The Neural Processes of Perceived Simultaneity and Temporal Order in Younger and Older Adults using EEG

by

Aysha Basharat

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Abstract

In order to make sense of the world, the central nervous system (CNS) must determine the temporal order of events and integrate cues that belong together. The process of integrating information from multiple sensory modalities is referred to as multisensory integration. The importance of this process is evident in everyday events such as speech communication or watching a movie. These events give rise to both auditory and visual sensations that are truly simultaneous or successive, which the CNS must determine. This thesis presents two experiments designed to determine how the CNS of younger and older adults processes audiovisual information to identify simultaneity and temporal order of events. 28 younger (experiment 1) and 28 older (experiment 2) adults participated in audiovisual tasks in which they were asked to decide whether audiovisual stimuli were presented simultaneously or successively (SJ) or which stimulus was presented first (TOJ). The probability of judging a light and a sound as occurring simultaneously, or whether a light occurred first were calculated to extract the point of subjective simultaneity (PSS) and the temporal binding window (TBW). The TBW represents the time within which auditory and visual cues are most likely perceived as being simultaneous. Event-related potentials (ERPs) time-locked to light and sound onset presented at 4 different stimulus onset asynchronies (SOAs) were also recorded. Results revealed task specific differences in perceiving simultaneity and temporal order, suggesting that each task may be subserved via different neural mechanisms. Auditory N1 and visual P1 ERP amplitudes confirmed that unisensory processing of audiovisual stimuli did not differ between the two tasks, indicating that performance differences between tasks arise from multisensory integration. Despite multisensory integration being implicated, the dissociation between SJ and TOJ was not revealed through auditory N1 and visual P1 amplitudes and latencies thus indicating that the decision-making role of higher-level networks may be contributing to the differences that exist between the two tasks. Consistent with previous literature, behavioural data tended towards older adults having a wider TBW than younger adults. While all participants had reported normal audition and vision, older adults showed a later visual P1 latency indicating that unisensory processing of visual information may be delayed with age. Compared to younger adults, older adults showed a sustained higher FCz auditory N1 ERP amplitude response across SOAs, which could correspond with broader response properties expected from an extended TBW. Together, this thesis provides compelling evidence that different neural mechanisms sub serve the SJ and TOJ tasks and that simultaneity and temporal order perception change with age.

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Background

In order to form a meaningful representation of the world, the central nervous system (CNS) must receive information from multiple different sensory modalities and determine whether or not they should be bound. For instance, many everyday events give rise to both auditory as well as visual sensations; such as watching a movie or listening to someone speak. Utilizing information from multiple different senses is advantageous as sensory redundancy can improve the ability to select meaningful information from noise. In addition, how the CNS determines whether to bind multisensory information affects decision-making and motor control, which depend on previously integrated information. In the examples mentioned above, watching a person's lip movements and facial expressions, as well as listening to the words they say, allows the observer to accurately understand what the actor or their friend is saying. Sensory information that is redundant is taken into account by the CNS in order to decide whether stimuli or events are synchronous or not. Thus the ability to differentiate between synchronous and asynchronous events allows the observer to determine whether the inputs from multiple sensory systems should be perceived as belonging together or to different events (Spence et al., 2003). Information from different sensory modalities is more likely to be treated as belonging together if they share more properties (Driver & Spence, 2000). Given this assumption, we observe that signals from different sensory modalities are more likely to be perceived as simultaneous if they occur at the same (or similar) time or space (Driver & Spence, 2000). In contrast, signals that originate from different external events are less likely to be perceived as simultaneous.

Determining the temporal coincidence of two events is difficult for the CNS, as it has to deal with both intrinsic and extrinsic differences in transmission time. For example, light travels faster than sound (300,000,000 m/s and 330 m/s respectively) therefore light arrives at the eyes before sound arrives at the ears (Spence & Squire, 2003). Additionally, transduction times differ for different sensory modalities (King & Palmer, 1985); 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 (Corey & Hudspeth, 1979). In contrast, the transduction latencies of photoreceptors found in the retina are 15-93 ms (Kuffler, 1953). Furthermore, the time for information to reach the CNS from the transducer (Von Békésky, 1963) also makes it difficult for the CNS to accurately perceive simultaneity. Additionally, attention can affect the speed at which the stimuli are processed, where attended stimuli are perceived earlier than unattended stimuli (Shore et al., 2001). Given these factors, it becomes clear that although two events may be simultaneous, they may not be perceived as such.

One of the theories as to how the CNS is able to work around these limitations states 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 (Stevenson et al., 2015). This theory, referred to as the temporal binding window (TBW), posits that the inputs from the sensory modalities must fall within a "window" of time. The TBW is defined as the maximal asynchrony or time between stimuli beyond which they are no longer perceived as synchronous (Sanders et al., 2011). Typically, pairs of stimuli are presented while varying the time between the stimuli, known as the stimulus onset asynchrony (SOA) (Zampini et al., 2003; Linares & Holcombe, 2014). Researchers have employed many different psychophysical tasks to assess the size of the TBW. The audiovisual simultaneity judgment (SJ) task and the audiovisual temporal order judgment (TOJ) task are two common methods used to behaviourally assess the TBW. During these experiments, participants are asked to assess whether the audiovisual pair of stimuli presented occurred simultaneously or successively and which stimuli came first respectively (Van Eijk et al., 2008; Love et al., 2011; Zampini et al., 2003; Bedard & Barnett-Cowan, 2016).

In addition to measuring the TBW, SJ and the TOJ tasks also measure the point of subjective simultaneity (PSS), the amount of asynchrony (in milliseconds) between two cues that most likely results in the perception of synchrony (Love et al., 2013). In a TOJ task, the PSS can be estimated as the point at which the "audio first" judgments are equal to the number of "video first" judgments (Van Eijk et al., 2008). In a SJ task, the PSS can be estimated as the point at which participants perceive maximum simultaneity or when the "simultaneous" judgments outnumber "successive" judgments (Vroomen & Keetels, 2010). Although the PSS can be derived from both the SJ and TOJ tasks, inconsistent PSS values have been obtained from these measures even when using a within subjects design (Love et al., 2013). Furthermore, some researchers have found no correlation between the PSS values obtained from the SJ and TOJ tasks (Van Eijk et al., 2008; Bedard & Barnett-Cowan, 2016). These results suggest that both of these tasks may be sub served by different neural mechanisms. Our research aims to further understand these mechanistic differences and also to assess whether differences in cortical responses to SJ and TOJ tasks change with age.

Old age (over the age of 65) affects the detection of both auditory and visual cues; reduces visual contrast sensitivity (Derefeldt et al., 1979) and sound detection thresholds, specifically at higher frequencies (Gordon-Salant, 2005). Additionally, stimuli presented at suprathreshold levels have been found to be closer to detection levels for older adults compared to younger adults (Chan et al., 2014a). Neural transmission is slower for stimuli that are closer to detection levels compared to suprathreshold stimuli, which may lead to differences in detection of the stimuli between young and older groups (Chan et al., 2014a). These differences in detection may lead to slower transduction of multisensory stimuli and therefore impact perception of synchrony in older adults (Chan et al., 2014a). For example, accurate synchrony detection is extremely important as it increases perceptual reliability. Research indicates that older adults have more difficulty separating the temporal order of auditory and visual stimuli and are more likely to perceive synchrony between stimuli that are not relevant to each other (Chan et al., 2014a). Further, erroneous integration of temporally disparate information is associated with higher fall risk (Setti et al., 2011b) and deficits in speech comprehension (Setti et al., 2011a). While some studies (Setti et al., 2011a; Diederich et al., 2008; Chan et al., 2014 b) using the SJ and the TOJ tasks have found that the temporal binding window is typically wider in older adults, not many studies have compared the performance of young and older adults on the SJ and the TOJ tasks using a within-subjects design. A direct comparison between the two populations allows us to understand how synchrony perception changes in the CNS of older adults.

In the present study, young healthy adults were recruited to establish the differences between the cortical responses that sub serve SJs and TOJs using event-related potentials (ERPs). ERPs measure electrical activity of postsynaptic potentials that are generated by large groups of pyramidal neurons in similar orientations (Woodman, 2010; Sur & Sinha, 2009). The excellent temporal resolution of ERPs allows us to capture the processing differences that exist when participants are asked to make SJs versus TOJs. To our knowledge ERPs of SJs and TOJs of younger adults have not been compared using a within-subjects design. A literature review pertaining to the perceived timing of sensory events, factors that affect sensory perception, the rationale behind our study, and hypotheses is presented below.

Perceived Timing of Sensory Events

One of the primary issues that the CNS faces is to determine whether or not stimuli belong together and whether they should be perceptually bound (Meredith et al., 1987). That is to say that it is quite difficult for the brain to find the relationship of simultaneity across the different sensory modalities due to different propagation energies, transduction latencies, processing speed of each modality, and different axonal lengths of regions processing stimuli from different modalities (King and Palmer, 1985; Pöppel et al., 1990; Bekesy, 2005). Although determining simultaneity may be difficult for the CNS, it is extremely important to accurately integrate sensory information in order to identify the temporal succession of stimuli. The inability to do so, would lead to an erroneous representation of the physical world. Given that such mistakes can lead to poor decision-making and subsequent action (i.e., poor multisensory integration is linked with increased risk of falling and speech deficits (Setti et al., 2011a, b)), the CNS has expectations or heuristics, in place to correctly determine the temporal order of events. Notably, spatial and temporal relationships between stimuli at least partly determine the relatedness of the information presented (Hillock-Dunn & Wallace, 2012). Thus information that is presented in close spatial and temporal coincidence will have a higher probability of being bound together and will be perceived as simultaneous.

Measuring the Perceived Timing of Sensory Events

Simultaneity is generally assessed using two methods: simultaneity judgment (SJ) task, and temporal order judgment (TOJ) task.

Simultaneity Judgments

In an audiovisual simultaneity judgment (SJ) task, auditory and visual stimuli are presented to the participant within a range of stimulus onset asynchronies (SOAs), using the method of constant stimuli (Zampini et al., 2005). Participants are required to decide whether the two sensory cues or stimuli (i.e., audio and visual) were presented simultaneously or successively. In other words, the participant must decide whether two stimuli were in or out of sync (Love et al., 2013). Typically, researchers plot the percentage of times participants reported "simultaneous" as a function of the SOA, which creates a peaked distribution (Harris et al., 2009). This function is approximated by a Gaussian function (Eq. 1: $y = a \cdot e^{(-0.5(\frac{x-x0}{b})^2)}$), where the peak of the Gaussian curve (x0) is used to define the point of subjective simultaneity (PSS) (Harris et al., 2009). The PSS is the amount of asynchrony (typically in milliseconds) between the two stimuli that results in the perception of simultaneity. Hence it is the SOA at which the participant is most likely to report "simultaneous" as their response (Zampini et al., 2005). In addition to the PSS, researchers are able to obtain the just noticeable difference (JND) from the Gaussian function. The JND is represented by the width of the curve and is defined as one standard deviation (±34%) from the PSS (Harris et al., 2009). The JND is indicative of the smallest change in interval that observers can reliably notice, thus it is a reflection of the participant's sensitivity (Harris et al., 2009; Keetels & Vroomen, 2012, p. 2). A wider curve would imply a larger JND that would indicate that the participant is not very precise (Spence et al., 2003).

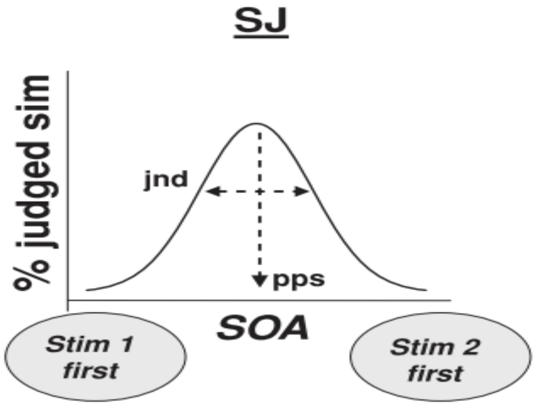

Figure 1. Simultaneity judgment (SJ) task from Harris et al., (2009; Fig. 15.1). The graph represents the percentage of time each SOA was chosen as simultaneous. The curve is approximated by a Gaussian, where the peak represents the PSS and one standard deviation from the PSS is the JND.

Temporal Order Judgments

Audiovisual temporal order judgments (TOJ) require the participant to indicate which of the two sensory stimuli (i.e., audio and visual) occurred first. A logistic function (Eq. 2: $y = \frac{100}{1+e^{\frac{x-x0}{b}}}\%$) is fit to the percentage of times a participant perceived one stimulus as occurring before the other (typically the probability of the perception of light) (Harris et al., 2009). Here, the 50% point of this "s" shaped logistic curve is used to measure the PSS and the slope of the curve is used to measure the JND. The PSS represents the point at which the participant is equally likely to say either stimulus came first and the JND is one standard deviation (±34%) from the PSS (Harris et al., 2009). The JND represents the sensitivity of the participant. Therefore the steeper the curve, the smaller the JND, which indicates that the participant is sensitive to small asynchronies (Keetels & Vroomen, 2012, p. 2; Zampini, Shore, & Spence, 2003).

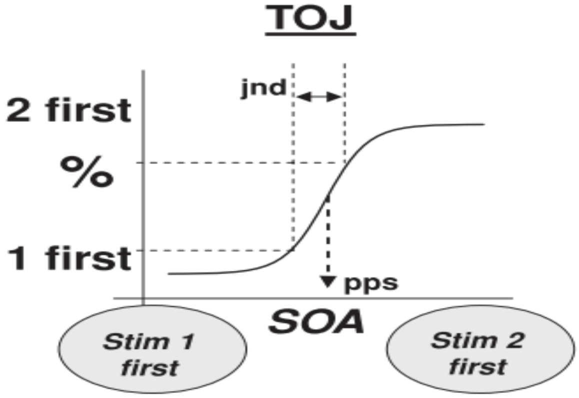

Figure 2. Temporal judgment (TOJ) task from Harris et al., (2009; Fig. 15.1). The graph represents the percentage of time the participants perceived one of the stimuli as appearing first. The curve is approximated by a cumulative Gaussian function, where the 50% point represents the PSS and one standard deviation (±34%) from the PSS is the JND.

Comparison of SJs and TOJs

Although both the SJ and the TOJ tasks produce PSS and JND values, research suggests that they should not be used interchangeably (Harris et al., 2009). Allan (1975) explored the relation between SJs and TOJs and suggested 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. Allan's work (1975) is further supported by more recent work conducted by van Eijk and colleagues (2008) in which they compared the effect of two tasks on PSS values. They asked participants to make simultaneity and temporal order judgments using three different experimental methods; a TOJ task where participants were to respond with either "sound first" or "video first", a SJ task where participants were required to respond with either "synchronous" or “asynchronous”, and lastly an SJ task where the participants had three options of “audio first”, “synchronous”, or “visual first”. They found that the PSS values from both of the SJ tasks were correlated, but the PSS values from the TOJ tasks were uncorrelated with the PSS values obtained from either of the SJ tasks. In addition to these findings, research indicates that although both audio-leading and video-leading PSSs have been obtained at the individual level, the mean PSS values differ between the two tasks (Van Eijk R. L. et al., 2008; Love et al., 2013). Average audio-leading PSSs have almost exclusively been found for TOJs while average video-leading PSSs are generally obtained for the SJ tasks (Van Eijk. et al., 2008). While some researchers support this view (Van Eijk R. L. et al., 2008; Love et al., 2013), others were not able to confirm this finding (Bedard & Barnett-Cowan, 2016). For example, Bedard & Barnett-Cowan (2016) found visual-leading PSS values for both the SJ and the TOJ tasks however Love et al., 2013 found audio-leading PSS values for the TOJ task and video-leading PSS values for the SJ task. These differences may be attributable to the different analysis techniques as well the SOAs utilized for these studies where Love et al. (2013), averaged data for each SOA across participants and fit a Gaussian and logistic function to these averaged SOAs, whereas Bedard and Barnett-Cowan (2016) fit Gaussian and logistic curves to each participant's respective data. Further, Bedard and Barnett-Cowan (2016) used 13 SOAs of 0, ±25, ±50, ±100, ±150, ±200, and ±300 ms, whereas Love et al. (2013) only used 11 SOAs of 0, ±67, ±133, ±200, ±267, and ±333 ms. The rationale behind choosing such a range of SOAs is that they are wide enough to capture the TBW but not too wide such that the participant is left waiting for too long. As Bedard and Barnett-Cowan (2016) used a wider range of SOAs as well as a larger sample (50 vs. 28 participants) they may have better measured the PSS, however further research is required to determine whether or not the PSS is truly video-leading for both the tasks. For now, based on the differences found in the literature, Van Ejik et al., (2008) have suggested that the SJ task should be preferred over the TOJ task when one is interested in measuring perception of audiovisual synchrony. However, due to the fact that we are interested in finding the differences between the two tasks, we will be utilizing both of them in our study.

In addition to PSS differences that are found between the two tasks, JND differences among tasks have also been reported in the literature (Sanders et al., 2011). The TBW can be derived from the JND, as both are a measure of how sensitive participants are to stimulus onset asynchrony (SOA). The TBW is also representative of a range of tolerances within which stimuli from different modalities are integrated together and perceived as being simultaneous. Hence a reliable detection of temporal order of events is not perceived within the TBW (Love et al., 2013). For example, during an SJ task, auditory and visual stimuli that are physically asynchronous will be integrated together and perceived as synchronous if they fall within the TBW. For audiovisual stimuli, the TBW is typically less than 100 ms in younger adults (Setti et al., 2011a) but is found to be wider in older adults (Bedard & Barnett-Cowan, 2016). Previous research indicates that a TOJ task may provide a better estimate of the width of the TBW than an SJ task (Sanders et al., 2011; Keetels & Vroomen, 2012, p. 2). This is 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 (Sanders et al., 2011; Keetels & Vroomen, 2012, p. 2; Harris et al., 2009). Additionally, in the SJ task, participants may assume that stimuli belong together merely because the "simultaneous" option is available, which may result in many “simultaneous” responses, thus a wide Gaussian may be obtained (Keetels & Vroomen, 2012, p. 2). When comparing the responses of the participant’s for the TOJ task, researchers report that participants may assume that stimuli presented are never simultaneous because only temporal order responses can be given; this may result in a low JND (Keetels & Vroomen, 2012, p. 2). Based on the literature review, it seems likely that the SJ and the TOJ tasks may rely on two different underlying neural mechanisms (Linares & Holcombe, 2014). An alternative method of measuring simultaneity perception is to use a variant of the simultaneity judgment task, where participants are asked to respond with “audio first”, “visual first”, or “simultaneous”. It was found that participants were more likely to respond with “synchronous” for video-leading trials more often in the simultaneity judgment task compared to the variant of the simultaneity judgment, indicating that the simultaneity judgment is more prone to bias compared to the variant simultaneity judgment task (Van Eijk et al., 2008). Although the variant of the SJ task may be a more reliable method of measuring PSS, we will not be utilizing it for our studies. Future studies should consider using it in the future.

Factors Influencing Time Perception

Stimulus Intensity

The PSS depends on many different factors, one of which is stimulus intensity. The general idea is that the more intense stimuli are, the faster they are processed (Smith, 1933; Roufs, 1963; Sanford, 1971). One of the earlier accounts of this phenomenon was presented by Roufs (1963), who compared how the intensity of a visual stimulus affected reaction time and thus the detection of simultaneity. It was shown that reaction time of the participant was logarithmically related to the strength or luminance of the stimuli. This meant that the brighter the stimulus was, the less time it took the participant to detect it (Roufs, 1963). This research was further bolstered by subsequent work, including Sanford's research (1971) that used auditory stimuli instead of visual stimuli. Sanford concluded that auditory detection of a stimulus and response time to it is dependent on the intensity (Sanford, 1971). In the proposed studies, all of the visual and the auditory stimuli are above detection thresholds.

Attention: Prior Entry and Spatial Location

The law of prior entry states that attended stimuli are faster to come to consciousness than unattended stimuli (Titchener, 1908). There are many definitions of attention; Titchener (1908) was one of the first researchers to describe attention in detail. Here, attention was described as the selective process of organizing "whereby one particular group of sensory factors is emphasized more than any other group; attention is merely a name for various phases of selective arrangement within experience" (p. 187). Attention can further be divided into passive and active components, where passive attention is automatic, stimulus driven, and transient, whereas active attention is voluntary, conceptually driven, and sustained (Kandal et al., 2012). Participants' attention can be modulated as discussed below. In this document we will be focusing on selective or active attention, which is the ability of the human information processing system to analyze selectively some stimuli and ignore others (Cacioppo et al., 2000). Evidence for prior entry comes from TOJ studies in which the PSS is typically shifted as a function of the focus of the participants' attention (Zampini, Shore, et al., 2005). The general expectation is a shift in PSS for pairs of stimuli due to the attentional manipulations (Spence, Shore, & Klein, 2001).

Here, when participants are asked to attend to visual stimuli, there is a reduction in the baseline PSS shift, where baseline PSS is represented by vision, meaning that when participants are asked to attend to vision, then less visual lead-time is required. However the opposite results are found when participants are asked to attend to the stimuli in other modalities (i.e., they observe an increase in baseline PSS shift when asked to attended to the auditory modality) (Zampini et al., 2005; Shore, & Spence, p. 89-95).

During these experiments, participants are asked to focus their attention on one sensory modality (i.e., visual modality in an audio-visual TOJ task). Responses from participants are used to calculate the average time one stimulus must lead the other in order for maximal simultaneity to be perceived leading to a shift in PSS (Zampini et al., 2005; Spence et al., 2001). Several early researchers failed to show that attention was capable of speeding up perception of the stimuli presented in the attended modality (Frey & Wilberg, 1975; Hamlin, 1895). However, many early and recent researchers have shown that attention to one sensory modality does in fact speed up the perception of simultaneity and shifts the PSS as a function of the attentional manipulation (Sternberg et al., 1971; Spence et al., 2001).

Using the TOJ in a series of experiments, Spence et al. (2001) asked participants whether visual-tactile, visual-visual, or tactile-tactile stimuli were presented to the left or the right of a fixation point. The tasks were manipulated to minimize response bias by asking participants to respond to the stimulus in a different dimension to which they were asked to attend to. This meant that participants responded to one of the sensory modalities when asked to attend to spatial location and vice versa. Thus, participants were asked to judge which side came first, while attending to vision or touch. Their research showed that stimuli that were presented at an attended location (i.e., right or left side) were perceived as occurring earlier than stimuli at unattended locations (Spence et al., 2001). Therefore both attention to modality and spatial location affect the shift in PSS, as they both have been found to speed up perceptual processing.

Further bolstering the research in this field, McDonald et al., (2005) used ERPs to investigate the neural mechanisms that sub serve attention-induced TOJs. Participants were presented with a sound either to the left or the right of the fixation point before the presentation of either a synchronous or an asynchronous visual stimuli of either green or red colour. The participants were asked to decide whether the target that was presented first was green or red. The researchers began by examining the ERPs elicited by the simultaneously presented visual targets by recording from the posterior (P1, P2) and occipital (P07, P08) areas which yielded peaks such as the visual C1 with an average latency of 72 ms, visual P1 with an average latency of 110 ms, visual N1 with an average latency of 160 ms, the visual P2 with an average latency of 210 ms, and visual N2 with an average latency of 260 ms. They also examined the ERPs of the non-simultaneous visual target, which were recorded contralateral to target 1 (T1) and consisted of T1-elicited P1 with an average latency of 116, N1 with an average latency of 165ms, the P2 with an average latency of 200 ms, and N2 with an average latency of 240 ms. The researchers found that directing attention to one side accelerated processing of the contralateral visual stimuli as attentional cueing increased the positivity over the hemisphere contralateral to the cued-simultaneous target. These increases in processing started 80 ms post target presentation and lasted for 140 ms (McDonald, Teder-Salejarvi, Russo, & Hillyard, 2005). Based on these results and previous research, the visual and auditory P1 and N1 are typically assessed as attention influences these components and not the C1 ERP (Clark, 1993; Gonzales et al., 1994). Due to this reason, this study will be analyzing the visual P1 and auditory N1 ERPs, as we will be directing the attention of our participants to the auditory and visual stimuli equally.

In addition to behavioural research conducted with human participants, research using single cell recordings from macaque monkey striate cells has also shown that spatial attention can modulate sensory processing. Moran and Desimone (1985) trained a monkey to attend to stimuli at one location and ignore another location and repeatedly had the monkey switch its attention from one location to the other. They found that spatial attention modulated sensory processing in extrastriate area V4 and the inferior temporal cortex, but not in the primary visual striate cortex. They found that the response was attenuated when recordings were taken from the unattended stimulus (Moran and Desimone, 1985). Given that in a typical TOJ and SJ task, participants are asked to fixate on a visual fixation cross, this could impact the results obtained, especially the PSS, which may shift. Overall, this research shows the large impact attention and spatial location can have on processing of cues from different modalities, indicating that researchers must be cognizant of such affects.

