented, and if a control condition was included. Note, that unless studies explicitly specified that the stimuli were suprathreshold or threshold level, they were documented under the 'no explicit information provided about the stimuli threshold level'. Please note that the numbers are associated with the bibliography found in the scoping review.Articles are sorted alphabetically and are located in the bibliography in the manuscript.

Table 10: Reported average scores for the Mini Mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA)

Table A.10: Table 10. This table provides further information regarding the average scores that were reported by studies that used the Mini Mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA) but did not report their cut-off scores. As can be seen below, many more studies that tested cognitive function with the MMSE reported only the averages as compared to the MoCA.

Mini Mental State Examination reported averages	**Montreal Cognitive Assessment reported averages**
M = 28.7	M = 27.45
M = 27.9	M = 27.28
M = 28.2	M = 29
M = 28.3	M = 27.3
M = 29.6	-
M = 28.98	-
M = 28.05	-
M = 27.8	-
M = 27.09	-
M = 28.7	-
M = 29.3	-
M = 28.2	-
M = 29.6	-
M = 29.1	-

Glossary

Analysis of Variance A statistical formula used to compare variances across the means of different groups; ANOVA.

Anterior Cingulate Cortex Is the frontal part of the cingulate cortex that surrounds the frontal part of the corpus callosum; ACC.

Anterior White Matter White Matter refers to areas of the central nervous system that are mainly made up of myelinated axons, also called tracts. These white matter tracts allow the left and right hemispheres of the brain to communicate, and deterioration in these regions has been implicated in age-related cognitive decline; AWM.

Area Under the Curve The area under the curve as obtained from the RMI; AUC.

Brain-Derived Neurotrophic Factor BDNF plays an important role in neuronal survival and growth, serves as a neurotransmitter modulator, and participates in neuronal plasticity; BDNF.

Catch Trials A trial within an experiment in which a stimulus is not present but the participants' responses nonetheless are recorded; CT.

Central Nervous System The central nervous system is the part of the nervous system consisting primarily of the brain and spinal cord; CNS.

Critical Flicker Fusion The frequency at which a flickering light is perceived as continuous. It is widely used for evaluating visual temporal processing; CFF.

Cumulative Distribution Function A function that gives the probability that a random variable is less than or equal to the independent variable of the function; CDF.

Cumulative Probability The probability that the value of a random variable falls within a specified range; CP.

DemTect The DemTect is an assessment used to administer and recognize the early stages of dementia and MCI.

Dual-Mixed Trial Two stimuli were presented at the same time in the centre of the screen (one animal and one celestial body). Participants were asked to respond as quickly and accurately as possible to both the stimuli without prioritizing responding to either animal or celestial body images; DM.

Exercise Self-efficacy Questionnaire The Exercise Self-Efficacy Scale assesses an individual's beliefs in their ability to continue exercising.

Flanker Task In this task, irrelevant stimuli have to be inhibited in order to respond to a relevant target stimulus.

Freiburg Visual Acuity and Contrast Test The Freiburg Visual Acuity test is an automated procedure for self-administered measurement of visual acuity; FrACT.

functional Magnetic Resonance Imaging A device that measures brain activity by detecting changes associated with blood flow; fMRI.

Gamma aminobutyric acid The main inhibitory neurotransmitter in the human cortex; GABA.

Geriatric Depression Scale The Geriatric Depression Scale is a self-report measure of depression in older adults; GDS.

Get Active Questionnaire The Get Active Questionnaire is structured to guide an individual through a series of four questions to help them decide whether they should consult a health care professional and/or a qualified exercise professional before becoming more active or starting a fitness program; GAQ.

Head Mounted Display Head Mounted Displays are image display units that are mounted on the head; HMD.

Heart Rate Reserve The heart rate reserve is the difference between a person's resting heart rate and maximum heart rate; HRR.

Insulin-like Growth Factor IGF is neurotrophic hormone that plays a crucial role in CNS development and maturation. IGF-1 has been shown to have potent effects on cellular neuroplasticity; IGF.

Inter-trial-intervals The duration of time between the onset of one trial and the onset of the next trial; ITI.

Lateral Intraparietal Cortex Found in the parietal cortex. It is a region involved in audiovisual integration; LIP.

left Superior Temporal Lobe This region of the brain is one of three gyri in the temporal lobe of the human brain, which is located laterally to the head, situated somewhat above the external ear. It is responsible for processing of auditory cues; lSTL.

Mild Cognitive Impairment Mild cognitive impairment refers to the transitional or prodromal state between the cognitive changes of normal aging and very early dementia. It presents an increased risk for the development of dementia; MCI.

Mini-Mental State Examination The Mini-Mental State Examination is a clinical assessment for detecting cognitive impairment; MMSE.