Visual, Auditory, & Tactile Latencies

Due to the fact that light travels faster than sound, there will always be a physical delay between a visual component and an auditory component when a single audiovisual stimulus is presented, such that the visual component will always be the first to arrive (Eijk et al., 2008). However these physical differences are not too detrimental over short distances to the perception of synchrony due to the fact that the transduction latencies of audio, visual, and tactile stimuli differ. Research indicates that compared to the somatosensory and the visual system, the auditory system has the fastest transduction processing once information reaches the sensory receptors (Pöppel, 1988; Eijk et al., 2008). This is due to the kinetics of the vertebrate hair cells, which transduce information in approximately 40 µs (Corey & Hudspeth, 1979). The transduction latency of tactile stimuli is also quite fast with latencies that can range from 500 µs to 2.6 ms (Alvarez-Buylla & de Arellano, 1952). The transduction latency of the visual system on the other hand takes a lot longer and can range from 15-93 ms (Kuffler, 1953). If transduction latencies were the only delays among the senses, it would be predicted that the visual stimulus must precede auditory and tactile stimuli in order for simultaneity to be perceived. However, differences in axonal length, stimulus intensity, and attention can affect perception of simultaneity. Thus, by using TOJ tasks, many researchers have found that for simultaneity to be perceived for an auditory-visual stimulus, the visual component must precede the sound by a few meters (approximately after 15 m) (Keetels & Vroomen, 2012) or by approximately 20 ms (Hirsh & Sherrick Jr., 1961; Sternberg et al., 1971; Spence et al., 2001). Additionally, somatosensory stimuli (i.e., touch) must precede an auditory as well as a visual stimulus in order for simultaneity to be perceived (Hirsh & Sherrick Jr., 1961; Harrar & Harris, 2008). Based on these findings, one can determine that the auditory system is the fastest at processing information, followed by the somatosensory system. The visual system is the slowest due to its long transduction latency.

Neural Correlates Reported for SJs and TOJs Using EEG

Although neural correlates involved in synchrony perception are crucial for our understanding of how the CNS processes synchronous and asynchronous information, they remain mainly unknown. However, some researchers have speculated that whole neural networks are involved (Keetels & Vroomen, 2012). Although preliminary research was conducted on animals (Meredith et al., 1987; Stein et al., 1963), some research has been conducted on humans using positron emission tomography (PET) (Bushara, Grafman, & Hallett, 2001), functional magnetic resonance imaging (fMRI) (Dhamala et al., 2007; Adhikari et al., 2013), Electroencephalography (EEG) (McDonald et al., 2005; Setti, et al., 2011a; Binder, 2012), and Magnetoencephalography (MEG) (Kösem, Gramfort, & Van Wassenhove, 2014). However in this section we will be focusing on a key finding obtained through EEG studies, as they are more relevant to our topic of research.

Using event related potentials (ERPs) Giard and Peronnet (1999), conducted a study where participants were asked to identify whether they observed object A or object B. Objects A and B were presented when a circle morphed either into a vertical or a horizontal ellipse. Participants were presented with the circle morphing into an ellipse and producing a sound, the circle morphing alone, or a sound alone. Behaviourally, they found that participants were faster and made fewer errors when the objects were presented with the auditory stimulus (AV condition). For their ERP analysis, Giard and Peronnet (1999) calculated the summed ERP response by subtracting the responses elicited by the unisensory modalities from the responses elicited from multisensory integration [Simultaneous auditory and visual stimuli (AV) – (auditory stimuli (Au) – visual stimuli (Vi))]. They found that multisensory interactions, as indicated by the 'summed' ERP, occurred very early on (approximately 40 ms) at the occipito-parietal sites and could be observed throughout different scalp regions within the first 200 ms of stimulus presentation.

Using a similar design, Molholm and colleagues (2002) conducted research to investigate the cortical processing of multisensory integration by presenting auditory and visual stimuli either simultaneously or successively. They tested 12 healthy young adults and asked them to make a speeded response when a stimulus in either modality was detected. They found that the reaction times to simultaneously presented stimuli were much faster than when the stimuli were presented alone. Furthermore, they found significant ERP differences between the simultaneous and successive conditions. They found a larger positivity for the 'sum' ERP (P1) from 45-80 ms, over the parieto-occipital region and a larger positivity for the 'sum' ERP at about 180 ms over the fronto-central electrodes. They also found a larger negativity for the 'summed' ERP (N1) at about 120 ms over the fronto-central electrodes. Their results also indicate that multisensory integration can occur extremely early on (45-80 ms) as was shown by Giard and Peronnet's (1999) work, whose results showed that the CNS responded uniquely to multisensory information as compared to unisensory auditory or visual cues.

More recently, Binder (2012) conducted two experiments to examine the effect of audiovisual temporal asynchrony on neural activity. In the first experiment, participants were asked to decide whether the audio and visual stimuli were synchronous or asynchronous. In a second experiment, the participants were asked to decide whether the audio and visual stimuli began simultaneously or not; the termination of the stimuli was always synchronous. Their results indicate that at approximately 200 ms after the second stimulus was presented, a strong positive ERP was obtained in the parieto-central sites, for trials that were only judged as non-simultaneous for both sound-first and audio-first stimuli. Binder (2012) suggested that the differences found between the perception of synchronous and asynchronous pairs might have contributed to temporal integration and separation of audiovisual stimuli respectively.

Setti and colleagues (2011) investigated the neural mechanisms that differ between young and the older populations using the TOJ task. Participants were presented with audiovisual asynchronous stimuli with SOAs of ±70 and ±270 ms (negative = sound first) and were asked to decide whether the light or the sound came first. Mean visual P1 ERP waveforms were extracted from the occipital electrodes (O1, O2, Oz, PO7, PO3, POz, PO4, PO8, P7, P5, P3, P1, Pz, P2, P4, P6, and P8) and mean auditory N1 ERP waveforms were extracted from the frontal electrodes (Fz, F1, F2, F3, F4, F5, F6, FCz, FC1, FC2, FC3, FC4, FC5, and FC6). Their rational for utilizing the auditory N1 and visual P1 was related to perception and modulation of perception by attention (Setti et al., 2011a; Molholm et al., 2008; Giard & Perronet, 1999). The data was divided into 'control' and 'experimental' conditions, where the ERP responses were taken from the initial stimulus only (i.e., visual P1 ERPs were extracted from the visual-auditory trials when participants were asked to respond to 'flashes') in the control condition. In the experimental condition on the other hand, ERP responses were taken from the second stimulus (i.e., visual P1 ERPs were extracted from the auditory-visual trials when participants were asked to respond to 'flashes').

The behavioural data revealed that younger adults were more accurate than older adults when completing the TOJ task but only for the SOA of 270 ms. The ERP data showed that the visual P1 amplitude in the 'experimental' condition was significantly smaller in older adults compared to younger adults. The auditory N1 amplitude in the 'experimental' condition was showed no main effect of age. The researchers also found that in the 'control' group, there was an age effect only on the visual P1 amplitude, which was smaller in older adults; no age effect on the auditory N1 was found. The researchers stated that this difference between the visual P1 and auditory N1 waveforms was observed because visual ERPs are more susceptible to change with aging than auditory ERPs (Setti et al., 2011a). Their results suggest a deficit in behavioural processing with aging when deciding which cross modal stimuli was presented first, especially when the stimuli are separated by long temporal intervals. This behavioural deficit is reflected at the neural level as well. Refer to figure 3 for a comparison of visual P1 and auditory N1 components between the younger adults and the older adults.

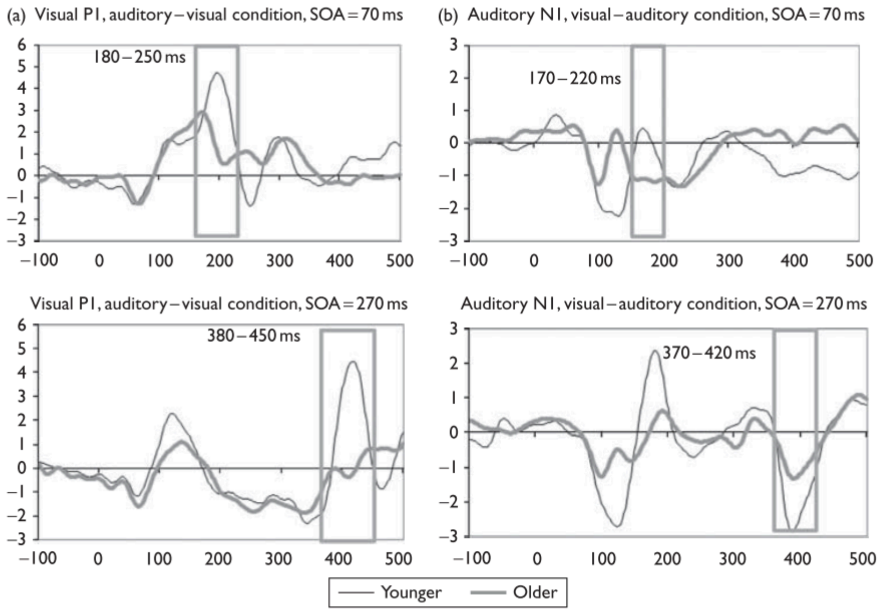

Figure 3. ERP results from Setti et al., (2011, figure 1). Visual P1 and auditory N1 components from the experimental condition are reported for younger adults and older adults. Thus these components are in response to the visual ‘flash’ stimulus in the auditory-visual condition and the auditory ‘beep’ in the visual-auditory condition respectively.

The research conducted by Setti and colleagues (2011) was one of the first to study how temporal order perception changes with age using ERPs. However, because it is one of the preliminary studies conducted in this field, there were some issues with the study's design that need to be addressed. Primarily, the authors only studied the differences that exist in audiovisual temporal order judgments between younger and older adults and did not take into account simultaneity perception, which does not provide a complete picture of the changes that occur as the CNS ages. Additionally, Setti and colleagues (2011) averaged the amplitude of the visual P1 and auditory N1 over 17 and 14 electrodes respectively, which may have increased their statistical power. Typically, ERP peak amplitudes and latencies are determined from individual electrodes and statistical analyses are run on those values (Luck, 2005). Lastly, Setti and colleagues (2011) did not compare the visual P1 and auditory N1 latencies obtained from younger and older adults. Building on the work of Setti and colleagues (2011), here we assess the possible differences that may exist between SJ and TOJ perception and whether they change with age. However, we will not be averaging across all of the electrodes of interest but rather will report statistics from each electrode. The electrodes were chosen based on the work conducted by Setti et al., (2011a), Molholm et al., (2008), and Giard & Perronet (1999) who showed maximal auditory N1 responses at the fronto-central sites and maximal visual P1 responses at the occipital sites. Furthermore, we will also compare latency values between the younger and older population in order to determine if any differences exist in terms of the response time at the cerebral level.

Rationale

The neural mechanisms that sub serve simultaneity and temporal order perception are relatively unknown. Much of the research conducted to understand temporal order perception has used behavioural tasks without monitoring electrophysiological activity of the CNS. Additionally, researchers have generally examined the SJ and TOJ tasks either using a between subject design (Smith, 1933; Vroomen et al., 2004) or have only focused on one task (Setti et al., 2011a; Spence et al., 2003). We propose to monitor the behavioural as well as the cerebral activity, using EEG during SJ and TOJ in order to understand how the CNS integrates multisensory information from both of these tasks. We will be using a within subjects design in order to monitor the relation between the two tasks. There are 5 main hypotheses for the first study:

1. The mean TBW and the mean PSS will be significantly different between the SJ and TOJ tasks (based on Love et al., 2013).
2. The TBW will be positively correlated between SJs and TOJs (based on Bedard & Barnett-Cowan, 2016).
3. The PSS from the two tasks will not be significantly correlated (based on Van Ejik et al., 2008; Love et al., 2013; Bedard & Barnett-Cowan, 2016).
4. There will be no significant differences in visual P1 and auditory N1 amplitude and latency components between the two tasks for the control conditions, as they are representative of unisensory integration.
5. There will be a significant main effect of task for at least one of the electrode sites for visual P1 (O2 or P4) and auditory N1 (FCz) ERP amplitude and latency components for the experimental conditions (based on Setti et al., 2011a; Dhamala et

al., 2007; Molholm et al., 2002).

There has been no study conducted to our knowledge that has compared the mechanistic differences that exist between the two tasks using ERP waveforms. Once a study has been conducted that determines the neural mechanisms that exist within a young population, we can begin to understand how synchrony perception changes with age, by comparing the young and older population. Based on the limited literature on this topic, there are 5 hypotheses for the within subject comparison (the same as those listed above for younger adults) and 7 hypotheses for the between subject comparison of study 2:

1. Older adults will have a wider TBW compared to younger adults on the TOJ task (based on Bedard & Barnett-Cowan, 2016; Setti et al., 2011a).
2. Both groups will perform similarly on the SJ task (i.e., PSS and TBW will not be significantly different between the two groups; based on Bedard & Barnett-Cowan 2016).
3. Older adults will have smaller amplitudes for the visual P1 ERPs compared to younger adults on the TOJ task in the control condition (based on Setti et al., 2011a).
4. Both groups will have similar amplitudes for the auditory N1 ERPs on the TOJ task for the control condition (unisensory perception; based on Setti et al., 2011a).
5. Older adults will have smaller visual P1 amplitudes and later latency values compared to younger adults for TOJs in the experimental conditions (multisensory integration; based on Setti et al., 2011a).
6. There will be no main effect of age on the auditory N1 amplitude and latency for the experimental conditions for TOJs (based on Setti et al., 2011a).

7. Younger and older adults will perform similarly with no significant differences in amplitude and latency values between the two groups for SJs (based on Bedard & Barnett-Cowan, 2016).

Research Objectives

This thesis is composed of two studies that have been designed to address the following research objectives:

Study 1: Determine the behavioural and neural differences that exist between the SJ and the TOJ tasks.

- Evaluate the differences that exist between the two tasks by using the PSS, TBW, and visual P1 and auditory N1 ERP waveforms

Study 2: Determine age-related differences that exist between the SJ and TOJ tasks in young and older adults both behaviourally and cerebrally

- Evaluate the differences that exist between the two tasks by comparing the PSS, the TBW, and visual P1 and auditory N1 ERPs between the young and older population

Study 1 - Determine the behavioural and neural differences that exist between the SJ and the TOJ tasks

Methods

Participants

The sample consisted of 28 healthy young adults (*n* = 11 females) without any auditory and visual deficits. Participants ranged between the ages of 18 and 26 (*M* = 21.6 years, *SD* = 0.37 years). All participants gave written consent to participate in the study. The study was approved through the University of Waterloo Research Ethics Committee and complies with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

Protocol and Materials

Each participant was seated in a soundproof booth and a chin rest was used to stabilize the participant's head. A 57-cm viewing distance from the ViewSonic V3D245 computer monitor was maintained. The auditory stimuli were presented through speakers (Altec Lansing Multimedia computer speak system, ACS95W) placed on each side of the monitor while the visual stimuli were presented in the form of white circles of 0.4° with an intensity of 49.3 cd/m^2 against a black background (0.3 cd/m^2), 2° below the fixation point. Both of the tasks were operated using a Macbook Pro that was kept outside of the booth. VPixx Technologies ProPixx hardware and DataPixx software version 3.01 were utilized for the experiment to ensure that the presentation of both the auditory and visual stimuli relative to each other in real-time were more precise than 1 ms. Participants utilized the

RESPONSEPixx 5-button response box to indicate their responses for each trial using their dominant hand.

Participants received instructions and provided informed consent prior to each task. Before the commencement of the experiment, each participant had an EEG cap fitted according to the international 10/20 system. Response accuracy was emphasized over speed thus the participants were instructed to respond as accurately as possible and not to worry about their reaction time in order to minimize mistakes that may have arose due to rushed responses. Participants completed five blocks of 100 trials for each the SJ and the TOJ tasks. Trials were presented using the method of constant stimuli. A central fixation cross with a visual angle of 0.5° was presented on the screen at all times and the participants were instructed to fixate on the cross throughout the experiment. Participants received as many practice trials as was necessary for both the tasks until they felt comfortable to begin the experimental procedure. Depending on the speed of each participant, the entire experiment took approximately one hour to one hour and thirty minutes to complete.

Simultaneity Judgment Task

Using the response box, participants were asked to report whether they perceived the auditory and visual stimuli to have occurred simultaneously (left button) or successively (right button). Visual stimuli were presented in the form of white circles against a black background below the fixation point for 17 ms. The visual stimuli were either preceded or followed by an auditory beep by 70 or 270 ms. The auditory stimuli had a frequency of 1850 Hz and an intensity of 71.7 dB, which was presented for 7 ms. 25 trials were presented for each SOA (25 x 4 = 100) for a total of 5 blocks (i.e., 500 trials). Practice trials preceded the experimental trials. Refer to figure 4 for a schematic representation of the SJ task.

Temporal Order Judgment Task

Using the response box, participants were asked to report whether they perceived the auditory stimuli (left button) or the visual stimuli (right button) to have occurred first. The visual and auditory stimuli were presented in the same manner as in the SJ task. 25 stimuli were presented for each SOA (25 x 4 = 100) for a total of 5 blocks (i.e., 500 trials). Practice trials preceded the experimental trials. Refer to figure 4 for a schematic representation of the TOJ task.

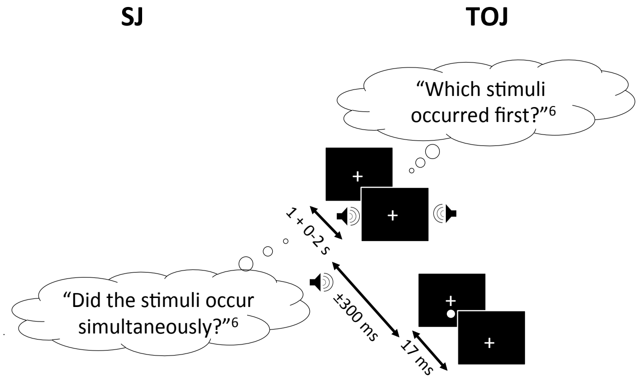

Figure 4. A representation of how the simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks are designed. For the SJ task (on the left), the auditory stimuli (i.e., beep) were either preceded or followed by the visual stimuli (flash) presented for 17 ms by either 270 or 70 ms. The auditory stimuli were presented for 7 ms, had a frequency of 1850 Hz and an intensity of 71.7 dB. The visual stimuli (i.e., flash) was presented against a black background in the form of a 0.4° white circle with an intensity of 49.3 cd/m^2. Participants were asked to report whether they perceived the audiovisual stimuli to be simultaneous or not. The same design was utilized for the temporal order judgment (TOJ) task (on the right)

with one difference. Participants were asked to report whether they perceived the auditory stimuli or the visual stimuli to have occurred first. Note, that the design is the same for both of the tasks and only the question asked is different. Each task will be presented separately in blocks of 100, fives times for a total of five hundred trials per task. The two tasks were counterbalanced in order to remove order effects.

Electroencephalogram (EEG) acquisition and Signal Processing

Participants performed the two tasks while electroencephalogram (EEG) was acquired from a 32-channel electrode cap (Quick-Cap, Neuroscan) that was positioned using the 10/20 international system guidelines. All EEG channels were referenced to the electrodes that were placed on the left and the right mastoid processes. EEG data was digitized at 1000 Hz (Neuroscan 4.5, SynAmps2, Compumedics, NC, USA) and channel impedances were maintained at < 5 KΩ. Epochs of 1000 ms were extracted. The epochs were bandpass filtered from 1 Hz to 30 Hz (24 dB/octave), and pre-stimulus baseline corrected. Based on the research conducted by Molholm et al., (2002), Giard and Peronnet (1999), and Setti and colleagues (2011), and based on the largest peak response elicited both at the group and individual level as well as a qualitative analysis of scalp maps, ERP peak amplitudes and latency values for the visual P1 waveform were extracted from parieto-occipital electrodes (O2 and P4). Auditory N1 ERP range amplitudes and latencies were extracted from the fronto-central electrode (FCz). The data was first visually inspected to remove alpha activity, blinks, and muscle movement. The scalp maps were generated using average ERPs from all of the participants (n = 22 younger and 21 older adults) and they provided an alternative method to visualize the results obtained. In study 2, they were visually inspected to determine the differences between younger and older adults. For each condition, individual average ERPs were created from the epochs. Analysis parameter intervals were chosen based on visual investigation of individual average and grand-average ERP waveforms. The parameter intervals were extracted for each SOA and categorized as either control or experimental conditions. Visual P1 and auditory N1 amplitudes were extracted by obtaining the maximum peak in the parameter extraction window.

The experimental conditions were categorized as representative of multisensory integration where amplitude and latency values were extracted from the second stimuli in each trial (i.e., experimental visual P1 ERP extracted from the response to ‘flash’ in beep-flash trials). The control conditions on the other hand represented unisensory responses (i.e., control visual P1 ERP extracted from the response to ‘flash’ in flash-beep trials). Table 1 lists the parameter intervals used.

Parameter Intervals Used To Extract Visual P1 and Auditory N1 ERPs

Condition	Parameter for Extraction Relative to zero	Parameter for Extraction Relative Used
-270 ms SOA; light; P1 experimental	90-180 ms	90-180 ms
-270 ms SOA; sound; P1 experimental	100-190 ms	370-460 ms
-70 ms SOA; light; P1 experimental	90-180 ms	90-180 ms
-70 ms SOA; sound; P1 experimental	100-180 ms	170-250 ms
70 ms SOA; light; N1 experimental	100-150 ms	170– 220 ms
70 ms SOA; sound; N1 experimental	85-150 ms	85-150 ms
270 ms SOA; light; N1 experimental	80-180 ms	350-450 ms
270 ms SOA; sound; N1 experimental	85-180 ms	85-150 ms
70 ms SOA; light; P1 control	90-170 ms	90-170 ms
270 ms SOA; light; P1 control	80-160 ms	80-160 ms
-270 ms SOA; sound; N1 control	80-160 ms	80-160 ms
-70 ms SOA; sound; N1 control	80-160 ms	80-160 ms

Table 1. The table lists all of the parameter intervals used in order to extract visual P1 and auditory N1 ERPs for both the control and the experimental conditions.

Statistical Analyses

Simultaneity Judgment and Temporal Order Judgment Task Analysis

In order to estimate the PSS values and the certainty with which participants made judgments, psychometric functions were fit to each participant's response as a function of

SOA using Sigmaplot version 12.0. The SJs and the TOJs were analyzed individually for each participant, and the data was fit by either a Gaussian function (EQ. 1) or by a logistic function (Eq. 2) respectively.

Eq. 1: $y = a \cdot e^{(-0.5(\frac{x - x\emptyset}{b})^2)}$, where a is fixed to 1, *xø* is the PSS and b is the standard deviation (proxy for the TBW).

Eq. 2: $y = \frac{100}{1+e^{\frac{x - x\emptyset}{b}}}\%$, where *xø* is the PSS and b is the slope (proxy for TBW)

The best parameter fits were found for each participant separately using Sigmaplot 12.0 and PSSs and TBWs were extracted for SJs and TOJs individually. Participants were excluded from further analysis either if they responded 100% for one category (e.g., 100% "simultaneous") or if their parameters were poorly estimated ($r^2 \leq 0.2$). 1 younger adult was excluded from further analysis due to poor parameter estimates ($r^2 \leq 0.2$). We used b values of the psychometric functions as a proxy for the size of the TBW, as we were interested in understanding the relation between the temporal binding window obtained from the SJ and the TOJ tasks and not their absolute size. Using the b value allowed us to avoid discrepancies in the literature that arise when defining the absolute size of the TBW. Paired t-tests were conducted to test for equality of variance for PSS and TBWs within younger and older adults. Furthermore, correlations between the TBWs and the PSSs of the two tasks will be conducted. These statistical analyses were used to test hypotheses 1, 2, and 3 respectively.

Simultaneity and Temporal Order Judgment ERP Analysis

The 'control' and 'experimental' conditions were analyzed using a priori repeated measures ANOVAs with a 2 (task) x 2 (SOA) design to test the auditory N1 component amplitude and latency differences for both visual and auditory time-locked conditions. Furthermore, a priori RM ANOVAs with a 2 (task) x 2 (SOA) were utilized to test the visual P1 component differences for both auditory and visual time-locked components. These statistical tests were used to test hypotheses 4 and 5 in study 1 and 2. Assessment of sphericity determines whether the variances of the differences between the conditions are equal; we used only 2 different repeated measures thus the difference score for our analyses is 1. Due to the fact that only two repeated measures were utilized, the GHG correction was not necessary.

Results

Out of 28 participants, data from 22 participants was utilized for all of the statistical analyses that follow. 6 participants were excluded because at least one block (out of 5, per task) had less than 80 trials out of 125 that were usable for further analysis. Trials were excluded due to alpha activity (frequency range of 7.5 – 12.5 Hz), blinks, or due to excessive muscle movement.

Behavioural Results

Assessment of Hypotheses 1, 2, and 3

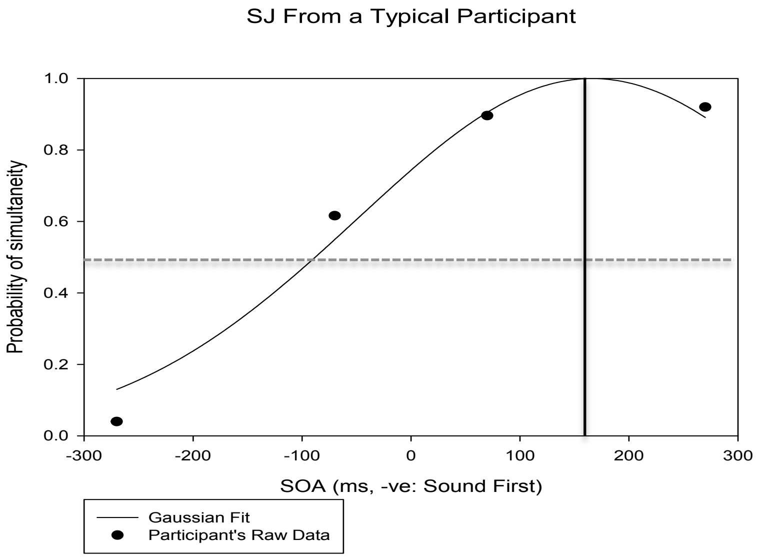

Figure 5. Study 1 behavioural raw data of a typical participant's (participant QZ04) performance on the SJ task fit to a Gaussian function. The Solid black line represents the PSS. The *b* value is 1 SD from the PSS, which is taken as a proxy for the TBW. Each point indicates the average of 125 (25 x 4 = 100 trials; 5 repetitions x 100 = 500 trials in total) SOA trials per task.