Minimum Audible Angle The minimum audible angle is the smallest angular separation at which two sounds are perceived as coming from distinct sources; MAA.

Minimum Audible Angle The minimum audible angle is the smallest angular separation at which two sounds are perceived as coming from distinct sources; MAA.

Montreal Cognitive Assessment MoCA is a brief cognitive screening test with high sensitivity and specificity for detecting mild cognitive impairment; MoCA.

Multisensory Integration The study of how information from multiple sensory modalities (such as sight and vision) is integrated by the central nervous system; MSI.

Neurotransmitters Neurotransmitters are often referred to as the body's chemical messengers. They are the molecules used by the nervous system to transmit messages between neurons, or from neurons to muscles; NTs.

Oral Trail Making Test Oral Trail Making Test is a neuropsychological measure that provides an assessment of task switching or sequential set-shifting; OTMT.

Physical Activity Affect Scale The Physical Activity Affect Scale measures four dimensions (positive affect, tranquillity, fatigue, and negative affect) of an individual's affective response to exercise; PAAS.

Physical Activity Scale for the Elderly The Physical Activity Scale for the Elderly is an pen and paper questionnaire that is easily administered and scored to measure the level of physical activity in individuals aged 65 years and older; PASE.

Point of Subjective Simultaneity The time at which participants are most likely to perceive stimuli as occurring simultaneously or the point at which they are equally likely to report 'light' or 'sound' for SJ and TOJ tasks respectively; PSS.

Race Model Inequality A common test for behavioral data in experiments with redundant signals to determine whether integration or co-activation is occurring; RMI.

Rate of Perceived Exertion Rate of perceived exertion is a way to measure the level of exertion a person feels during physical activity; RPE.

Redundant Signal Effect The observation that individuals respond more quickly to stimuli when information is presented as multisensory, redundant stimuli (e.g., aurally and visually), rather than as a single stimulus presented to either modality alone; RSE.

Response Time Task or Simple Response Time A psychophysical task where participants are presented with a response as quickly as possible to one or more stimuli, where the same response is made regardless of stimulus type; RT or SRT.

right Inferior Frontal Gyrus This region of the brain is the lowest positioned gyrus of the frontal gyri, of the frontal lobe, and is part of the prefrontal cortex. The rIFG is involved in response inhibition; rIFG.

Simultaneity Judgment Task A psychophysical task where participants are subjected to two stimuli of differing modalities and are asked to determine whether the two stimuli are simultaneous; SJ.

Single-Mixed Trial Both an animal and a celestial body appeared on the left and right side of the screen, however, only one image appeared in the centre of the screen that participants were asked to match its corresponding image on either the left or right side of the screen; SM.

Single-Pure Trial A single stimulus consisting of either an animal or a celestial body was presented and participants were asked to match the image presented in the centre of the screen to the corresponding animal or celestial body; SP.

Sound Induced Flash Illusion A psychophysical task where a single flash accompanied by two beeps in close temporal proximity leads to the perception of two flashes; SIFI.

Standard Deviation The standard error of the mean is the variability of sample means in a sampling distribution of means; SD.

Standard Error of Mean The standard error of the mean is the variability of sample means in a sampling distribution of means; SEM.

Stimulus Onset Asynchrony the duration of time between the onset of one stimulus and the onset of another stimulus; SOA.

Superior Temporal Sulcus The sulcus separating the superior temporal gyrus from the middle temporal gyrus in the temporal lobe of the brain. It is a region involved in audiovisual integration; STS.

Supplementary Motor Area This region of the brain occupies the posterior one third of the superior frontal gyrus and is responsible for planning of complex movements; SMA.

Target Heart Rate Target heart rate is a percentage of one's maximum heart rate; THR.

Temporal Binding Window The maximal asynchrony, or time between stimuli, beyond which they are no longer perceived as synchronous; TBW.

Temporal Order Judgment Task A psychophysical task where participants are subjected to two stimuli of differing modalities and are asked to determine which stimulus came first; TOJ.

Traumatic Brain Injury Traumatic brain injury is a form of acquired brain injury, that occurs when a sudden trauma causes damage to the brain; TBI.

Two-Interval Forced Choice In a 2-IFC task, a single experimental trial consists of two temporal intervals. The observer is required to report the interval in which the signal was presented; 2-IFC.

Vascular Endothelial Growth Factor Vascular Endothelial Growth Factor is a signal protein produced by many cells that stimulates the formation of blood vessels; VEGF.

Verbal Fluency Verbal Fluency is a cognitive function that facilitates information retrieval from memory. Tests of verbal fluency evaluate an individual's ability to retrieve specific information within restricted search parameters; VF.

Virtual Reality VR is a simulated experience that can be similar to or completely different from the real world; VR.