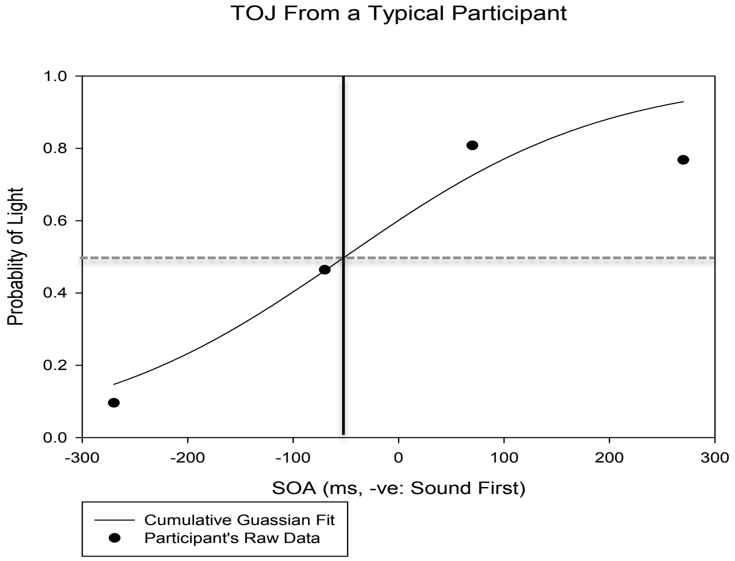

Figure 6. Study 1 behavioural raw data of a typical participant's (participant QZ04) performance on the TOJ task, fit to a cumulative Gaussian function. The vertical solid line represents the PSS. The *b* value (slope of the line between .25 and .75) is 1 SD from the PSS, which is taken as a proxy for the TBW. Each point on the graph represents the average of 125 trials per SOA.

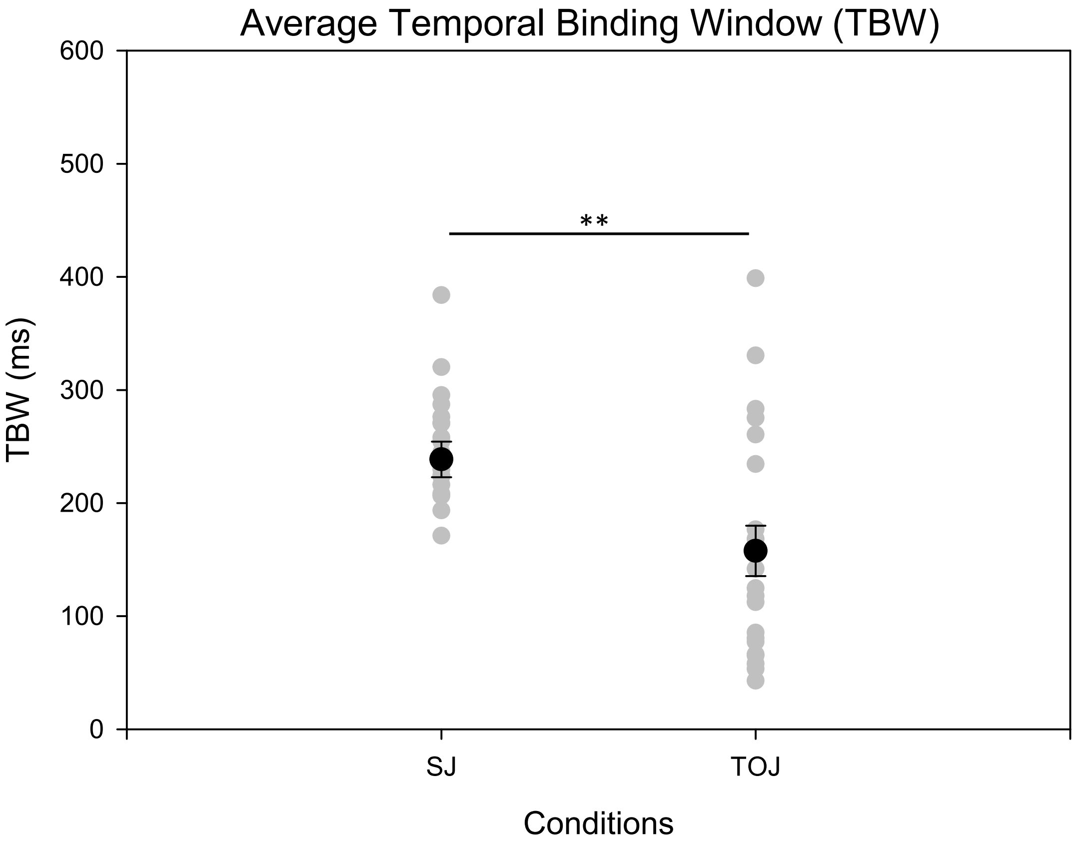

Figure 7. Study 1 behavioural results. Average TBW for the SJ and TOJ tasks. A paired t-test reveals a statistical difference between the means of the two tasks; t(20) = 4.96, $p < 0.001$. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM. *** indicates $p < 0.001$.

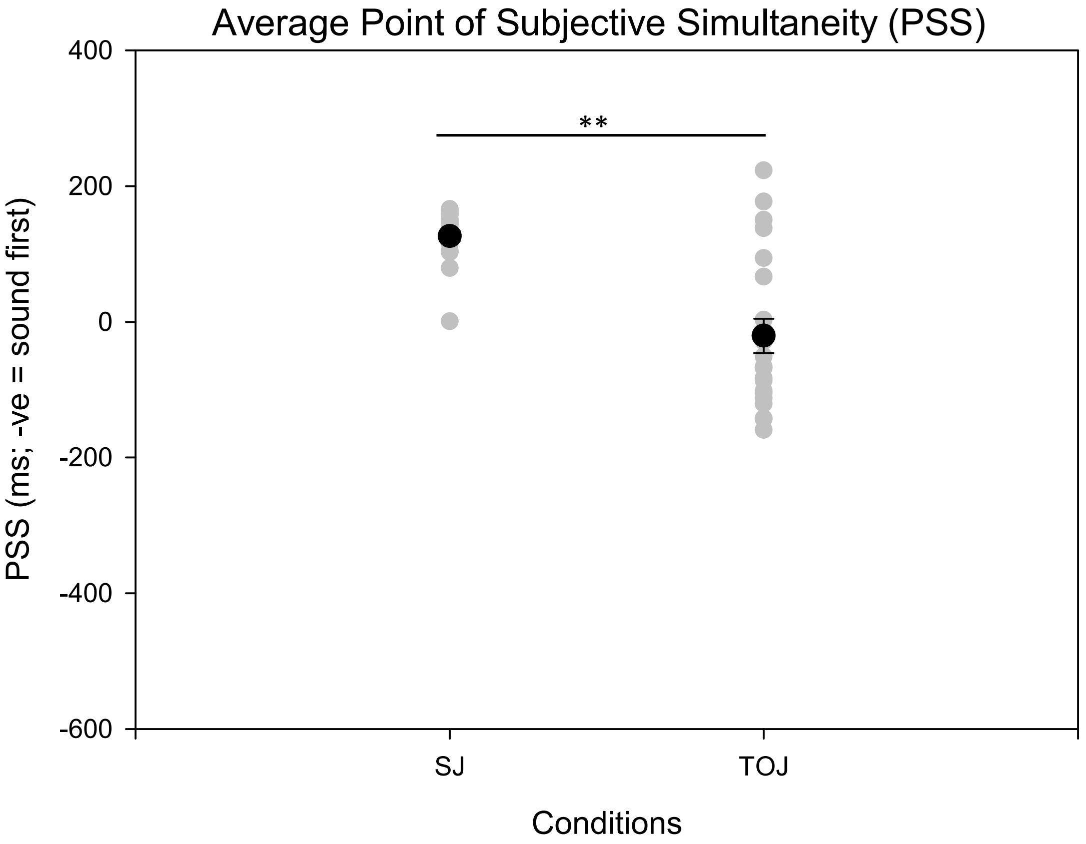

Figure 8. Study 1 behavioural results. Average PSS for the SJ and TOJ tasks. A paired t-test reveals a significant difference between the means of the two tasks; t(20) = 5.24, p < 0.001. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM. *** indicates p < 0.001.

Paired t-tests and Correlations from Study 1 assessing Hypotheses 1, 2, and 3 in Younger Adults

Task	**Statistical Analysis**	**Result**
SJ and TOJ TBW	Paired t-test	SJ TBW (M = 238.48, SD = 72.05) and TOJ TBW values (M = 157.64, SD = 102.03); t (20) = 4.96**, p < 0.001***
SJ and TOJ PSS	Paired t-test	SJ PSS values (M = 126.40, SD = 36.14) and TOJ PSS values (M = -20.45, SD = 115.98); t (20) = 5.24, **p < 0.001***
SJ and TOJ TBW	Correlation	r(21) = 0.682, **p = 0.001**
SJ and TOJ PSS	Correlation	r(21) = -0.206, **p = 0.371**

Table 2. Represents the t-test and correlation results obtained from younger adults from study 1. *** p < 0.001; ** p < 0.01

Responses from the participants were converted to probabilities at each SOA and were fit with equations 1 or 2 for SJ and TOJ respectively, which allowed for the extraction of PSS and slope for further analysis. Figures 5 and 6 show what the raw data of a typical participant looks like when it is fit with the Gaussian and cumulative Gaussian function respectively. Hypothesis 1 stated the mean TBW and the mean PSS would be significantly different between the SJ and TOJ tasks. This hypothesis was confirmed (figure 7 and 8); refer to table 2 for the statistics obtained. Hypothesis 2 stated that the TBW would be positively correlated between SJs and TOJs. This hypothesis was confirmed (table 2).

Hypothesis 3 stated that the PSS from the two tasks would not be significantly correlated. This hypothesis was confirmed (table 2).

Assessing Changes in Performance Over Time

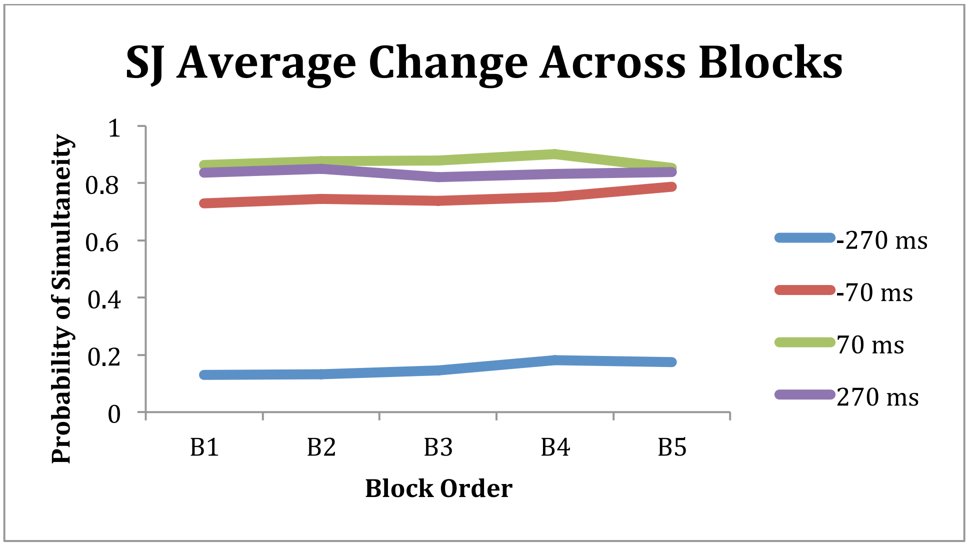

Figure 9. Study 1 represents the average change across blocks for the SJ task for each SOA.

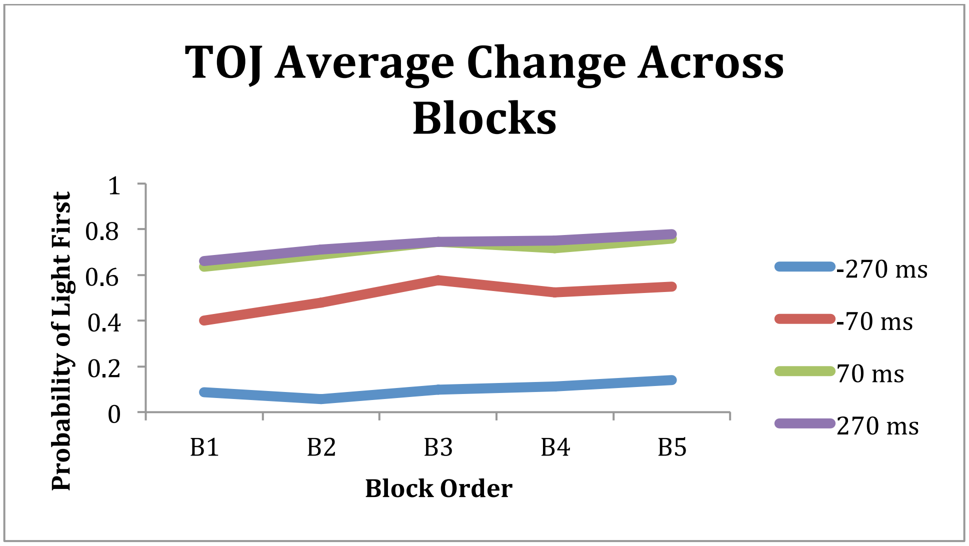

Figure 10. Study 1 represents the average change across blocks for the TOJ task for each SOA.

Participants were asked to complete the SJ and TOJ tasks in blocks of 100. Although the method of constant stimuli was utilized within each task, and each task was presented in a randomly assigned order, a 4 (SOA) x 5 (blocks) RM ANOVA design was used for each task to ensure there was no effect of order. If Sphericity was violated ($p \leq 0.05$), we utilized the Greenhouse-Geisser correction. Results indicate there was a significant main effect of SOA for the SJ task, $F(1.92, 38.33) = 233.76$, $p < 0.001$, $\eta^2_p = 0.921$ (figure 9). There was no main effect of block order and there was also no interaction between SOA and block order for SJ. For the TOJ task, there was a main effect of SOA, $F(1.67, 16.15) = 115.41$, $p < 0.001$, $\eta^2_p = 0.852$ (figure 10). There was also a main effect of block order $F(2.14, 42.81) = 3.59$, $p = 0.033$, $\eta^2_p = 0.152$ (figure 10). However there was no interaction between SOA and block order (figure 10). These results indicate that although the block order did not have an impact on the behavioural results obtained from the SJ task, TOJ performance was affected. This suggests that TOJs are more malleable and prone to change than SJs, but future work is required to assess this hypothesis as to our knowledge this has not been addressed specifically in the literature.

Event-Related Potential Results

Assessment of Hypothesis 4 (Control Condition) Using 2x2 RM-ANOVA

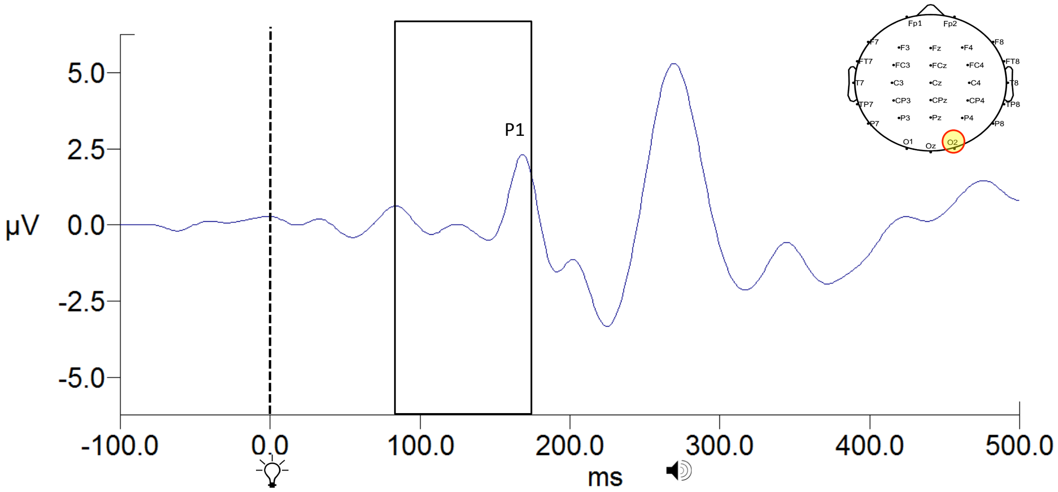

Figure 9. Study 1 ERP waveform from a typical participant (participant AQ20) while completing the SJ task when light was presented 270 ms before sound and time-locked to light. Obtained from the O2 electrode; the visual P1 peak amplitude and latency is marked on the graph.

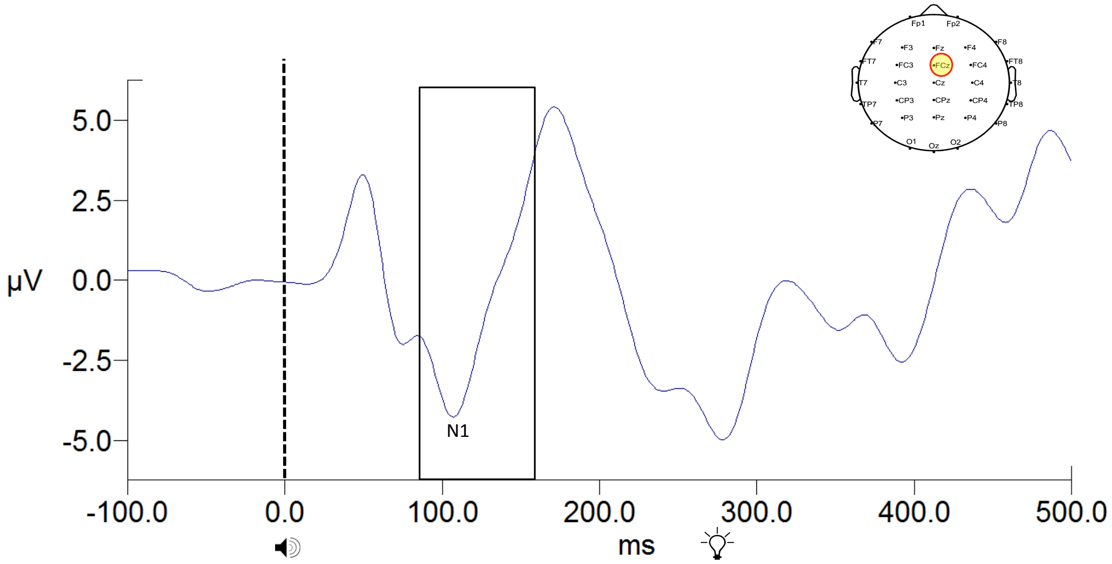

Figure 10. Study 1 ERP waveform from a typical participant (participant AQ20) completing the SJ task when sound was presented 270 ms before light and time-locked to sound. Obtained from the FCz electrode; the auditory N1 peak amplitude and latency is marked on the graph.

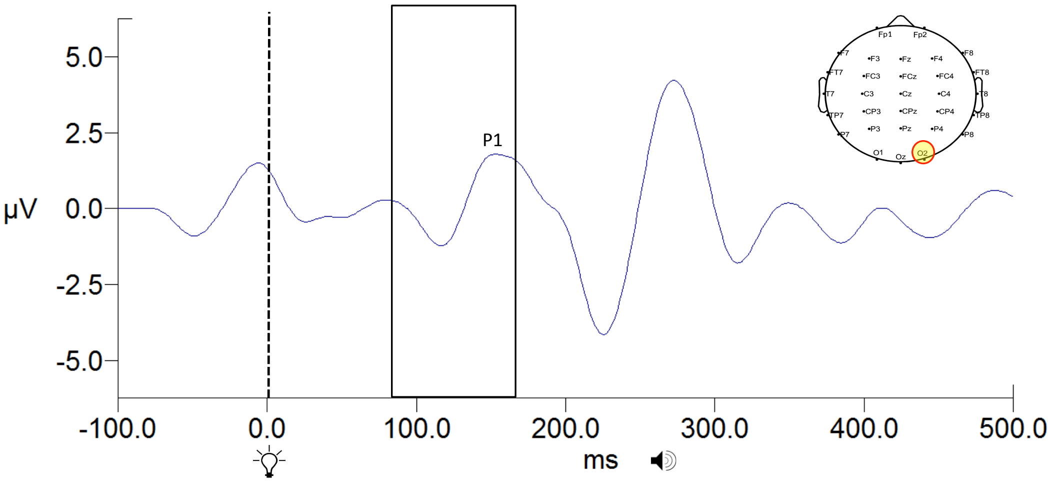

Figure 11. Study 1 ERP waveform from a typical participant (participant AQ20) while completing the TOJ task when light was presented 270 ms before sound and time-locked to light. Obtained from the O2 electrode; the visual P1 peak amplitude and latency is marked on the graph.

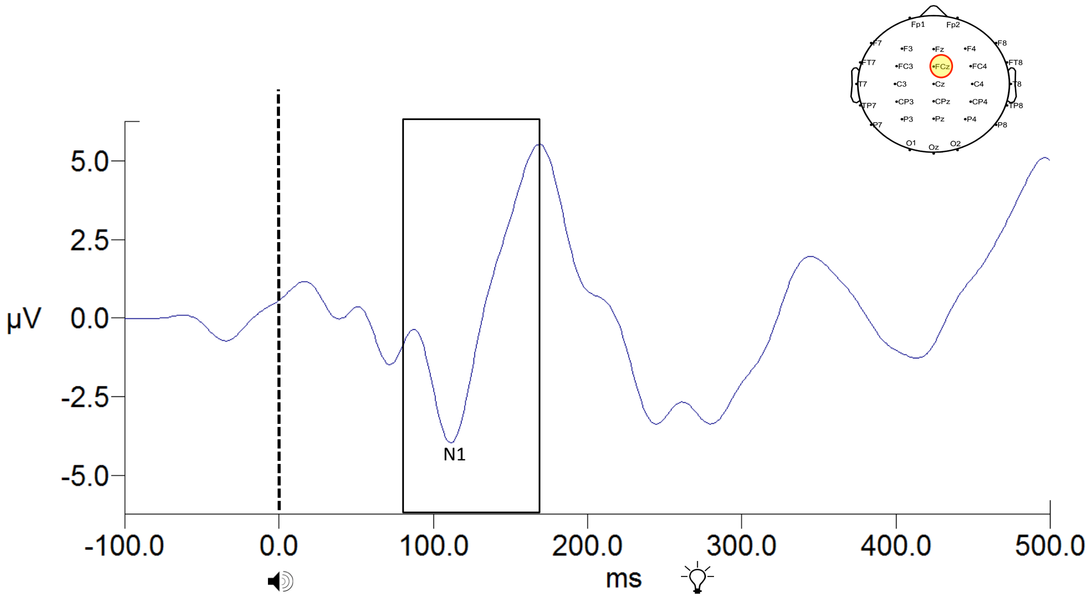

Figure 12. Study 1 ERP waveform from a typical participant (participant AQ20) completing the TOJ task when sound was presented 270 ms before light and time-locked to sound. Obtained from the FCz electrode; the auditory N1 peak amplitude and latency is marked on the graph.

Figures 9, 10, 11, and 12 are visual representations of the waveforms used to extract visual P1 and auditory N1 amplitudes and latency values for the control conditions. A 2 (SOA: 270ms, 70 ms, time-locked to light) x 2 (task: SJ, TOJ) RM ANOVA design was utilized to test the amplitudes and latencies for the control visual P1 condition. A 2 (SOA: -270ms, -70 ms, time-locked to sound) x 2 (task: SJ, TOJ) RM ANOVA design was utilized to extract the amplitudes and latencies for the control auditory N1 condition. Although there was no main effect of task, the results did indicate a main effect of SOA for both the visual P1 peak amplitude and latency values obtained from the P4 electrode, when the SOAs of 270 ms and 70 ms were time-locked to light; $F(1, 20) = 13.96$, $p = 0.001$, $\eta^2_p = 0.411$ and $F(1, 20) = 6.77$, $p = 0.017$, $\eta^2_p = 0.253$ respectively. Hypothesis 4 indicated that there would be no significant difference between the SJ and TOJ tasks for the control conditions due to the fact that they represent unisensory processing. The results obtained support hypothesis 4 that unisensory processing of light or sound does not change regardless of the task that the participants are completing.

Assessment of Hypothesis 5 (Experimental Conditions) Using RM ANOVA

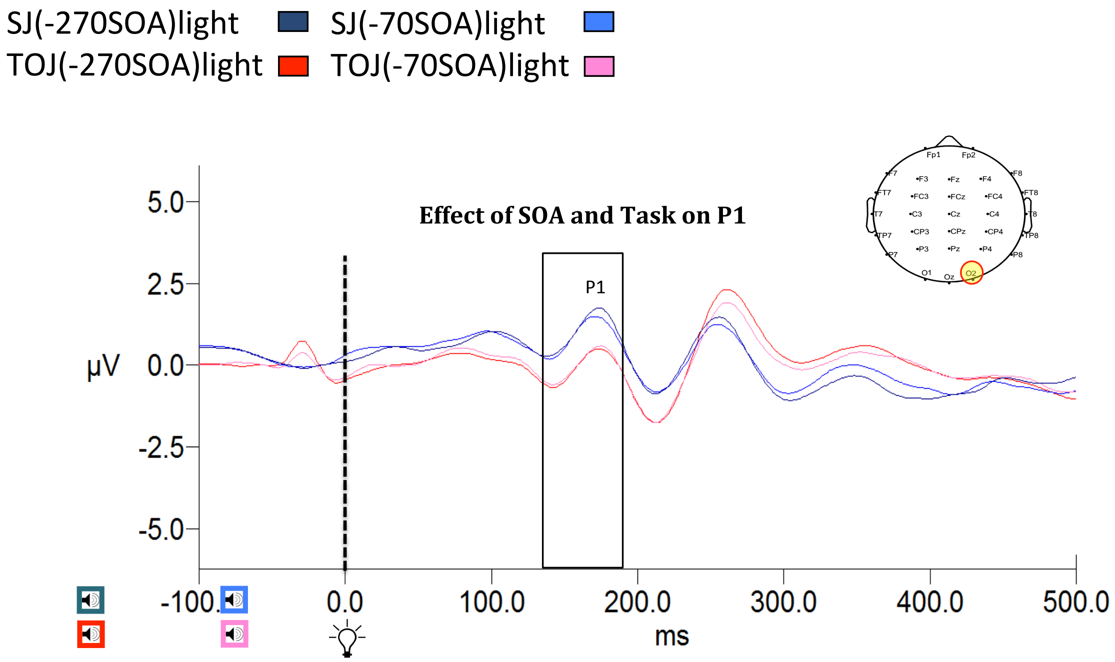

Figure 13. Study 1 ERP obtained from an average of all of the participants. Here we compare the SJ (in shades of blue) with the TOJ tasks (in shades of red) as well as their respective SOAs (-270 ms, -70 ms) presented in the legend. The visual P1 ERP amplitude and latency values were obtained from the O2 electrode. Both of the tasks were time-locked to light. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

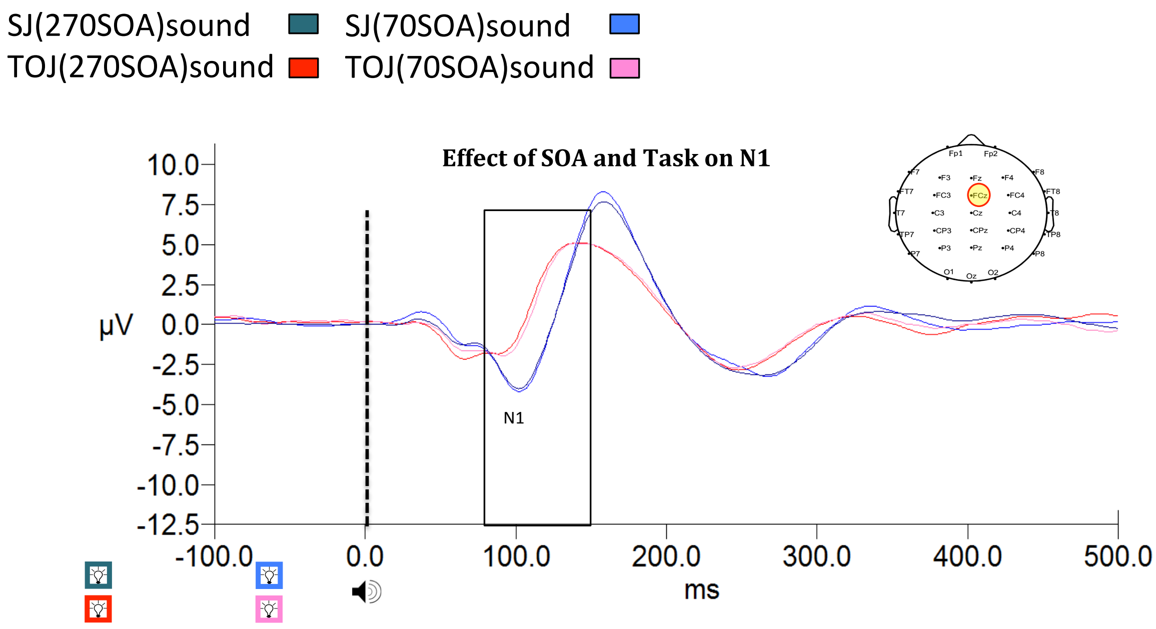

Figure 14. Study 1 ERP obtained from an average of all of the participants. Here we compare the SJ (in shades of blue) with the TOJ tasks (in shades of red) as well as their respective SOAs (270 ms and 70 ms) presented in the legend. The auditory N1 ERP amplitude and latency values were obtained from the FCz electrode. Both of the tasks were time-locked to sound. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

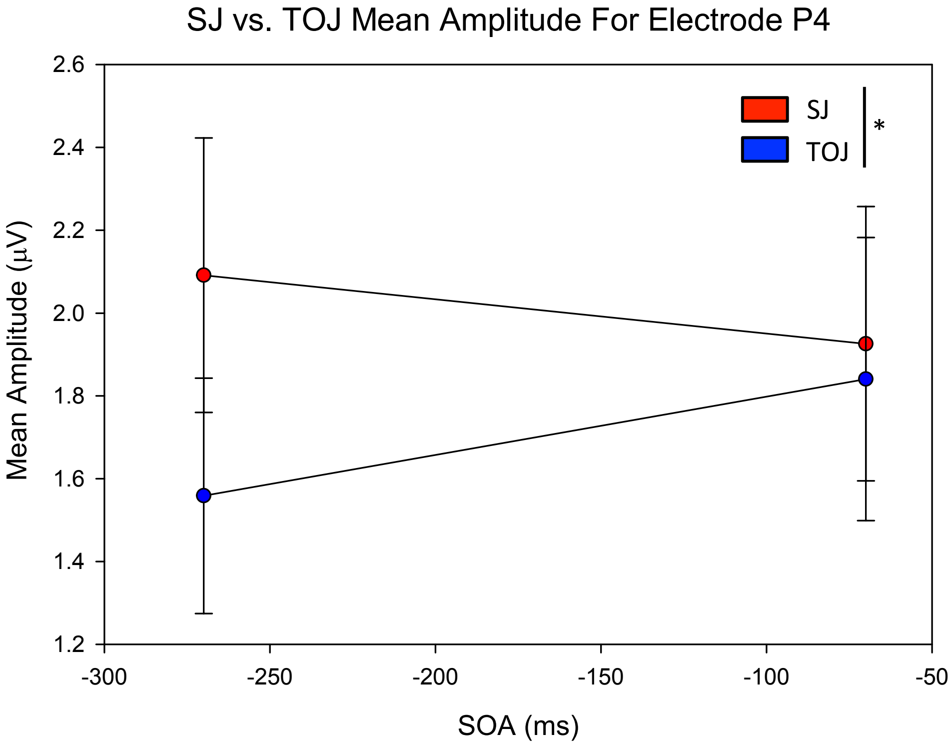

Figure 15. Study 1 ERP comparison of the peak amplitude values obtained from SJ (red) and TOJ (blue) tasks for the SOA of -270ms, -70 ms. The visual P1 ERP was recorded at the P4 electrode and was time-locked to sound. A significant main effect of task was found; F(1,18) = 6.020, $p < 0.025$, $\eta^2_p = 0.25$ Error bars are ±1 SEM. *: $p < 0.05$.

Repeated Measures ANOVA from Study 1 assessing Hypothesis 5

Condition	Electrode	Statistical Analysis	Result
P1 amp; time-locked to sound	P4	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,18) = 6.020, **p < 0.025***, η^2_p = 0.25; main effect of task
P1 amp; time-locked light	O2	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,20) = 15.925, **p = 0.001****, η^2_p = 0.44; main effect of SOA
P1 amp; time-locked sound	O2	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,20) = 13.65, **p = 0.001****, η^2_p = 0.41; main effect of SOA
P1 amp; time-locked light	P4	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,18) = 7.001, **p = 0.016***, η^2_p = 0.28; main effect of SOA
P1 amp; time-locked sound	P4	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 11.93, **p =0.003****, η^2_p = 0.40; main effect of SOA
N1 amp; time-locked sound	FCz	2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1,16) = 17.84, **p = 0.001****, η^2_p = 0.520; main effect of SOA
N1 lat; time-locked light	FCz	2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1, 20) = 3.840, **p = 0.064**, η^2_p = 0.161; main effect of SOA

Table 3. Represents the ANOVA results obtained from younger adults for visual P1 and auditory N1 from study 1. Notice that the last input is approaching significance. ** p < 0.01;

* $p < 0.05$

Figure 13 and 14 are visual representations of the grand average ERPs; each participant's data was averaged together to form this image. Visual P1 and auditory N1 ERP amplitude and latencies were extracted from each participant's individual waveforms and not from the average. A 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ) design was utilized for the results obtained below for both the visual P1 and a 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ) design was used for the auditory N1 amplitudes and latencies. Hypothesis 5 stated that there would be a significant main effect of task for at least one of the electrode sites for the visual P1 and auditory N1 ERP amplitude and latency component for the experimental conditions. Although the results revealed a main effect of task for amplitude at the P4 electrode site when it was time-locked to sound (figure 15; table 3), there was no main effect of task for latency. Furthermore, no main effect of task was obtained for the auditory N1 amplitude and latency. Thus the results obtained do not completely support hypothesis 5. Refer to table 3 for all of the statistics obtained for this section.

Power Analysis: RM ANOVA for Visual P1 Waveform

Electrode and Condition	Degrees of Freedom	F-value	p-value	Partial-eta^2	Observed Power	Total Sample Size Expected for p = 0.05
O1 (SOA) latency: time-locked to light	3,45	2.55	0.068	0.145	0.591	38
OZ (interaction) amplitude: time-locked to sound	1.90, 28.55	2.90	0.073	0.162	0.511	46

Table 4. The table lists results from the power analysis that was conducted for the RM ANOVA analyses for the visual P1 waveform that were not significant but were approaching significance. Results were included if they had a p-value of less than 0.1.

Power Analysis: RM ANOVA for Auditory N1 Waveform

Electrode and Condition	Degrees of Freedom	F-value	p-value	Partial-eta^2	Observed Power	Total Sample Size expected for p = 0.05
F4 (interaction) amplitude: time-locked to sound	3,45	2.35	0.085	0.136	0.553	40
F4 (task) latency: time-locked to sound	1,15	3.60	0.077	0.194	0.427	28
FC3 (interaction) latency: time-locked to light	3,45	2.25	0.096	0.130	0.532	42

Table 5. The table lists results from the power analysis that was conducted for the RM ANOVA analyses for the auditory N1 waveform that were not significant but were approaching significance. Results were included if they had a p-value of less than 0.1.

Discussion

In the present study, 28 participants between the ages of 18 and 26 were asked to complete the simultaneity judgment (SJ) and temporal order judgment (TOJ) tasks during which they were asked to decide if the auditory and visual stimuli presented were simultaneous or successive or which stimulus came first respectively. EEG was collected while the participants completed 5 blocks of each task that were randomly interleaved with one another. We found compelling evidence for significant differences between the two tasks at the behavioural level. The ERP revealed that unisensory processing did not differ between simultaneity and temporal order perception. However, we did not find sufficient evidence for a significant difference of multisensory integration within younger adults suggesting perhaps that our ERP protocol based on Setti et al (2011) may not have been sensitive enough for detecting differences between the SJ and TOJ tasks if any exist.

Behavioural Results

As predicted, our results indicate that the PSSs and the TBWs obtained from the two tasks are significantly different between the SJ and TOJ tasks. Consistent with our hypothesis, we found that the TBWs were strongly correlated between SJ and TOJ. In agreement with previous literature, we found that the PSSs from the two tasks were not significantly correlated. The behavioural results obtained in our study are consistent with previous literature (Bedard & Barnett-Cowan, 2016; Love et al., 2013; van Ejik et al., 2008). Love et al., 2013 reported significant difference between the mean PSSs and the means TBWs from the SJ and TOJ tasks. Bedard & Barnett-Cowan (2016) reported significant correlations between the TBW in the TOJ and SJ task as well as no significant correlations for PSS; the sample size of their study was 50 young adults. Furthermore, there was a significant difference between the mean TBW and PSS values obtained from the two tasks. The average PSS values obtained from the TOJ task in this study however were negative and while negative values are not uncommon on an individual basis (van Ejik et al., 2008), an overall negative trend is not common. This difference in our behavioural results from the standard trend indicates that changing the design of the study from having multiple different SOAs to just 4 different SOAs can affect the performance of participants.

ERP Results

Consistent with our prediction, we found that there were no differences between SJ and TOJ tasks in amplitude and latency for both visual P1 and auditory N1 ERPs for the control condition. Although the results showed no main effect of task on unisensory processing, effects of SOA were found, indicating that unisensory processing may be affected by the inter-stimulus interval (ISI). A main effect of task was found for the visual P1 amplitude, however we were unable to confirm any other differences between amplitude and latency for the experimental condition. An effect of SOA was however found at all of the electrode sites (O2, P4, and FCz) indicating that both visual P1 and auditory N1 ERPs are affected by the ISI. Thus indicating that ISI has an affect on not just the response elicited by unisensory stimuli perception but also for multisensory integration.

Although we were able to confirm behavioural differences between the two tasks, only one out of two of our hypotheses regarding the ERP data were supported. The results indicate that further exploration of the tasks is required but with a different approach. As indicated by the negative PSS value obtained for the TOJ task, there is a change in the way participants behave based on the SOAs utilized in the study. This may be avoided in the future by designing the study following Bedard & Barnett-Cowan's (2016) design by utilizing the following SOAs: 0, ±25, ±50, ±100, ±150, ±200, and ±300 ms. Although a main effect of task was found at the P4 electrode site, it was not found at the O2 and FCz electrode sites. Thus the choice of electrodes for this study may seem poor. However, for the current experimental design, the decision to use the O2 and FCz electrodes was based on the work conducted by Molholm et al. (2002), Giard and Peronnet (1999), and Setti and colleagues (2011). Furthermore, a qualitative analysis of the data was conducted in order to verify that the electrodes with the largest effect were chosen for analysis. During the qualitative analysis, it was found that the P4 electrode showed larger effects that the O2 electrode for some of the conditions and hence it was also utilized in the analysis for the visual P1 ERP component. Another limitation may be that although Molholm et al. (2002) and Giard and Peronnet (1999) used single electrode sites for their statistical analyses, Setti et al. (2011a) averaged the visual P1 ERP over 17 electrode sites and the auditory N1 over 14 electrode sites. Given that the design of our study was based on Setti and colleagues' (2011a) work, it may be expected that we average the data over 17 occipito-parietal and 14 fronto-central electrodes like Setti and colleagues (2011a), however we did not follow this procedure. This is due to the fact that using the average response from multiple different electrodes may have artificially increased the statistical power in Setti and colleagues' (2011a) study. Typically, ERP peak amplitudes and latencies are determined from individual electrodes and statistical analyses are run on those values (Luck, 2005).

Previous Literature - Neurological Correlates

Our ERP technique did not confirm hypothesis 5, however, previous research using fMRI has found different neural networks that were active during simultaneity and temporal order perception. Dhamala et al. (2007) asked their participants to judge whether audiovisual stimuli presented were simultaneous, whether a sound was presented first, a light was presented first, or if they couldn't tell. The behavioural task was completed while fMRI was being recorded. The results from the study indicate that the primary auditory and visual sensory cortices, parietal, and prefrontal cortices were activated during perception of asynchrony. On the other hand, the perception of synchrony recruited the superior colliculus and disengaged the inferior parietal lobule (Dhamala et al., 2007).

Adhikari and colleagues (2013) more recently utilized fMRI to examine the specific brain region involved in the TOJ task. The participants were asked to identify if the audio-visual stimuli were simultaneous, if the flash came first, if the beep came first, or if they couldn't tell. The results showed that the right temporo-parietal junction, right dorsolateral prefrontal cortex (DLPFC), the left inferior parietal lobule, and left medial frontal gyrus were active during perception of asynchrony. Further correlations revealed that during the perception of audiovisual asynchrony, the DLPFC coordinated with the right temporo-parietal and the left temporo-parietal cortices. The results indicate that audiovisual TOJ is sub served via a network that is located between the parietal and the prefrontal cortices (Adhikari et al., 2013).

In a study conducted by Zmigrod & Zmigrod (2015) using transcranial Direct Current Stimulation (tDCS) participants were asked to perform the SJ task while some of the participants experienced anodal stimulation (which generally increases the excitability of neurons), others experienced cathodal stimulation (which generally decreases neural excitability), while control participants performed the task without any tDCS. The participants in the experimental conditions were randomly assigned to stimulation to the right posterior parietal cortex (PPC), the left PPC, or the left DLPC. Their results showed that anodal stimulation over the right PPC narrowed the TBW when compared to the performance of the participants in both the control as well as in the cathodal stimulation group. These results suggest that the right PPC is involved in perception of simultaneity and that the TBW can be manipulated in a short period of time by using tDCS.

Limitations

Given that research on human subjects using fMRI and tDCS have revealed significant differences in how the SJ and TOJ tasks are processed at the cortical level, it may be that the lack of statistically significant main effects of task for auditory N1 and visual P1 amplitudes and latencies in our results is related to the fact that ERPs are not as sensitive at detecting the differences that exist between the two tasks as the neuroimaging devices used in previous literature. fMRI has great spatial resolution, which can be utilized to observe the different areas involved in SJ and TOJ perception (Dhamala et al., 2007; Adhikari et al., 2013). tDCS on the other hand does not have as great a spatial resolution as fMRI nor as good temporal resolution as EEG, however it does stimulate a large area of the brain and also promotes long term potentiation (LTP). The LTP may have caused the neuronal changes that were detected by Zmigrod & Zmigrod (2015). In terms of EEG, the differences between the two tasks may have been too subtle to be detected. An additional limitation may be that our participants may not have been attentive throughout the experiment due to the long duration and repetitive nature of our study. Note that although we collected data from 28 participants, due to lack of attention (excessive alpha activity or inability to perform the task), we were only able to utilize data from 22 participants, which may have limited the statistical power of our study. Note that after testing 16 people initially (proposal stage), a power analysis was conducted (table 4 and 5) on multiple electrode sites, which indicated that we needed at least 28 people in total in order to achieve a power over 0.80. After collecting data from 28 participants, we had to exclude 6 participants, which means that our analysis may still be underpowered.

Although our neural imaging results did not indicate a difference between the effect of simultaneity and temporal order perception on multisensory integration, our behavioural results indicate otherwise. Thus there is a strong need to identify and understand the neural networks that are involved in synchrony perception. By identifying the specific networks that are involved in each task, we can work towards creating a rehabilitative recalibration paradigm that can target the neural mechanisms that are not preserved with aging. Study 2 will include 28 older adults as well.

Study 2 - Determine the Age-Related Differences That Exist Between the SJ and the TOJ Tasks in Younger and Older Adults Both Behaviourally and at the Neural Level

Introduction

Although multisensory integration is essential to optimally perceive our external environment, discriminating temporal order of stimuli from different modalities becomes exceedingly difficult with age (Setti et al., 2011a; Ulbrich, Churan, Fink, & Wittmann, 2009; Bedard & Barnett-Cowan, 2016). Numerous studies using the SJ task (Chan, Pianta, McKendric, 2014) and the TOJ task (Setti et al., 2011a; Diederich, Colonius, Schomburg, 2008) have concluded that the temporal binding window is typically wider in older adults.

The TBW appears to be quite malleable; it tends to decrease in size and becomes more fine-tuned through middle childhood (Hillock et al., 2011; Hillock-Dunn & Wallace, 2012). However with the aging process, the TBW increases in size, making temporal order discrimination and simultaneity perception more difficult (Setti et al., 2011a; Bedard & Barnett-Cowan, 2016; Chan, Pianta, McKendrick, 2014). This increase in the width of the TBW is concerning as information that should be encoded as temporally separate is integrated as one. Erroneous integration of multisensory information has been associated with increased fall risk (Setti, et al., 2011a; Setti et al., 2011b) and decreased speech comprehension (Setti et al., 2011a, Setti et al., 2011b). Due to the plasticity of the TBW, recalibration to decrease the size can be thought of as a rehabilitation technique that can be used to prevent decision-making errors and increase motor control (Bedard & Barnett-Cowan, 2016).

Recently, Bedard & Barnett-Cowan (2016) compared the temporal binding windows obtained from younger and older adults on the SJ and the TOJ tasks. 50 young and 50 older adults between the ages of 18 and 80 years were recruited to participate in their study. They found that for the TOJ task, younger adults required the visual stimulus to be presented approximately 20 ms before the auditory stimulus to be perceived as simultaneous, whereas older adults required the visual stimulus to be presented approximately 110 ms prior to sound. Additionally, psychophysical analyses revealed a wider temporal binding window in older adults, implying impaired perception of temporal order of audiovisual events in older adults for the TOJ task but not for the SJ task. As there was no indication of a widened temporal binding window in older adults in the SJ task, the researchers speculated that simultaneity perception may be preserved with age, whereas temporal order perception may not be. Furthermore, they speculated that these differences may be a product of different neural mechanisms required in simultaneity and temporal perception.

The deficits associated with cognitive aging can be well explained by the work of Gazzaley and colleagues (2008) who used EEG to study cognitive impairment associated with aging. They presented 20 younger and 26 older adults with two faces and two natural scenes and asked the participants to either: remember the faces and ignore the scenes, remember the scenes and ignore the faces, or passively view the faces. They used 5 measures of EEG, including visual P1, to test the differences between the younger and older group. They found an age-related suppression deficit (i.e., smaller visual P1 amplitude) meaning that the older adults were unable to ignore irrelevant information in the visual stream but only during the early stages of processing. Their results suggest that suppression ability is not completely abolished but rather delayed in older adults (suppression is delayed until 500-650 ms). The delay also suggests that their performance deficits may also be attributable to an overall decline in processing speed. Although the research conducted by Gazzaley et al. (2008) does not look into multisensory integration, it offers great insight into the potential reasons why older adults may perceive information differently from younger adults. Given their findings, we expect to see smaller visual P1 ERP amplitudes and later latency values for older adults compared to younger adults.

In the literature review for study 1, Setti and colleagues (2011a) work was described in great detail. They compared audiovisual temporal order perception of younger and older adults while recording EEG and found that behaviourally, older adults were less accurate (number of correct answers/number of incorrect answers) than younger adults at the SOA of 270 ms but not at the SOA of 70 ms. Their ERP results for the experimental conditions matched the behavioural results where the amplitudes did not differ between the two groups at the SOA of 70 ms, but did so for the SOA of 270 ms. Where both the visual P1 and the auditory N1 were significantly smaller in older adults. In the control group, they found that older adults had a smaller visual P1 amplitude but no main effect of age on the auditory N1 amplitude compared to younger adults. Although the work described above is valuable to the design of this study, it was incomplete as they did not compare the performance of younger and older adults on simultaneity perception in addition to temporal order perception.

More recently, Chan et al. (2017) investigated audiovisual simultaneity perception between 14 younger and 16 older adults using EEG. Participants were instructed to decide whether pairs of audiovisual stimuli were simultaneous or successive. It was found that behaviourally older adults perceived fewer sound-lead pairs as synchronous but synchrony perception of truly simultaneous and sound-lag pairs was similar to younger adults. These results indicate that older adults perceive sound-lag stimuli as synchronous over a wide temporal window, which may likely be a result of compensation as sound-lag audiovisual pairs are more naturally occurring in the environment (Van Eijk et al., 2008; Chan et al., 2017). It was found that older adults recruited more spatially distributed areas in order to maintain similar performance to that of younger adults. This may mean that in order to compensate for aging, older adults utilize more cortical areas in order to conduct the same task. Both the younger and the older adults showed onset of neural activity for audiovisual stimuli around 40-70 ms after the first stimulus indicating that there is no slowing in audiovisual synchrony perception in older adults. Although there was no potential slowing in processing found, older adults did show a reduced fronto-central (auditory) N1 ERP between 50-110 ms. However, no significant differences were found for the posterior (visual) P1. These results may help explain why Bedard and Barnett-Cowan (2016) found no significant differences between the performance of younger and older adults on simultaneity perception.

Research on Aging using EEG

Given the relevance of integration of information from multiple senses, it is crucial for researchers to understand the changes in perception that occur as we age. However not many studies have compared the performance of young and older adults on the SJ and the TOJ tasks using a within-subjects and between-subjects design. Measuring the behavioural as well as cerebral activity via electroencephalography (EEG) will allow us to further understand the differences that exist between the young and the aging population and will aid in developing optimal techniques for TBW recalibration.

Methods

Participants

The sample consisted of 28 healthy older adults without any auditory and visual deficits. Participants ranged between the ages of 65 and 79 years. All participants gave written consent to participate in the study. The study was approved through the University of Waterloo Research Ethics Committee and complies with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

Protocol and Materials

The experimental procedure was the same as study 1. At the beginning of the experiment, participants were asked to fill out a short health form where they indicated that they had normal, or corrected to normal vision and hearing.

Statistical Analyses

Behavioural Data

Psychometric functions were fit to the responses made for SJ and TOJ tasks as a function of SOA using Sigmaplot 12.0 in order to extract PSS and *b* values. The SJ data for each individual participant was fit by a Gaussian function (see Eq. 1) and the TOJ data was fit by a logistic function (see Eq. 2). Participants were excluded from further analysis either if they responded 100% for one category (e.g., 100% "simultaneous") or if their parameters were poorly estimated ($r^2 \leq 0.2$). In total, 3 older adults performed poorly on the behavioural task and were thus excluded from further analysis. Paired samples t-tests were used to test for equality of variance, using the PSS and *b* values, between the two tasks. Additionally, correlations between the TBWs and the PSSs of the two tasks will be conducted. These statistical analyses will be used to test hypotheses 1, 2, and 3 respectively.

In addition to the within subjects comparisons, behavioural data obtained from the younger and older adults will also be compared. Independent t-tests between the PSSs and the TBWs comparing the performance of the two groups on each of the tasks will be conducted in order to test hypotheses 1 and 2. If Lavene's test for equality of variance was violated ($p \leq 0.05$), we utilized the correction. Multiple comparisons were corrected for comparison between SJ and TOJ task (based on Bedard & Barnett-Cowan, 2016).

EEG Data

The 'control' conditions are reported first, where the control condition is representative of unisensory stimulus presentation. In the control condition, ERP amplitudes and latency values are extracted with respect to the response from the first stimulus (i.e., visual P1 amplitude and latency extracted from response to 'flash' in flash-beep trial). The 'experimental' condition results will follow, where the experimental condition represents integration from auditory and visual stimuli. For the experimental condition, amplitude and latency values are extracted with respect to the response from the second stimulus (i.e., visual P1 amplitude and latency values extracted from the response to 'flash' in the beep-flash trial). The same amplitude and latency extraction parameters were used as younger adults (refer to table 1 for the complete list).

The 'control' and 'experimental' conditions were analyzed using a priori repeated measures ANOVAs with a 2 (task) x 2 (SOA) design to test the auditory N1 component amplitude and latency differences for both visual and auditory time-locked conditions. Furthermore, a priori RM ANOVAs with a 2 (task) x 2 (SOA) were utilized to test the visual P1 component differences for both auditory and visual time-locked components. These statistical tests will be used to test hypotheses 4 and 5.

In addition to within subject comparisons, the results obtained from younger adults are compared to the results obtained from older adults. RM ANOVAs were utilized for each condition for both of the tasks. RM ANOVAs with a 2 (group - young or older participants) x 2 (task -SJ or TOJ) x 2 (SOA) design for the control conditions and an RM ANOVA with a 2 (group) x 2 (task) x 2 (SOA) design for the experimental conditions were conducted for both auditory and visual time-locked components. These statistical analyses will be used to test hypotheses 3, 4, 5, 6, and 7.

Furthermore, scalp maps were generated using average ERPs from all 22 younger and 21 older participants. Although they act as a complementary approach by providing an alternative method of visualizing the results, our main source of interpreting and understanding the results were via the waveforms created for each individual participant for each condition.

Results

Out of 28 participants, data from 21 participants was utilized for all of the statistical analyses that follow. 4 participants were excluded because at least one block (out of 5, per task) had less than 80 trials out of 125 that were usable for further analysis. EEG trials were excluded due to alpha activity (frequency range of 7.5 – 12.5 Hz), blinks, or due to excessive muscle movement. 3 participants were excluded to poor performance on the behavioural tasks.

Within-Subjects Analysis

Assessment of Within-Subjects Hypotheses 1, 2, and 3

Figures 16 and 17 shows the raw data of an older participant (participant HZ11) fit with a Gaussian and cumulative Gaussian function respectively. Figures 18 and 19 represent the average TBW and PSS obtained from the older participants.

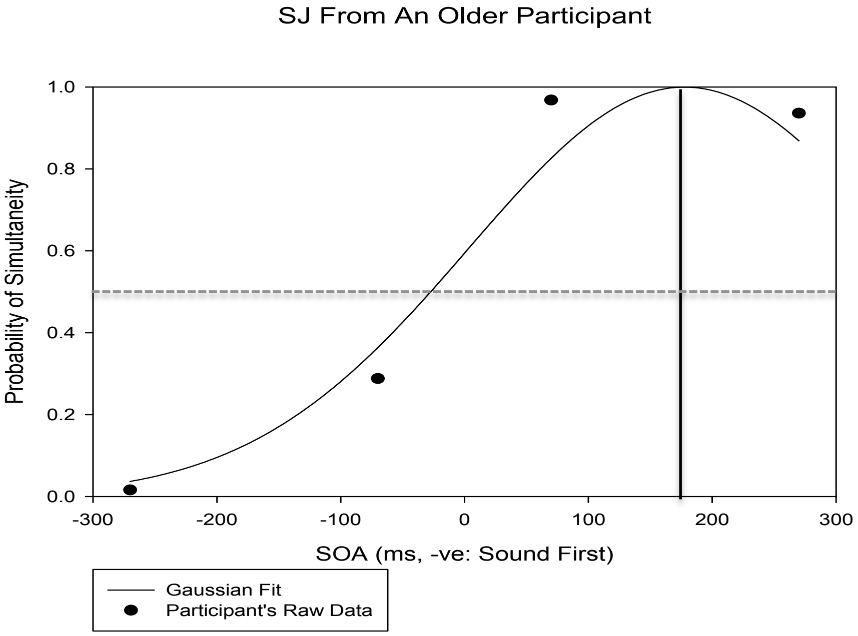

Figure 16. Study 2 behavioural raw data of an older participant's (participant HZ11) performance on the SJ task fit to a Gaussian function. The vertical line black line represents the PSS and the dashed grey line represents the TBW (*b*). Each point represents the average of 125 trials per SOA.

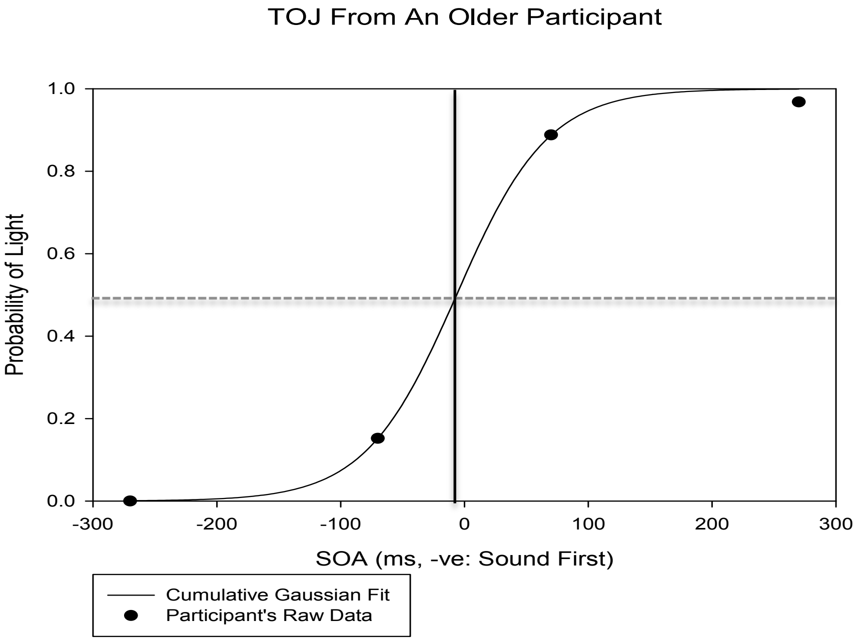

Figure 17. Study 2 behavioural raw data of an older participant's (participant HZ11) performance on the TOJ task fit to a cumulative Gaussian function. The vertical black line represents the PSS and the slope represents the TBW (b). Each point represents the average of 125 trials per SOA.

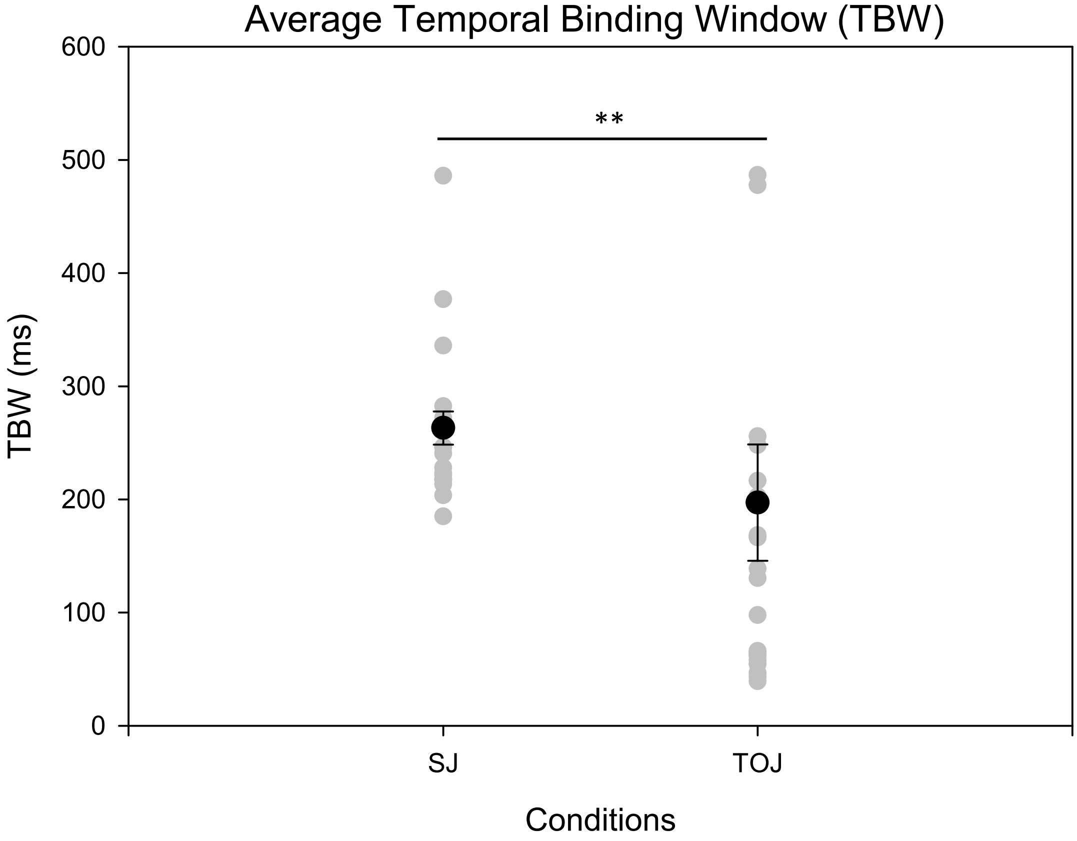

Figure 18. Study 2 behavioural results. Average TBW for the SJ and TOJ tasks); t(19) = 3.50, p = 0.002. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM. ** indicates $p < 0.01$.

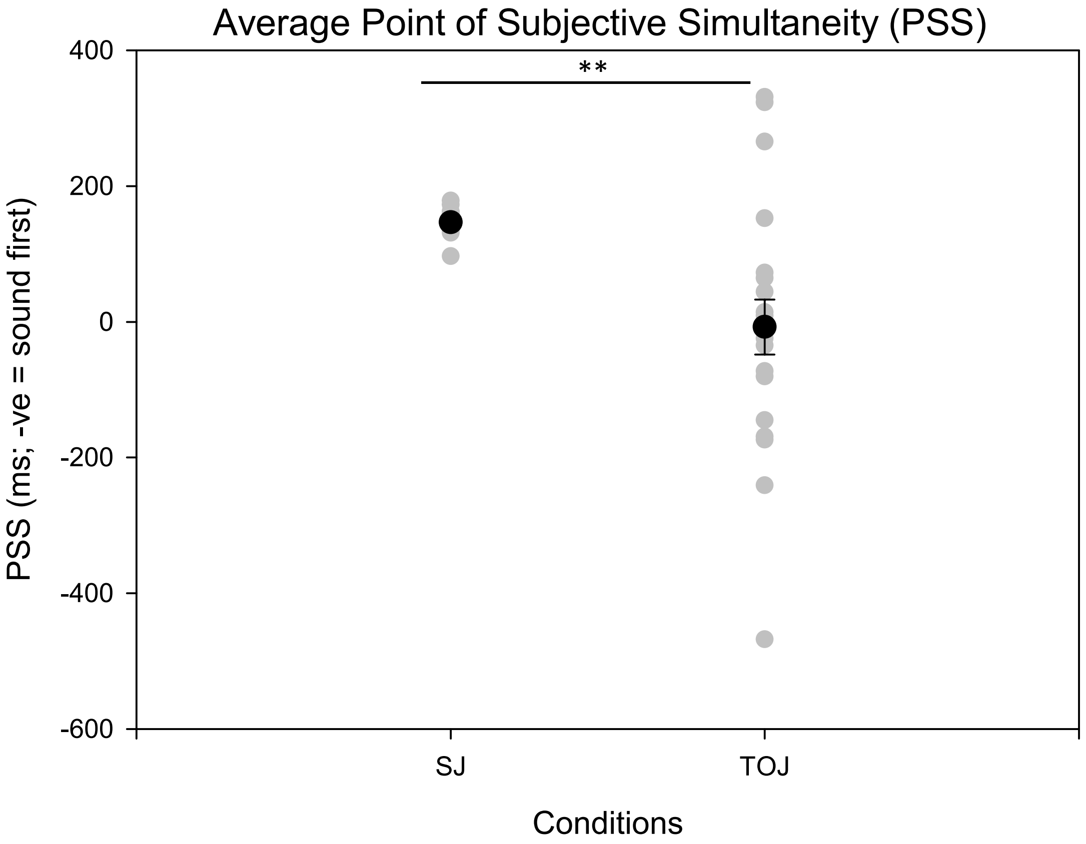

Figure 19. Study 2 behavioural results. Average PSS for the SJ and TOJ tasks; t(20) = 3.74, p = 0.001. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM. ** indicates p < 0.01.

Paired t-tests and Correlation from Study 1 assessing Hypotheses 1, 2, and 3 in Older Adults

Task	Statistical Analysis	Result
SJ and TOJ TBW	Paired t-test	SJ TBW (M = 257.37, SD = 63.62) and TOJ TBW (M = 154.14, SD = 132.60); t(19) = 3.50, **p = 0.002****
SJ and TOJ PSS	Paired t-test	SJ PSS (M = 146.65, SD = 17.10) and TOJ PSS (M = -7.45, SD = 185.66); t(20) = 3.74, **p = 0.001****
SJ and TOJ TBW	Correlation	r(21) = 0.45, **p = 0.04***
SJ and TOJ PSS	Correlation	r(21) = -0.135 **p = 0.56**

Table 6. Represents the t-test and correlation results obtained from older adults from study 2. ** p < 0.01; * p < 0.05

Responses from the participants were converted to probabilities at each SOA and were fit with equations 1 or 2 for SJ and TOJ respectively, which allowed for the extraction of PSS and slope for further analysis. Figures 16 and 17 show what the raw data of a typical participant looks like when it is fit to the Gaussian and cumulative Gaussian function respectively. Hypothesis 1 stated that the mean TBW and the mean PSS would be significantly different between the SJ and the TOJ tasks; this hypothesis was confirmed (figure 18 and 19; table 6). Hypothesis 2 stated that the TBW would be positively correlated between the SJ and the TOJ tasks; this hypothesis was confirmed (table 6). Hypothesis 3 stated that the PSS from SJ and TOJ would not be significantly correlated; this hypothesis was confirmed (table 6).

Assessing Changes in Performance Over Time

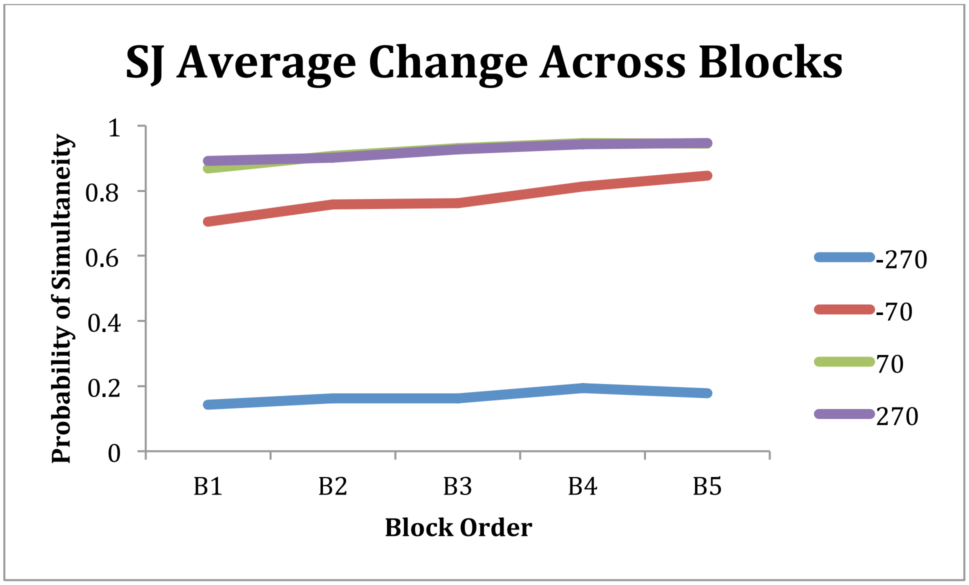

Figure 20. Study 2 represents the average change across blocks for the SJ task for each SOA.

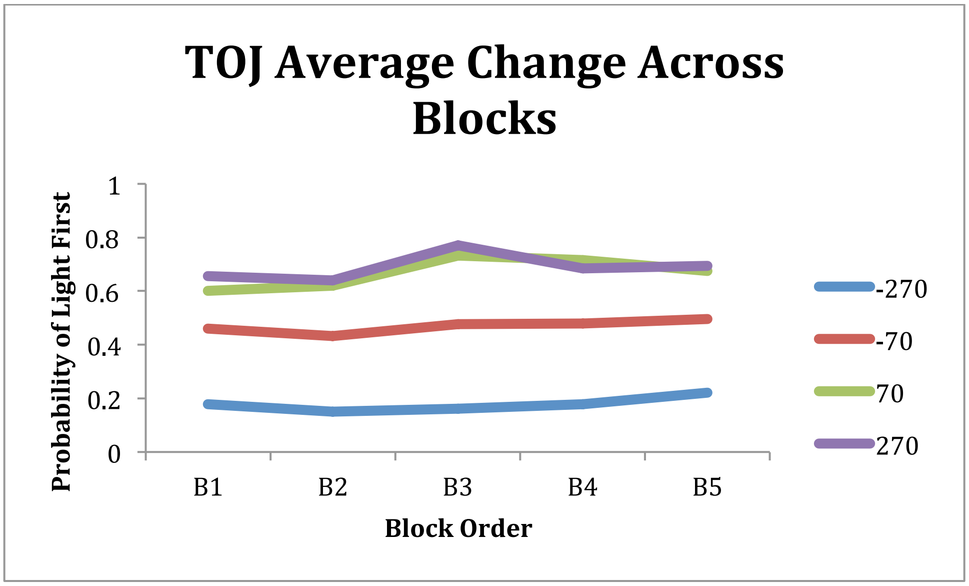

Figure 21. Study 2 represents the average change across blocks for the SJ task for each SOA.

Participants were asked to complete the SJ and TOJ tasks in blocks of 100 trials. Although the method of constant stimuli was utilized within each task, and each task was presented in a randomly assigned order, a 4 (SOA) x 5 (blocks) RM ANOVA design was used for each task to ensure there was no effect of order. If Sphericity was violated ($p \leq 0.05$), we utilized the Greenhouse-Geisser correction. Results indicate there was a significant main effect of SOA for the SJ task, $F(1.49, 29.98) = 220.29$, $p < 0.001$, $\eta^2_p = 0.917$ (figure 20). There was also a main effect of block order, $F(2.72, 52.58) = 8.13$, $p < 0.001$, $\eta^2_p = 0.289$ (figure 20). However there was no interaction between SOA and block order for SJ. Additionally, there was a main effect of SOA for the TOJ task, $F(1.49, 29.89) = 30.613$, $p < 0.001$, $\eta^2_p = 0.605$ (figure 21). However there was no main effect of block order and no interaction between SOA and block order.

Event-Related Potential Results

Assessment of Hypothesis 4 (Control Conditions) Using 2x2 RM-ANOVA

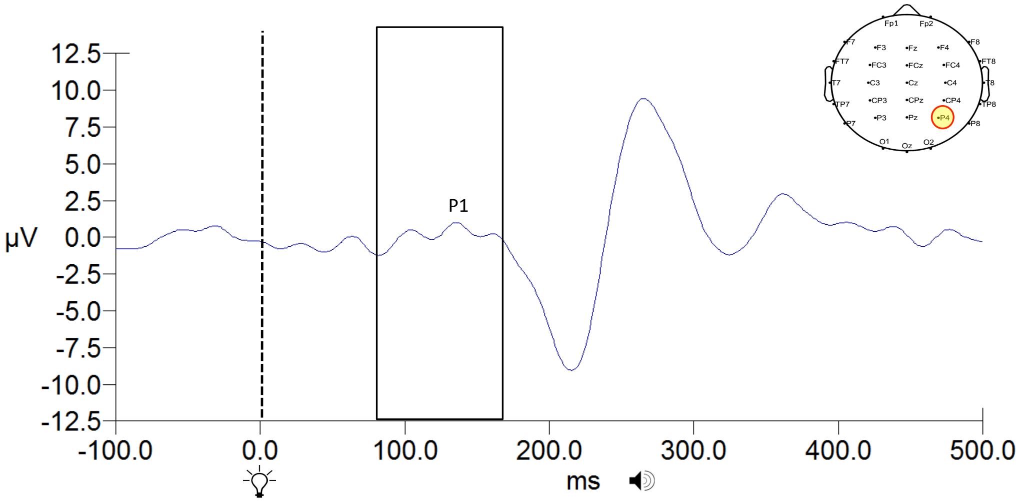

Figure 20. Study 2 ERP waveform from a typical participant (participant AQ20) while completing the SJ task when light was presented 270 ms before sound and time-locked to light. Obtained from the P4 electrode; the visual P1 peak amplitude and latency is marked on the graph.

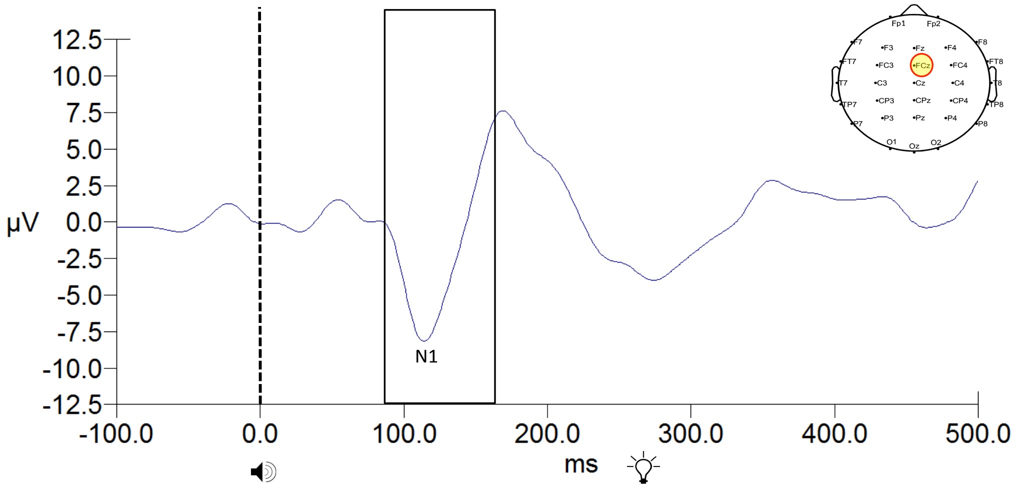

Figure 21. Study 2 ERP waveform from a typical participant (participant AQ20) completing the SJ task when sound was presented 270 ms before light and time-locked to sound. Obtained from the FCz electrode; the auditory N1 peak amplitude and latency is marked on the graph.

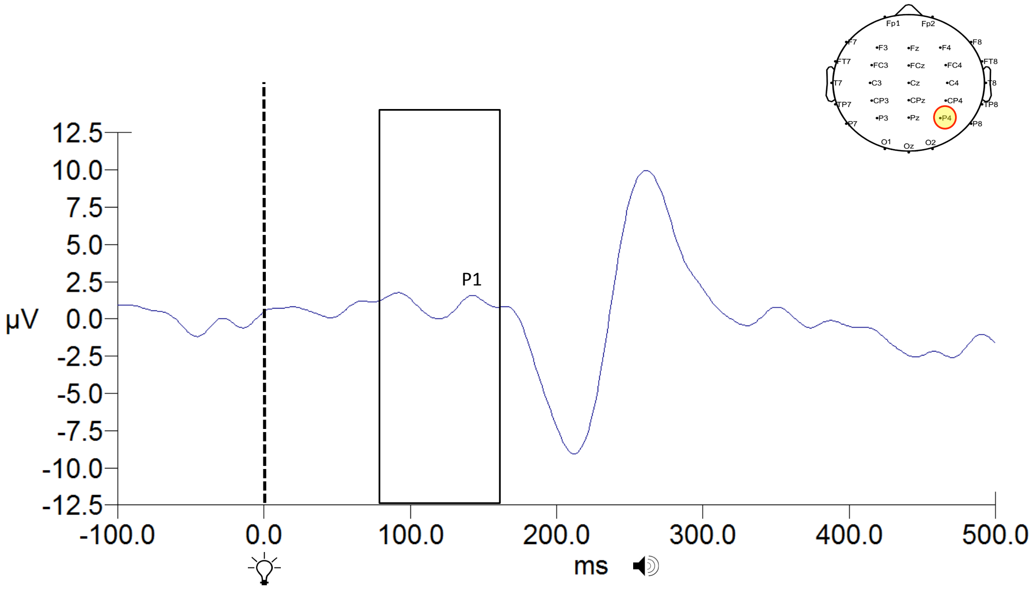

Figure 22. Study 2 ERP waveform from a typical participant (participant AQ20) while completing the TOJ task when light was presented 270 ms before sound and time-locked to light. Obtained from the P4 electrode; the visual P1 peak amplitude and latency is marked on the graph.

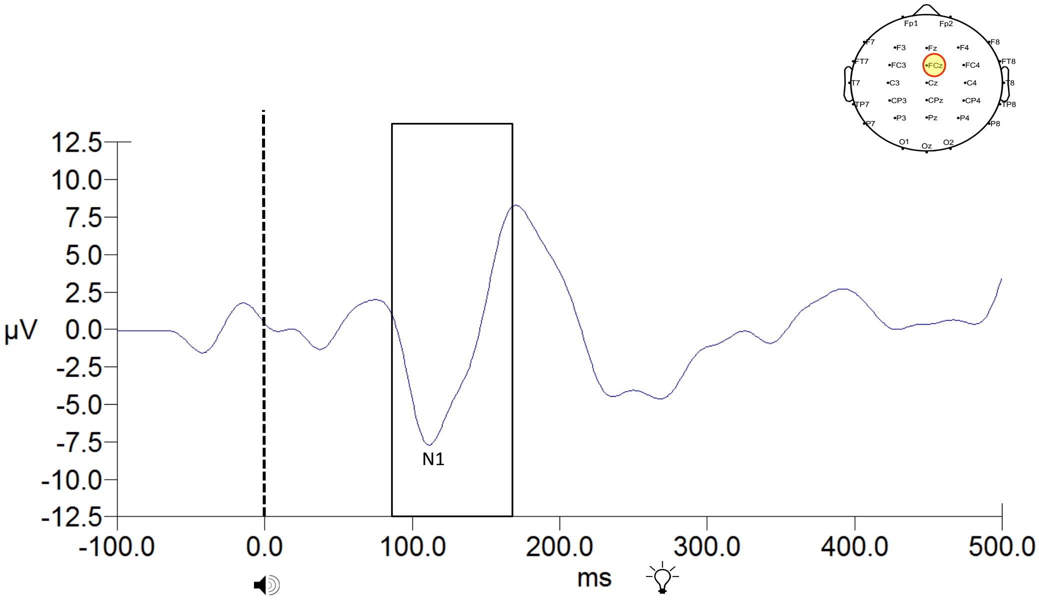

Figure 23. Study 2 ERP waveform from a typical participant (participant AQ20) completing the TOJ task when sound was presented 270 ms before light and time-locked to sound. Obtained from the FCz electrode; the auditory N1 peak amplitude and latency is marked on the graph.

Figures 20, 21, 22, and 23 are visual representations of the waveforms used to extract visual P1 and auditory N1 amplitudes and latency values for the control conditions. A 2 (SOA: 270ms, 70 ms, time-locked to light) x 2 (task – SJ, TOJ) RM ANOVA design was utilized to extract the amplitudes and latencies for the control visual P1 condition. A 2 (SOA: -270ms, -70 ms, time-locked to sound) x 2 (task – SJ, TOJ) RM ANOVA design was utilized to extract the amplitudes and latencies for the control auditory N1 condition. Although there was no main effect of task, the results did indicate an interaction between SOA and task for both the visual P1 peak latency obtained from the O2 electrode, when the SOAs of 270 ms and 70 ms were time-locked to light; $F(1, 20) = 4.74$, $p = 0.042$, $\eta^2_p = 0.192$.

Hypothesis 4 stated that there would be no difference between the two tasks for the control conditions; hypothesis 4 was confirmed.

Assessment of Hypothesis 5 (Experimental Conditions) Using 2x2 RM-ANOVA

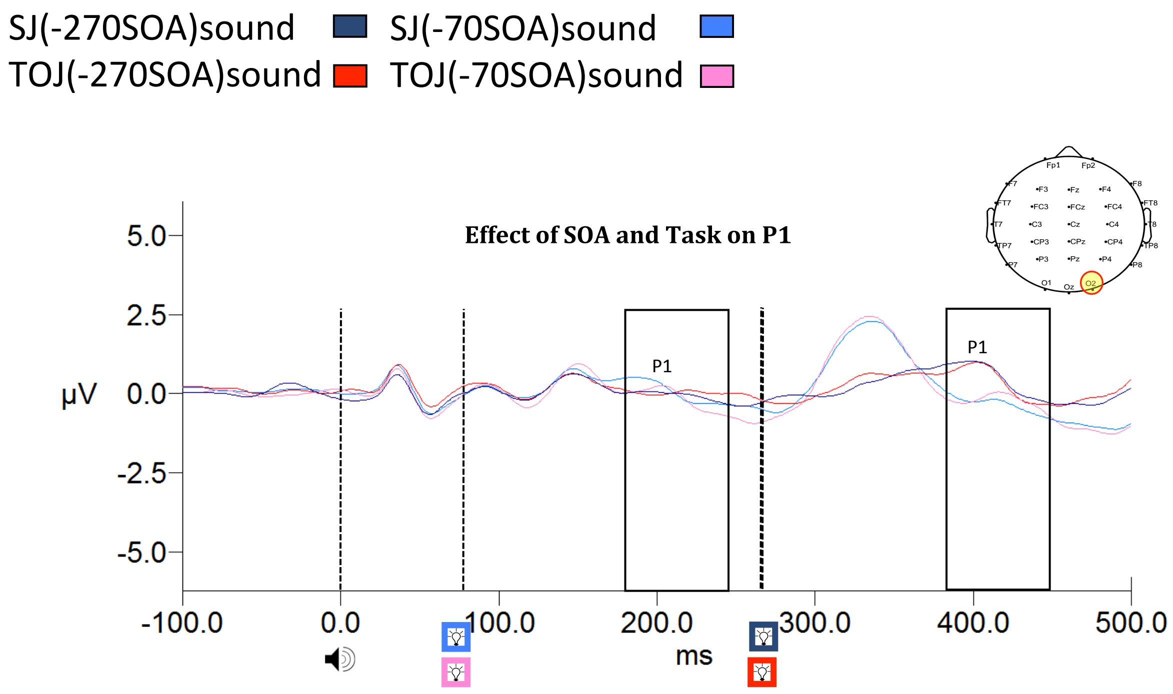

Figure 24. Study 2 ERP obtained from an average of all of the participants. Here we compare the SJ (in shades of blue) with the TOJ tasks (in shades of red) as well as their respective SOAs (-270 ms, -70 ms) presented in the legend. The ERP amplitude and latency values were obtained from the O2 electrode. Both of the tasks were time-locked to sound. The boxes indicate the extraction parameters that were used to extract the peak amplitudes and peak latencies.

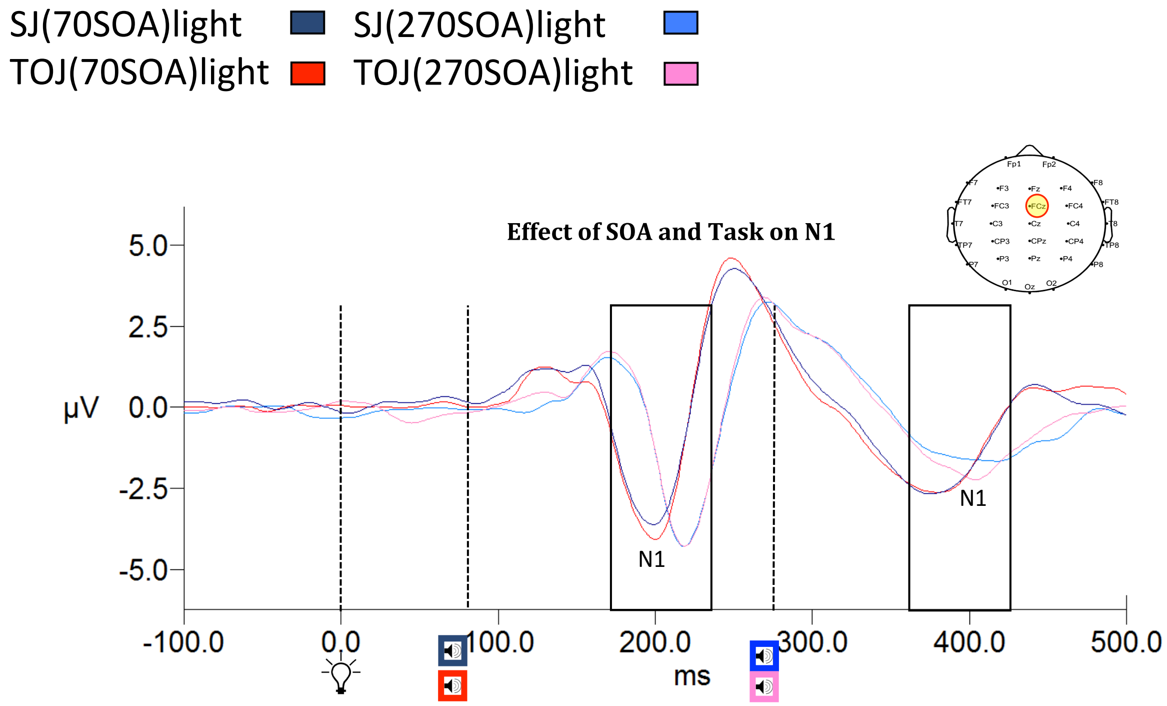

Figure 25. Study 2 ERP obtained from an average of all of the participants. Here we compare the SJ (in shades of blue) with the TOJ tasks (in shades of red) as well as their respective SOAs (70 ms and 270 ms) presented in the legend. The ERP amplitude and latency values were obtained from the FCz electrode. Both of the tasks were time-locked to light. The boxes indicate the extraction parameters that were used to extract the peak amplitudes and peak latencies.

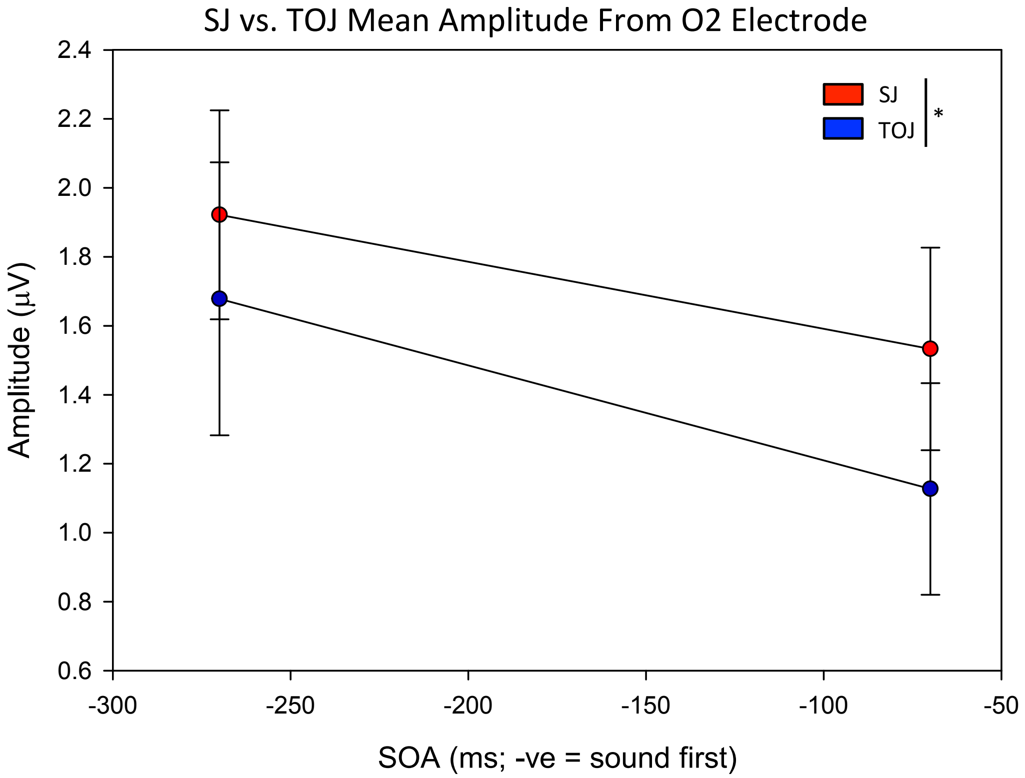

Figure 26. Study 2 ERP comparison of the peak amplitude values obtained from SJ (red) and TOJ (blue) tasks for the SOA of -270ms, -70 ms. Recorded at the O2 electrode and was time-locked to sound. A significant main effect of task was found; F(1,20) = 4.91, p = 0.038, η^2_p = 0.197. Error bars are ±1 SEM. * indicates $p < 0.05$

Repeated Measures ANOVA from Study 2 assessing Hypothesis 5

Condition	Electrode	Statistical Analysis	Result
P1 amp; time-locked to sound	O2	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,20) = 4.91, **p = 0.038***, η^2_p = 0.197; main effect of task
P1 amp; time-locked to sound	O2	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,20) = 6.66, **p = 0.018***, η^2_p = 0.25; main effect of SOA
P1 latency; time-locked light	P4	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 7.63, **p = 0.012***, η^2_p = 0. 27; main effect of SOA
P1 latency; time-locked sound	P4	2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1,19) = 3.75, **p = 0.068**, η^2_p = 0.165; main effect of SOA
N1 amp; time-locked light	FCz	2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1,20) = 8.71, **p = 0.008****, η^2_p = 0.303; main effect of SOA
N1 amp; time-locked sound	FCz	2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1,20) = 3.97, **p = 0.06**, η^2_p = 0.166; main effect of task

Table 7. Represents the ANOVA results obtained from older adults for visual P1 and auditory N1 from study 2. Notice that some of the statistical analysis are not significant, but rather are approaching significance. ** $p < 0.01$; * $p < 0.05$

Figures 24 and 25 are visual representations of the grand average ERPs; each participant's data was averaged together to form this image. Visual P1 and auditory N1 ERP amplitude and latency values were extracted from each participant's waveforms individually and not from the average. A 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ) design was used for the results obtained for the visual P1 amplitude and latency and a 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ) was utilized for the auditory N1 amplitude and latency analyses. Hypothesis 5 stated that there would be a significant main effect of task for at least one of the electrode sites for both the visual P1 and auditory N1 ERP amplitude and latency components. The results revealed a main effect of task only for amplitude at the O2 electrode site when it was time-locked to sound (figure 26; table 7) but no main effect of task for the latency. A main effect of task was also found for the auditory N1 amplitude when time-locked to sound (table 7); however no main effect of task was found for the latency. Thus the results obtained do not completely support hypothesis 5. Refer to table 7 for the statistics obtained.

Between-Subjects Analysis

Assessment of Hypotheses 1 and 2

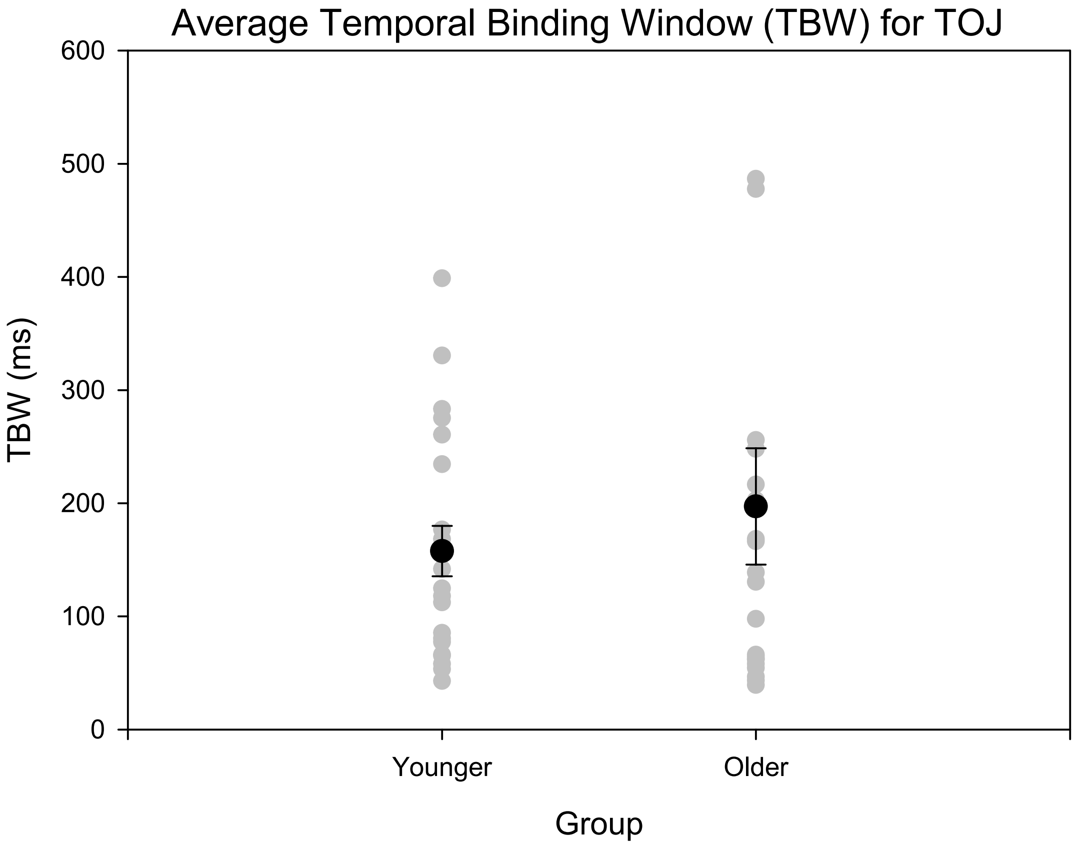

Figure 27. Study 2 behavioural results. Average TBW for older and younger adults on the TOJ task. An independent t-test revealed no statistical difference between the means of the two groups; t(20) = 0.704, p = 0.485. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM.

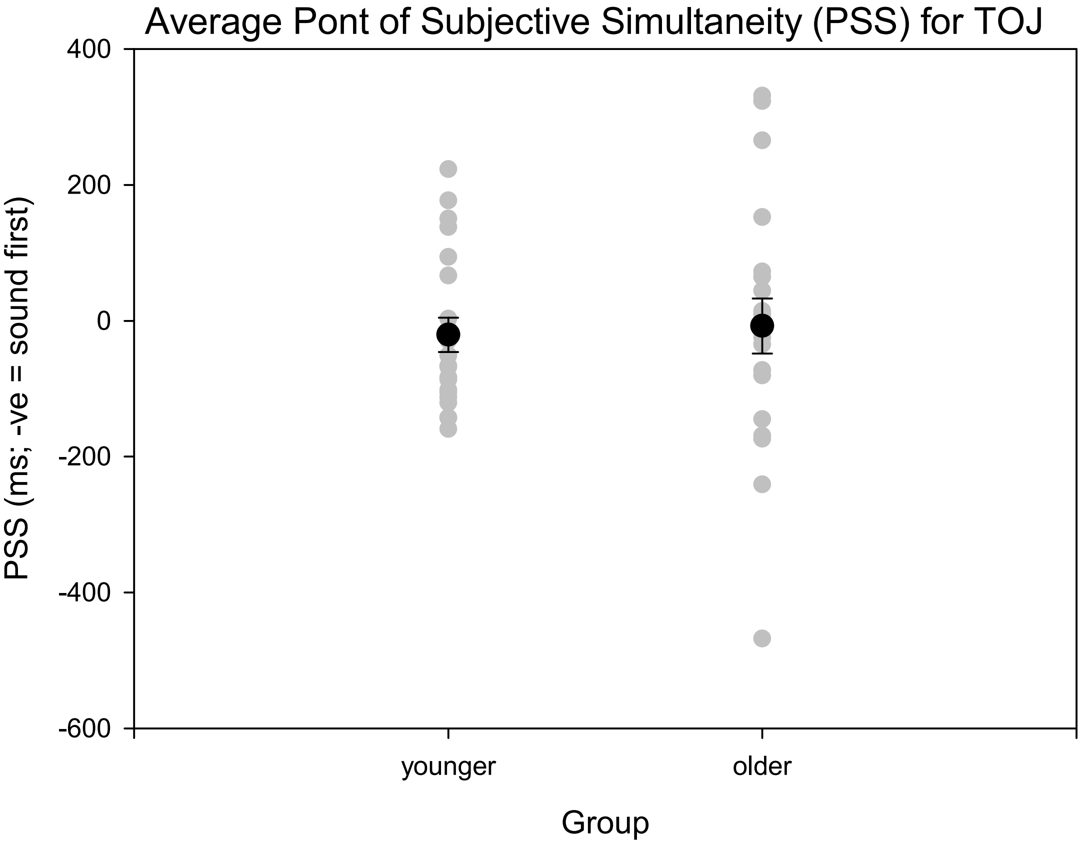

Figure 28. Study 2 behavioural results. Average PSS for older and younger adults on the TOJ task. An independent t-test revealed no statistical difference between the means of the two groups; t(20) = 0.272, p = 0.787. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM.

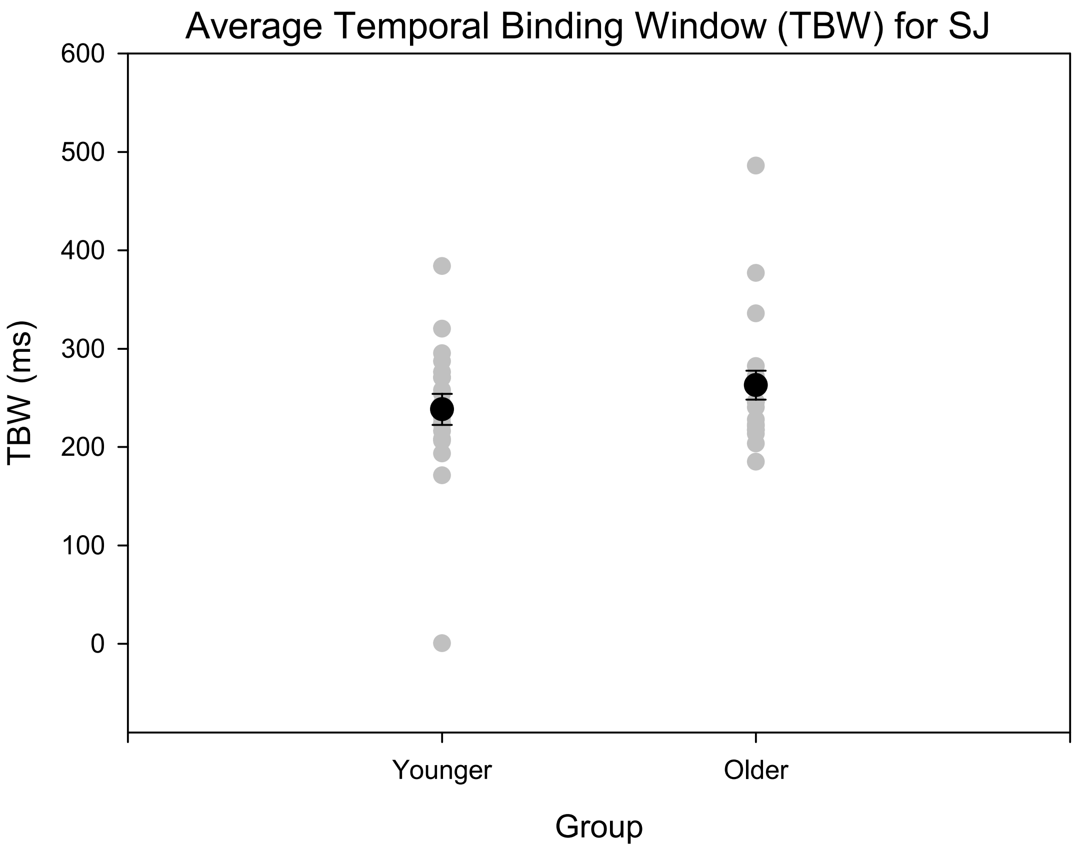

Figure 29. Study 2 behavioural results. Average TBW for older and younger adults on the SJ task. An independent t-test revealed no statistical difference between the means of the two groups; t(20) = 1.143, p = 0.260. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM.

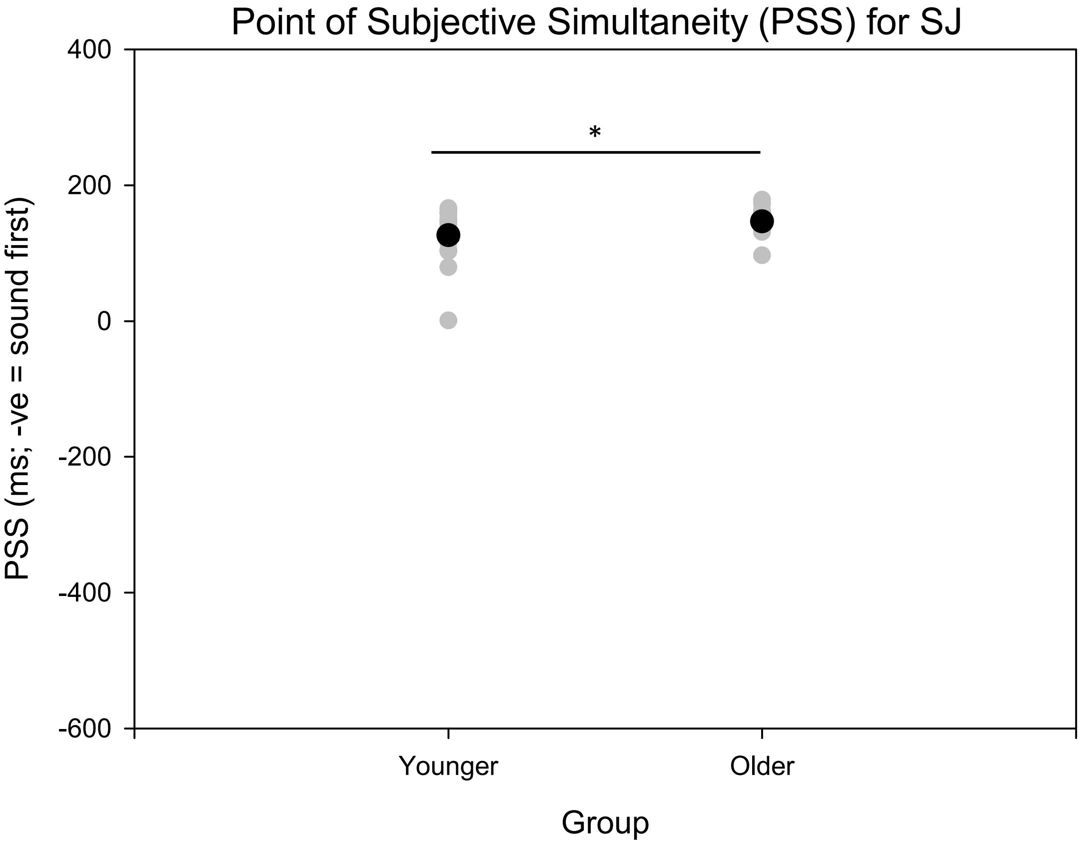

Figure 30. Study 2 behavioural results. Average PSS for older and younger adults on the SJ task. An independent t-test revealed a statistical difference between the means of the two groups; t(20) = 2.321, p = 0.025. The lighter circles represent each individual participant's data whereas the darker circle represents the average obtained. Error bars are ±1 SEM. * indicates $p < 0.05$

Independent t-tests from Study 2 assessing Hypotheses 1 and 2 by Comparing Older and Younger Adults

Task	Statistical Analysis	Result
TOJ TBW	Independent t-test	Older TBW (M = 197.09, SD = 235.47) and younger TBW (M = 157.64, SD = 102.03); t(40) = 0.704, **p = 0.485**
TOJ PSS	Independent t-test	Older PSS (M = -7.45, SD = 185.66) and younger PSS (M = -20.45, SD = 115.98); t(37) = 0.272, **p = 0.787**
SJ TBW	Independent t-test	Older TBW (M = 263.06 SD = 67.27) and younger TBW (M = 238.48, SD =72.05); t(40) = 1.143, **p = 0.260**
SJ PSS	Independent t-test	Older PSS (M = 146.65, SD = 17.10) and younger PSS (M = 126.40, SD = 36.14); t(40) = 2.321, **p = 0.02544***

Table 8. Represents the independent t-test results obtained from a comparison between older and younger adults from study 2. * $p < 0.05$

Hypothesis 1 stated that older adults would have a wider TBW compared to younger adults on the TOJ task; this hypothesis was not confirmed (figure 27; table 8). The explore function of SPSS version 21.0 was utilized to identify outliers. When the outliers were removed from the sample and the statistics were re-calculated, very similar results were found (i.e., only SJ PSS was significant). Multiple comparisons were corrected for SJ and TOJ (based on Bedard & Barnett-Cowan, 2016) but not for PSS and TBW (based on Bedard & Barnett-Cowan, 2016). Based on the correction applied, the SJ PSS between the two groups was slightly over the corrected alpha value (0.05/2 = 0.025). Thus hypothesis 2 was confirmed as it stated that older and younger adults would perform similarly on the SJ task (PSS and TBW will not be significantly different) (figure 29 and 30; table 8).

Event-Related Potential Results

Assessment of Hypotheses 3 and 4 (Control Conditions) Using 2x2x2 RM-ANOVA

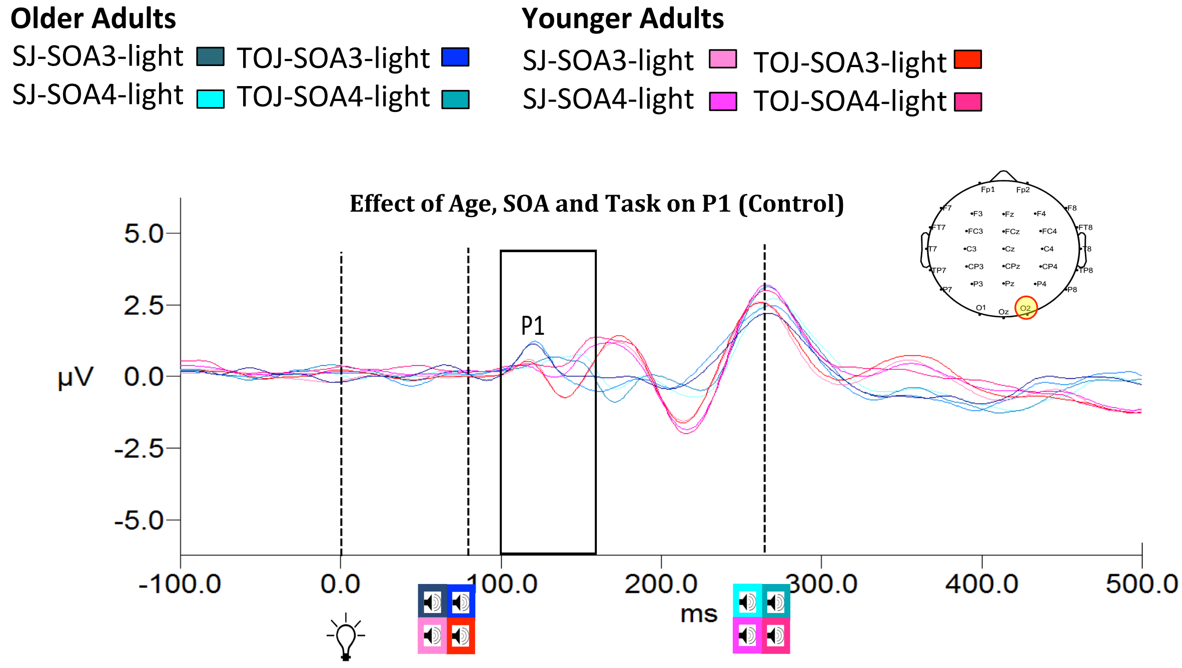

Figure 31. Study 2 ERP obtained from an average of all of the older and younger participants. Here we compare older (in shades of blue) with younger (in shades of red) as well as the two tasks and their respective SOAs (270 ms, 70 ms) presented in the legend. The ERP amplitude and latency values were obtained from the O2 electrode. Both of the

tasks were time-locked to light. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

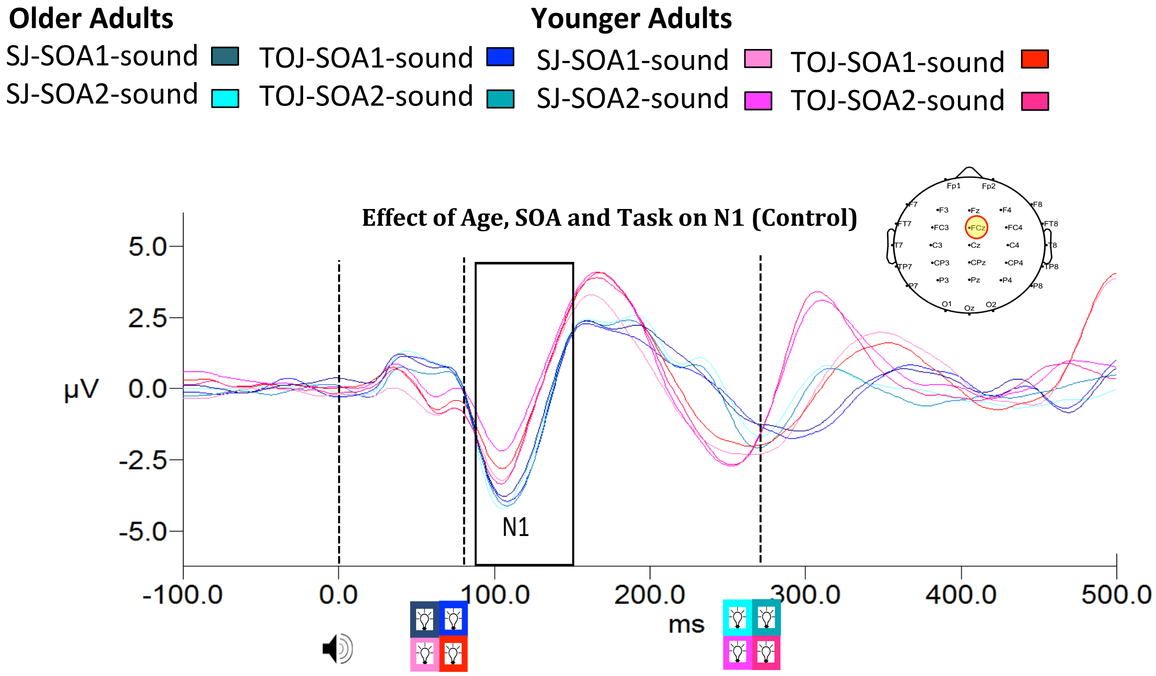

Figure 32. Study 2 ERP obtained from an average of all of the older and younger participants. Here we compare older (in shades of blue) with younger (in shades of red) as well as the two tasks and their respective SOAs (-270 ms, -70 ms) presented in the legend. The ERP amplitude and latency values were obtained from the FCz electrode. Both of the tasks were time-locked to sound. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

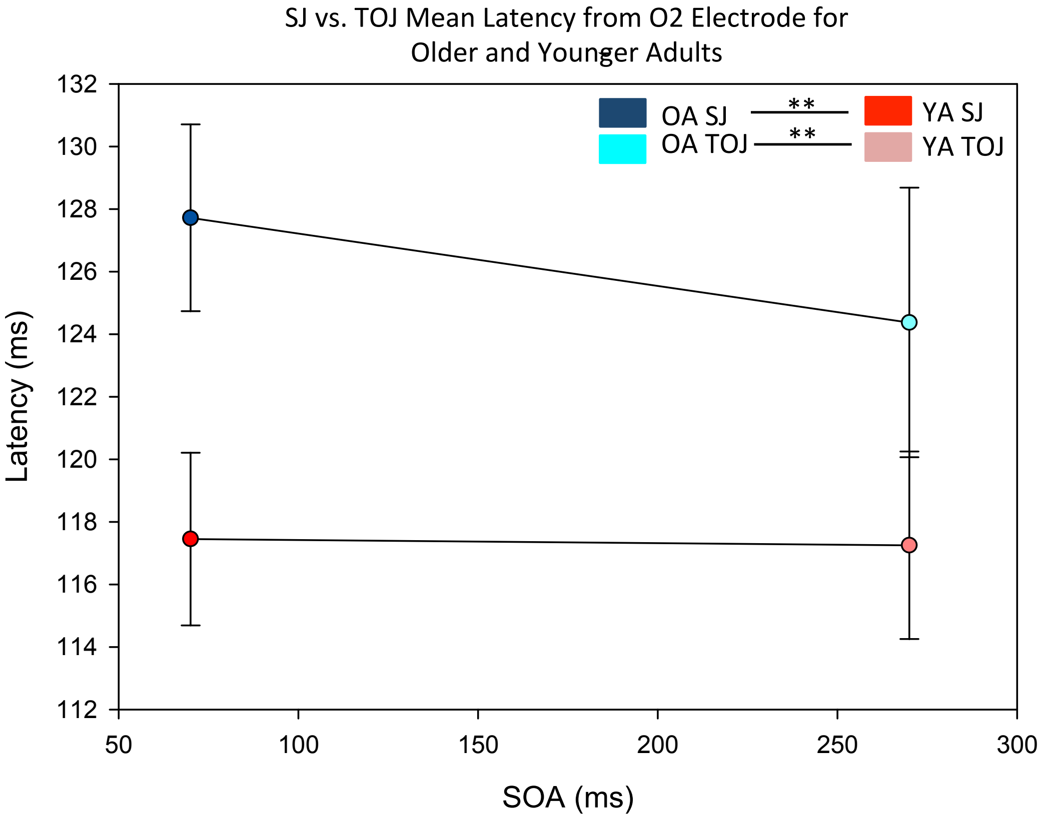

Figure 33. Study 2 ERP comparison of the peak visual P1 latency values obtained from older and younger adults for SJ and TOJ tasks for the SOA of 270ms and 70 ms. Recorded at the O2 electrode and was time-locked to light. A significant main effect of age was found; F(1, 19) = 14.39, p = 0.001, η^2_p = 0.431. Error bars are ±1 SEM. ** represents p <0.01

Repeated Measures ANOVA from Study 2 Assessing Hypotheses 3 and 4 by Comparing Older and Younger Adults

Condition	Electrode	Statistical Analysis	Result
P1 latency; time-locked to light	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 14.39, **p = 0.001****, η^2_p = 0.431; OA lat (M = 126.05, SD = 2.98); YA lat (M= 117.35, SD = 2.174); main effect of age
P1 amp; time-locked light	P4	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 20) = 9.7, **p = 0.005****, η^2_p = 0.327; main effect of SOA
P1 latency; time-locked light	P4	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 20) = 5.27, **p = 0.033***, η^2_p = 0.21; main effect of SOA

Table 9. Represents the RM ANOVA results obtained from a comparison between older and younger adults for the visual P1 and auditory N1 from study 2. ** $p < 0.01$; * $p < 0.05$

Figures 31 and 32 are visual representations of the grand average ERPs; each participant's data was averaged together to form this image. Visual P1 and auditory N1 ERP amplitude and latency values were extracted from each participant's waveforms individually and not from the average. A priori RM ANOVAs with a 2 (group: older and younger) x 2 (task: SJ and TOJ) x 2 (SOA: ± 270, ± 70 ms) design was used to test the visual P1 and auditory N1 amplitude and latency differences between older and younger adults for both visual and auditory time-locked stimuli.

Hypothesis 3 stated that older adults would have smaller visual P1 peak amplitudes compared to younger adults for the TOJ task; this hypothesis was not confirmed (table 9). However, the results did reveal a main effect of age for the visual P1 latency where older adults showed a later onset of response (M = 126.05, SD = 2.98) than younger adults (M= 117.35, SD = 2.174) (figure 33; table 9). Hypothesis 4 stated that there would be no significant differences between the auditory N1 amplitudes obtained from the older and younger adults; this hypothesis was confirmed (table 9).

Assessment of Hypotheses 5, 6, and 7 (Experimental Conditions) Using 2x2x2 RM-ANOVA

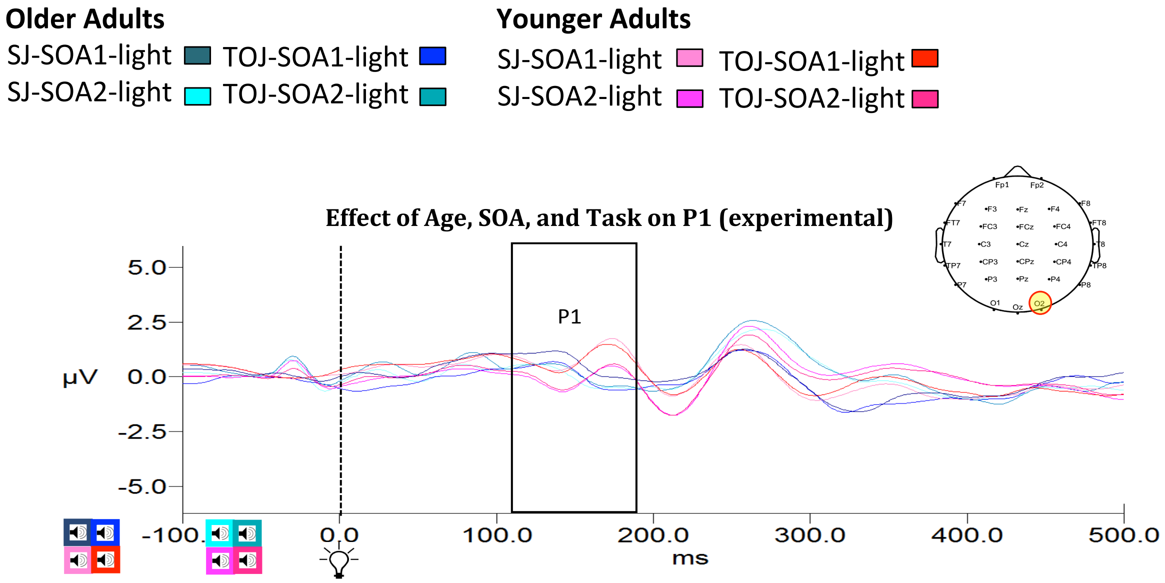

Figure 34. Study 2 visual P1 ERP obtained from an average of all of the older and younger participants. Here we compare older (in shades of blue) with younger (in shades of red) as well as the two tasks and their respective SOAs (-270 ms, -70 ms) presented in the legend. The visual P1 ERP amplitude and latency values were obtained from the O2 electrode. Both of the tasks were time-locked to light. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

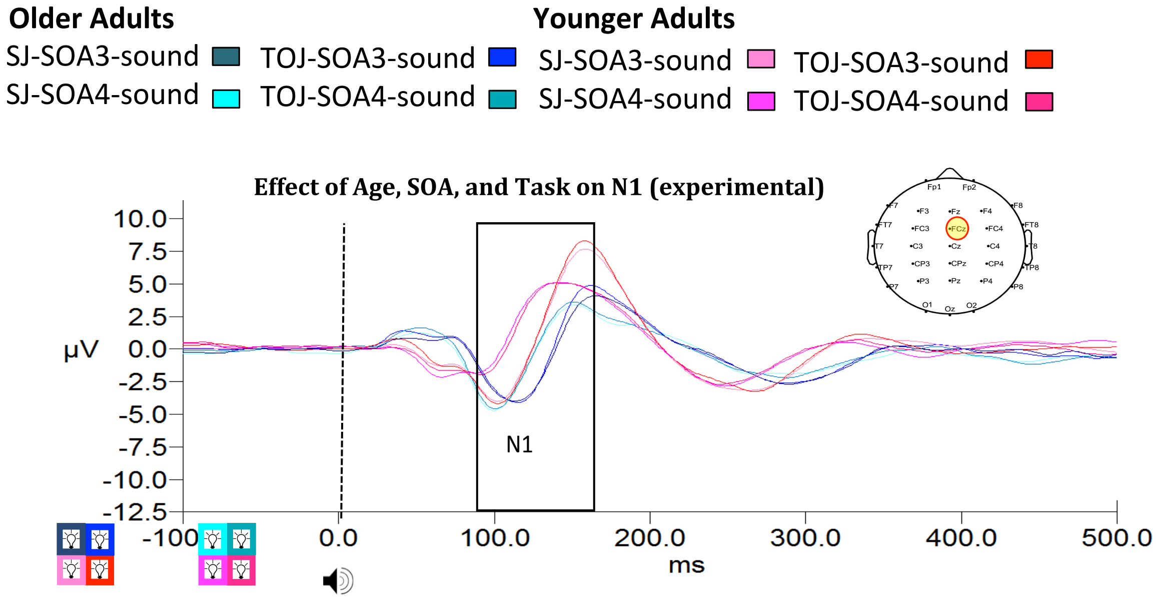

Figure 35. Study 2 auditory N1 ERP obtained from an average of all of the older and younger participants. Here we compare older (in shades of blue) with younger (in shades of red) as well as the two tasks and their respective SOAs (270 ms, 70 ms) presented in the legend. The auditory N1 ERP amplitude and latency values were obtained from the FCz electrode. Both of the tasks were time-locked to sound. The box indicates the extraction parameter that was used to extract the peak amplitudes and peak latencies.

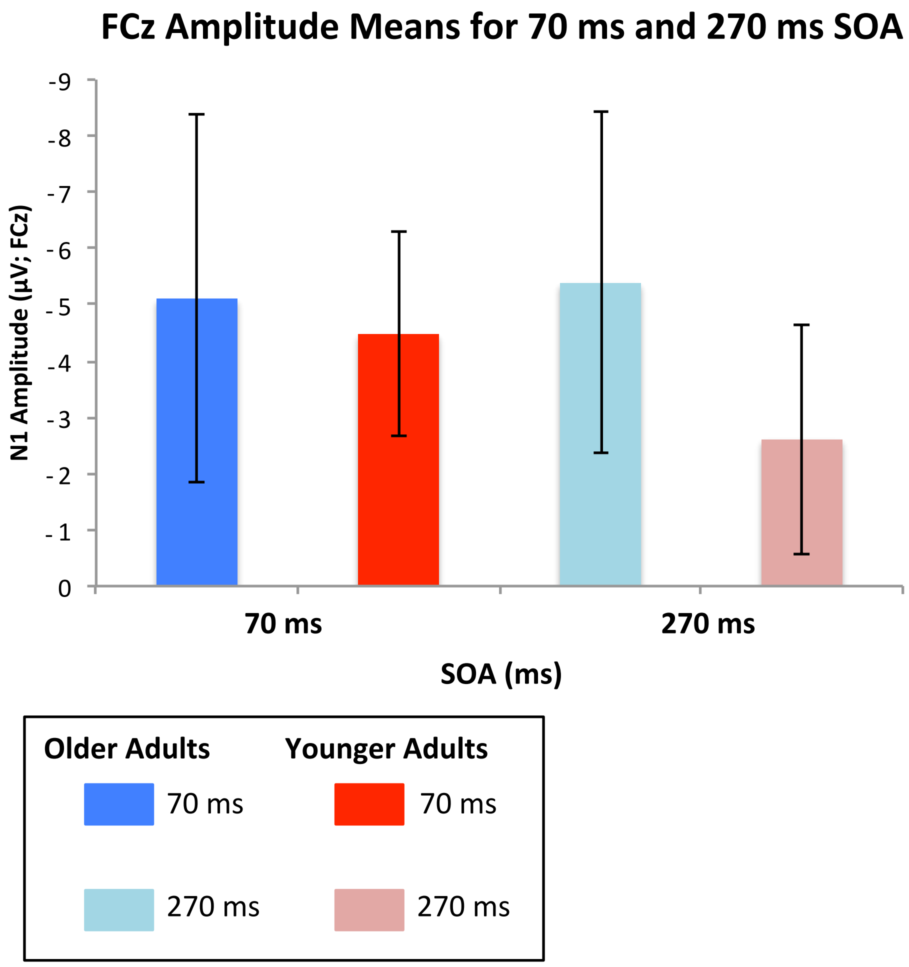

Figure 36. Study 2 ERP amplitudes obtained from an average of all of the participants. Here we compare older and younger auditory N1 amplitudes for the SOAs of 70 ms and 270 ms; refer to legend. The fronto-central auditory N1 ERP amplitudes and were obtained from the FCz electrode. The responses of the participants for both of the tasks were averaged for each SOA. Error bars are ±1 SEM.

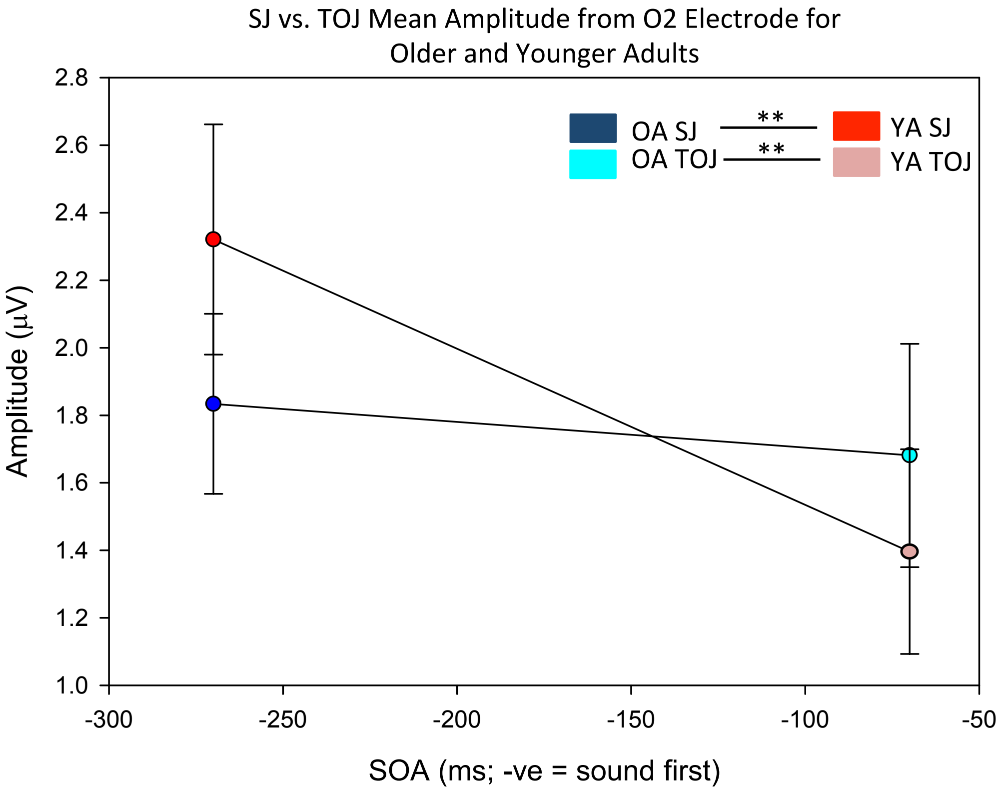

Figure 37. Study 2 visual P1 ERP comparison of the peak amplitude values obtained from older and younger adults for SJ (black) and TOJ (red) tasks for the SOA of -270ms and -70 ms. Recorded at the O2 electrode and was time-locked to light. Recorded at the O2 electrode and was time-locked to sound. A significant main effect of age was found A significant main effect of SOA and an interaction between age and SOA were found; F(1, 18) = 10.30, p = 0.005, η^2_p = 0.36 and F(1, 18) = 7.56, p = 0.013, η^2_p = 0.30 (older amplitude M = 1.76, SD = 0.29; younger amplitude M = 1.86, SD = 0.30) respectively. Error bars are ±1 SEM.

Visual P1 ERP Amplitudes for Older and Younger Adults when Time-Locked to Sound (O2) – Assessment of Hypotheses 5 and 7

Group	SOA	Mean	Std. Error
Older	SJ	1.829	0.356
	TOJ	1.349	0.295
Younger	SJ	1.994	0.337
	TOJ	1.404	0.306

Table 10. Study 2 main effect of task obtained for the visual P1 peak amplitude when time-locked to sound from the O2 electrode; F(1, 19) = 6.58, p = 0.019, η^2_p = 0.26. The table summarizes the visual P1 amplitude values obtained by the older and younger adults.

Visual P1 ERP Amplitudes for Older and Younger Adults when Time-Locked to Sound (P4)– Assessment of Hypotheses 5 and 7

Group	Task	Mean	Std. Error
Older	SJ	2.695	0.328
	TOJ	2.477	0.355
Younger	SJ	2.045	0.291
	TOJ	1.743	0.279

Table 11. Study 2 main effect of task obtained for the visual P1 peak amplitude when time-locked to sound from the P4 electrode; F(1, 17) = 9.58, p = 0.007, η^2_p = 0.36. The table summarizes the visual P1 amplitude values obtained by the older and younger adults.

Repeated Measures ANOVA from Study 2 Assessing Hypotheses 5, 6, and 7 by Comparing Older and Younger Adults

Condition	**Electrode**	**Statistical Analysis**	**Result**
P1 amp; time-locked to light	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 7.56, **p = 0.013**,* η^2_p = 0.30; OA amp M =1.76, SD = 0.29; YA amp M = 1.86, SD = 0.30; interaction: age x SOA
P1 amp; time-locked light	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 10.30, **p = 0.005****, η^2_p = 0.36; main effect of SOA
P1 amp; time-locked sound	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 6.58, **p = 0.019***, η^2_p = 0.26; main effect of task
P1 amp; time-locked sound	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 19)= 16.10, **p = 0.001****, η^2_p = 0.46; main effect of SOA
P1 latency; time-locked light	O2	2 (group) x 2 (SOA: −270 ms, −70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 11.19, **p = 0.003****, η^2_p = 0.371; OA lat M = 136.54, SD = 3.76; YA lat M = 153.04, SD = 4.27;main effect of age
P1 latency; time-locked sound	O2	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 11.79, **p = 0.003****, η^2_p =0.383; OA lat M = 138.07, SD = 3.78; YA lat M =

			155.09, SD = 3.68; main effect of age
P1 amp; time-locked light	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 8.04, **p = 0.011***, η^2_p =0.31; OA amp M = 2.60, SD = 0.29; YA amp M = 2.26, SD = 0.197 interaction: age x SOA
P1 amp; time-locked light	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 3.50, **p = 0.078**, η^2_p = 0.163; interaction: task x SOA
P1 amp; time-locked sound	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 17) = 9.58, **p = 0.007****, η^2_p = 0.36; main effect of task
P1 latency; time-locked light	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 18) = 5.36, **p = 0.033***, η^2_p = 0.23; OA lat M = 144.21, SD = 3.87; YA lat M = 134. 33, SD = 3.64; main effect of age
P1 latency; time-locked sound	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 17) = 11.18, **p = 0.004****, η^2_p = 0.40; main effect of SOA
P1 latency; time-locked sound	P4	2 (group) x 2 (SOA: -270 ms, -70ms) x 2 (task: SJ, TOJ)	F(1, 17) = 3.27, **p = 0.088**, η^2_p = 0.161; interaction: age x SOA
N1 amp; time-locked light	FCz	2 (group) x 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 12.07, **p = 0.003****, η^2_p = 0.39; main effect of SOA

N1 amp; time-locked sound	FCz	2 (group) x 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1, 15) = 16.28, **p = 0.001****, η^2_p = 0.520; OA amp M = -4.84, SD = 0.771; YA amp M = -3.55, SD = 0.39; interaction: age x SOA
N1 amp; time-locked sound	FCz	2 (group) x 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1, 15) = 5.20, **p = 0.038***, η^2_p = 0.26; main effect of SOA
N1 latency; time-locked light	FCz	2 (group) x 2 (SOA: 270 ms, 70ms) x 2 (task: SJ, TOJ)	F(1, 19) = 19.51, **p < 0.001*****, η^2_p = 0.520; OA lat M = 129.45, SD = 2.21; YA lat M = 112.96, SD = 2.52; main effect of age

Table 12. Represents the RM ANOVA results obtained from a comparison between older and younger adults for auditory N1 and visual P1 ERPs from study 2. Note that not all of the values reported are significant. *** p < 0.001; ** p < 0.01; * p < 0.05

Pairwise Comparisons from Study 2 assessing Hypothesis 7 in Older and Younger Adults

Task	Statistical Analysis	Result
SJ	Independent t-test	Older latency (M = 144.52, SD = 17.38) and younger latency (M = 131.34, SD = 19.51); t (19) = 2.20**, p < 0.034***
TOJ	Independent t-test	Older latency (M = 143.89, SD = 19.30) and younger latency (M = 137.31, SD = 19.63); t (19) = 1.042, **p < 0.304**

Table 13. Represents the multiple comparisons conducted for a comparison between older and younger adults for SJ and TOJ tasks for auditory N1 ERP from study 2. The latency was recorded from the FCz electrode, time-locked to light. * p < 0.05

Figures 34 and 35 are visual representations of the grand average ERPs; each participant's data was averaged together to form this image. Visual P1 and auditory N1 ERP amplitude and latency values were extracted from each participant's waveforms individually and not from the average. Results reported below are obtained from a priori RM ANOVAs with a 2 (group: older and younger) x 2 (task: SJ and TOJ) x 2 (SOA: ± 270, ± 70 ms). Hypothesis 5 stated that older adults would have smaller visual P1 amplitudes and later latencies compared to younger adults for the TOJ task. Although a main effect of task (table 10 and 11) and a main effect of age was found (table 12), no interactions between age x task were found. Here it was found that for some of the conditions, older adults had smaller visual P1 amplitudes compared to younger adults while for others younger adults had smaller visual P1 amplitudes. On average, older adults had earlier visual P1 latencies compared to younger adults. Based on the results, we conclude that there is insufficient evidence to accept hypothesis 5 (table 12; figure 37). Hypothesis 6 stated that there would be no main effect of age for the auditory N1 amplitude and latency. Although a main effect of age was found for the auditory N1 latency when time-locked to sound, a main effect of age was not found for amplitude. An interaction between age x SOA was also found for the auditory N1 amplitude when time-locked to sound (table 12; figure 36). It was found that older adults tended to have later latencies, and larger auditory N1 amplitudes that were sustained over SOAs compared to younger adults (table 12). Thus hypothesis 6 was only partially confirmed. Hypothesis 7 stated that younger and older adults would perform similarly with no significant differences in amplitude and latency on the SJ task. Main effects of task (table 10 and 11) and main effects of age (table 12) were found between the groups; however pairwise comparisons did not reveal any significant differences for amplitude. A significant difference in latency was found between younger and older adults for the SJ task (table 13). Notice, there were no significant differences in latency obtained form the visual electrodes. Based on these results, hypothesis 7 was partially rejected.

Discussion

The present study aimed to test both within and between subject differences in older and younger adults between simultaneity and temporal order perception. Previous behavioural results have indicated that simultaneity and temporal order perception may be sub served via different neural mechanisms. In study 1, we confirmed behaviourally that these differences exist between the SJ and TOJ task within younger adults. We also confirmed that there were no differences in vision and audition perception for the control conditions between the two tasks, indicating that unisensory perception does not effect the perception of simultaneity and temporal order of events. We were unable to confirm multisensory integration differences between the two tasks within younger adults. We speculate that if any differences do exist, our ERP protocol based on Setti et al (2011) may not have been a sensitive enough measure or the design of the study was not optimal for capturing any differences if they did exist.

Study 2 aimed to determine whether using a population with a deficit in temporal order perception would provide an alternative option to capture the differences between simultaneity and temporal order perception. Previous research has shown that older adults are impaired in determining the temporal order of events (Bedard & Barnett-Cowan, 2016; Setti et al., 2011a) and thus it was speculated that testing older adults would allow us to better understand the differences that exist between the two tasks and would also allow us to investigate how simultaneity and temporal order perception changes with time.

Within-Subjects Design

In summary, we found compelling evidence indicating that simultaneity and temporal order perception differ at the behavioural level. The ERP data revealed that unisensory perception of light and sound are not effected based on the task (SJ or TOJ) being completed as indicated by lack of difference between the amplitudes and latencies of the visual P1 and auditory N1 ERPs between the two tasks. Contrary to our prediction, we found that integration of auditory and visual stimuli are not significantly different when completing SJ and TOJ tasks. This lack of difference at the multisensory integration level may be due to the fact that the design of the study may not have been ideal for assessing the different neural mechanisms that exist between the two tasks or that EEG was not sensitive enough to measure the differences even if they did exist.

Within-Subjects Design – Behavioural Results

Consistent with our prediction, we found that the TBW as well as the PSS were significantly different between the two tasks. Our results were in line with previous studies (Bedard & Barnett-Cowan, 2016; Love et al., 2013), indicating that the two tasks may be sub served via different neural networks (Linares & Holcombe, 2014). As predicted, a strong positive correlation between the TBWs from the SJ and the TOJ tasks was found. Our results were in line with previous literature (Bedard & Barnett-Cowan, 2016) indicating that although it is speculated that simultaneity and temporal order perception may be processed differently, regardless the TBWs obtained from the two tasks may be supported by similar neural mechanisms.

In line with previous literature (Bedard & Barnett-Cowan, 2016; Linares & Holcomb et al., 2014; Love et al., 2013; Van Eijk et al., 2008), we did not find a significant correlation between the PSSs from the two tasks. These results suggest that perception of simultaneity and temporal order may be sub served via different neural networks with respect to PSS. Allan (1975) asked their participants to decide whether the offset of audiovisual stimuli were simultaneous or successive and were subsequently asked to indicate whether the light preceded sound or vice versa, regardless of their initial response (simultaneous vs. successive). During the audiovisual task the onset of the stimuli was always simultaneous and the offset was varied. Allan (1975) found that successiveness or the detection of asynchrony was a necessary requirement for temporal order perception thus suggesting that different networks were involved in synchrony and temporal order detection. Love et al., (2013) also postulated that different perceptual mechanisms were utilized by the two tasks. Their participants were presented with auditory and visual stimuli that were varied by the following SOAs: ±333, ±267, ±200, ±133, ±67, and 0 ms and were asked to make either simultaneity or temporal order judgments in randomized blocks. They found that participants exhibited a video-leading PSS for the SJ task and an audio-leading PSS for the TOJ task. Our results parallel these findings, where a positive PSS was found for the SJ task and a negative PSS was found for TOJ. Additionally, previous research has shown that PSS estimates from the TOJ task may be susceptible to individual response strategies rather than to reflect the true PSS (Van Ejik et al., 2008) and thus the lack of correlation between SJ and TOJ PSS may be reflective of differences in individual response strategies (Van Eijk, 2008).

Within-Subjects Design – Functional Imaging Results

The ERP results showed that unisensory perception of light and sound are not modulated by task, as predicted by our hypothesis stating that there would be no significant difference in both the visual P1 and auditory N1 amplitudes and latencies between the two tasks for the control condition. These results indicate that although simultaneity and temporal order perception may utilize different neural mechanisms, unisensory processing is not affected by the priming effect that occurs when participants are informed of the task that they will be completing during each block. Furthermore, we hypothesized that in the experimental conditions, SJ and TOJ amplitudes and latencies would differ for both the visual P1 as well as the auditory N1 ERPs; this was not confirmed. These results indicate that older adults may be perceiving simultaneity and the temporal order of events similarly. This is contrary to previous research (Setti et al., 2011a; Adhikari et al., 2013; Dhamala et al., 2007; Noesselt et al., 2007; Bushara et al., 2001) that indicates that different neural networks sub serve the two tasks. This lack of difference may be due to multiple different factors (i.e., EEG not sensitive enough, behavioural study not designed optimally, etc.) that are mentioned below in greater detail.

Between-Subjects Design

The present study aimed to determine whether simultaneity and temporal order perception differ between older and younger adults. It is the first study to our knowledge to compare both behavioural as well as ERP techniques to test the differences that might exist in SJ and TOJ perception between the two groups. There were 7 main hypotheses for study 2. In summary, in line with our prediction, we found that older and younger adults performed similarly on the SJ task, as they exhibited no differences in PSS and TBW. As hypothesized, we found compelling evidence indicating no difference in auditory perception, both in amplitude and latency, between older and younger adults for the control condition. In agreement with previous literature, we were able to confirm that older and younger adults would have similar visual P1 and auditory N1 amplitudes for the SJ task in the experimental condition. Contrary to our prediction, we were unable to confirm that older adults have a wider TBW compared to younger adults for the TOJ task. Although we expected to find smaller visual P1 amplitudes in older adults compared to younger adults for the TOJ task in the control condition, this was not the case. However older adults did display a later latency for the visual P1 ERP compared to younger adults in the control condition, indicating that a delay in the perception of vision exists between the two groups. We were unable to find smaller amplitudes and later latencies for the visual P1

ERPs in older adults compared to younger adults for the TOJ task in the experimental condition. Contrary to our prediction, we were unable to confirm a lack of difference between the older and younger adults for the auditory N1 amplitudes and latencies for the experimental condition, indicating that multisensory integration of auditory and visual information is affected by age.

Between-Subjects Design – Behavioural Results

In this study, we were successfully able to replicate Bedard & Barnett-Cowan's (2016) work indicating that older and younger adults do not have different sizes of the TBW for the SJ task. Additionally, we were also able to replicate similar PSSs between the two groups for the SJ task. Although older adults showed wider TBWs compared to younger adults for the TOJ task, they were not statistically different. The TBWs obtained from the TOJ task were not statistically different between the two groups, however the data was in the same direction as Bedard & Barnett-Cowan (2016) who found that older adults had significantly wider TBWs compared to younger adults. This lack of statistical difference may have arose from that fact that Bedard & Barnett-Cowan (2016) tested 50 older and 50 younger adults, whereas the sample size for this study consisted of only 28 older and 28 younger adults.

The breakdown of performance of older and younger adults in blocks indicated that older adults showed a significant change in performance on the SJ task whereas younger adults showed a significant change in performance on the TOJ task. Both the older and younger adults self-reported the TOJ task being more difficult than the SJ task; here we see that the younger brain is better able to adapt by learning to differentiate between the order of stimuli whereas the older brain has a lot more difficulty. Given that the older adults only showed a change in performance for the SJ task, it can be speculated that the older brain failed to learn to better differentiate between the temporal order of events due to the wider TBW. This is in line with previous research, showing that older adults have a wider TBW compared to younger adults on the TOJ task but not on the SJ task (Bedard & Barnett-Cowan, 2016).

Between-Subjects Design – Functional Imaging Results: Control Condition

Consistent with previous literature (Čeponiene et al., 2008), our results indicate that auditory ERPs are less susceptible to aging compared to visual ERPs, as we found no significant difference in the auditory N1 amplitude between the older and younger adults. Čeponiene et al., (2008) presented 19 younger and 19 older adults with two different conditions while EEG was recorded. In one of the conditions, the participants were asked to shift their attention following the cues to either "hear" or "look" for the stimuli. In the other condition, they were told to attend to the same modality during the entire block. The participants were asked to press a button upon detection of the target. They found that the auditory P1 and N1 ERPS were unaffected, however the visual P1 and N1 ERPs were diminished in older adults compared to younger adults. As there isn't much evidence indicating differences in neuro-biological aging in visual and auditory sensory regions, the differences may be explained by attention. Vision tends to be more reliant on attention than audition, as acoustic information is free to enter the auditory system regardless of attention (Čeponiene et al., 2008). These results add to the growing literature indicating that older adults have poorer visual than auditory perception compared to younger adults. We failed to confirm that older adults have smaller visual P1 peak amplitudes compared to younger adults for the TOJ task. The results did however show that older adults exhibited an earlier latency than younger adults at the P4 electrode (older = 126.05, younger = 117.35). This finding is in line with previous research that shows a later latency for visual P1 with aging (Gazzaley et al., 2002) and indicates that regardless of normal or corrected-to-normal vision, older adults respond later to visual information compared to younger adults. Given that the visual P1 ERP is modulated by attention (Setti et al., 2011a; Čeponiene et al., 2008), one of the reasons as to why we may be seeing larger visual P1 ERP amplitudes for older adults may be due to the fact that older adults are more attentive in the task than younger adults are.

Between-Subjects Design – Functional Imaging Results: Experimental Condition

In agreement with previous literature that found older and younger adults performed similarly on the simultaneity judgment (Bedard & Barnett-Cowan, 2016), we found that older and younger adults elicited similar visual P1 and auditory N1 ERP amplitudes for the SJ task. It was however found that older adults exhibited later auditory N1 latencies than younger adults indicating that although simultaneity perception may be preserved with age, older adults may be processing the information later than younger adults. The later latency observed for the SJ task in older adults is consistent with the behavioural results indicating that older adults had a more positive (video-leading) PSS compared to younger adults. Contrary to our prediction, we found that older adults did not have smaller amplitudes or later latencies for the visual P1 ERPs compared to younger adults. Despite the results being non-significant for main effect of age (main effect of task was found), older adults exhibited smaller visual P1 amplitudes than younger adults (older = 1.35 younger = 1.40) for one of the conditions and larger visual P1 amplitudes than younger adults for the other condition (older = 2.48, younger = 1.74). These results indicate two narratives: either older adults have larger visual P1 peak amplitudes compared to younger adults or that older adults have smaller visual P1 peak amplitude compared to younger adults for the TOJ task. The latter is more consistent with the literature (Setti et al., 2011a; Gazzaley et al., 2008). As mentioned above, visual P1 is modulated by attention and our results indicate that older adults may have been more attentive than the younger adults, conferring the older adults an advantage. Our results also showed that the simultaneity perception elicited larger visual P1 amplitudes compared to temporal order perception in both older and younger adults. These results are consistent with the rationale that the perception of simultaneity of audiovisual stimuli would elicit a larger response than the perception of stimuli presented at different times (Molholm et al., 2002).

Contrary to our prediction that there would be no difference between older and younger adults for the auditory N1 amplitude, we found that older adults exhibited larger auditory N1 amplitudes compared to younger adults across the SOAs whereas younger adults showed a decrease in amplitude at the 270 ms SOA (figure 36). Given that older adults showed a larger sustained cortical response across the SOAs, we speculate that this is representative of a wider TBW in older adults. In order to further explore this idea and whether a relation existed between the TBW and the sum auditory N1 amplitudes, we ran correlations between the two measures, however the results didn't indicate a relation. The difference between younger and older adults may also be explained by attention as auditory N1 can be modulated via attention (Setti et al., 2011a). It has been reported that older adults show greater enhancement in performance when bimodal stimuli are presented (Diederich et al., 2008). Hence an enhancement in performance due to the use of audiovisual stimuli in addition to greater attentiveness in our older participants may have yielded larger auditory N1 amplitudes compared to younger adults (Čeponiene et al., 2008).

The between-subjects comparison did not reveal any interaction between age and task, which indicates that although there are differences between the older and younger brain, these differences may not be impacted by the tasks. One possibility for this lack of interaction may be that there is no difference between the SJ and TOJ tasks. However this is unlikely to be the case, as many previous researchers have found a significant difference in performance on the SJ and the TOJ tasks (Bedard & Barnett-Cowan, 2016; Love et al., 2013, Van Ejik, 2008) as well different neural mechanisms to be involved (Adhikari et al., 2013; Dhamala et al., 2007; Noesselt et al., 2007; Bushara et al., 2001).

Although only a few EEG studies have been conducted looking at temporal order perception (Setti et al., 2011a) and synchrony perception (Chan et al., 2017), evidence from younger adults indicates that synchronous and successive stimuli evoke different responses from the CNS. In a study conducted by Noesselt et al. (2007), fMRI data was collected from 24 young healthy participants while streams of flashes and beeps appeared with random jittered timing in 2-second intervals. They manipulated the stream such that the audiovisual stimuli were either simultaneous or successive. Participants were asked to monitor a central fixation cross and indicate when it brightened via a button press. The participants were told that the auditory-visual task was irrelevant. They found that the BOLD signal increased during synchronous audiovisual conditions and decreased during successive trials in the superior temporal sulcus (STS). Their results indicate that the CNS reacts differently to stimuli when they are spatially related versus when they are not.

Research conducted by Bushara et al., 2001 further bolsters these results. 12 participants were asked to decide whether or not a circle was presented simultaneously with a tone while PET was collected. They were also asked to complete a control condition where the audiovisual stimuli were always simultaneous and the participants were asked to decide the colour of the visual stimuli. The results revealed that temporal order processing is mediated via subcortical tecto-thalamo-insula pathways. Although many areas such as the right anterior inslua, the right ventrolateral prefrontal cortex, the right inferior parietal lobe, and left cerebellar hemisphere are involved in audiovisual synchrony and asynchrony detection, the insula is more dominantly involved in synchrony perception (Bushara et al., 2001). Given that research indicates that simultaneity and temporal order perception are sub served by different neural mechanisms, it is very unlikely that there is no difference between the SJ and TOJ tasks.

Study 2 Limitations

The behavioural results obtained from this study 2 were not representative of the typical results found on average in previous literature (Bedard & Barnett-Cowan, 2016; Van Ejik et al., 2008). The different results obtained may be due to design differences between this and other studies or the recruitment of a sample of participants who showed more variability compared to the types of participants used in previous literature. Thus the failure to capture the difference could be due to the individual differences in our sample. Another reason might be that although different neural mechanisms may sub serve the two tasks, the ERP protocol we used based on Setti et al (2011) may not be sufficiently sensitive to measure these differences. Additionally, using only 2 electrodes to extract visual P1 and 1 electrode to extract auditory N1 ERPs may not not have been sufficient to capture the differences that exist. Indeed, our scalp maps and previous literature (Chan et al., 2017: Setti et al., 2011a; De sanctis et al., 2008) indicate that older adults have more spatially distributed neural activity, thus averaging over multiple electrodes may have helped to better capture these differences. Furthermore, measuring the peak relative to an adjacent peak in the waveform is an alternative method that can be used to quantify a component's amplitude instead of using measuring the amplitude relative to the baseline. Using this method allows the amplitude to remain free from residual noise, DC shifts, and other confounding factors that may affect the baseline (Handy et al., 2005).

Additionally, the lack of difference found between SJ and TOJ tasks may be due to design differences with our experiment and previous work; by using only 4 SOAs, we may not have been able to capture the true relation that exists between the two tasks and their respective impacts on aging. In this study, SOAs of ±270 ms and ±70 ms were utilized which were based on Setti and colleagues' (2011a) design. These SOAs may not have captured the true relation between the two age groups and the two tasks as most previous studies have used substantially more SOAs with smaller intervals (Bedard & Barnett-Cowan, 2016; Love et al., 2013; Van Ejik et al., 2008). Based on Bedard and Barnett-Cowan's (2016) work, we speculate that a difference in the performance of younger and older adults may be dependent on the SOAs that they are exposed to.

General Discussion

The aim of this project was to establish how simultaneity perception changes over the course of human aging. Behavioural work had previously suggested that simultaneity perception may be preserved with age while temporal order perception may not be

(Bedard & Barnett-Cowan). Furthermore, previous functional imaging studies speculated that there may be different underlying mechanisms that sub serve simultaneity and temporal order judgment tasks (Binder, 2012; Dhamala et al., 2007; Setti et al., 2011a). Here we assessed how the CNS processes synchronous and asynchronous audiovisual information differently among younger and older adults. Overall we found that although there is generally little difference in unisensory (control condition) perception between younger and older adults, the results indicate that integration of simultaneous and temporally disparate stimuli may be processed differently in the younger and the older adult brain, but that these differences are not necessarily task specific.

Although the literature suggests a dissociation between simultaneity and temporal order processing, with changes in temporal order occurring with age, we did not find supportive evidence for this in our ERP data. A lack of an age by task interaction may be due to certain limitations of the study, including study design differences with previous literature required for an ERP design versus a behavioural task, or ERP study designs not being sensitive to such an interaction effect. Here, the inconsistent visual P1 ERP amplitudes among older adults that were larger in some cases and smaller in other speak to the amount of variability present in our study design. In addition, the general result of older adults showing later latencies compared to younger adults was not always found and older adults also showed larger sustained auditory N1 ERP amplitudes across SOAs in comparison to younger adults. Although these results suggest a wider TBW for older adults, it is difficult to confirm or deny whether that is the case with such poor resolution due to the fact that we are constricted to such few SOAs. One possible explanation for the observed differences could be attention. Given that both visual P1 and auditory N1 are modulated by attention (Setti et al., 2011a), one can speculate that older adults may have been more attentive throughout the study compared to younger adults as older adults were expected to yield smaller ERP amplitudes, but this was not always the case. The law of prior entry states that attention accelerates sensory processing and shortens the time to perception (Schneider & Bavelier, 2003). The fact that older adults showed earlier latencies on average for the visual P1 ERPs and a larger amplitude auditory N1 amplitude that was sustained across the SOAs also indicates that older participants were more attentive. In a future study, attention should be intentionally modulated in order to test the degree to which visual P1 and auditory N1 ERP amplitudes and latencies are impacted in younger and older adults.

Although all participants were required to have normal or corrected-to-normal vision and hearing, this was self-reported and not verified which may not have been an adequate measure of visual and auditory acuity. It is possible that the sensory acuity of older adults was not similar to that of younger adults, which may have affected our results. Given that age affects the detection of both auditory and visual cues (Gordon-Salant, 2005), our older adults may not have been perceiving the stimuli at the same intensity as younger adults, which may have affected their ability to detect the stimuli as quickly. These differences in detection may lead to slower transduction and perception of multisensory inputs in older adults (Chan et al., 2014a). In the future, we recommend that vision and audition are tested and that the stimuli are presented at a suprathreshold level for each participant based on the results found.

Despite some of these limitations, this work has the potential to guide future research that could include the creation and implementation of rehabilitative programs that aim at decreasing the width of the TBW in order to enhance perception of everyday events such speech comprehension and the ability to balance. Previous research has shown that recalibration of the TBW can have lasting effects for at least a week after training. Powers and colleagues (2009) asked 22 young adults to complete an audiovisual SJ task where after each trial participants were provided with positive (☺) or negative (☹) feedback if the participant responded with the correct or incorrect answer respectively. Training consisted of 5 hours (1 hour per day) and participants were asked to return a week after their last day of training to determine if training would impact their TBW even after no training for a week. It was found that training narrowed the TBW by approximately 40%. Powers and colleagues (2009) also found that the effectiveness of the training paradigm was correlated with the initial size of the TBW where participants with wider TBWs showed the greatest increase in acuity with training. These results recommend that older adults, who on average have been found to have wider TBWs compared to younger adults, should benefit the most from training and recalibration. We speculate that using both behavioural as well as ERP measures can help create rehabilitative programs that are able to target the TBW more efficiently. We hope this work can be used to increase the quality of life of older adults by combining both behavioural as well as neuroimaging methods to decrease the width of the TBW.

In conclusion, this thesis reveals differences in audiovisual simultaneity and temporal order perception within and between younger and older adults. Visual P1 and auditory N1 amplitudes show that unisensory perception does not differ between SJ and TOJ tasks, suggesting that multisensory integration is driving the differences between the two tasks. Although both older and younger adults reported normal or corrected-to-normal vision and hearing, older adults exhibited later visual P1 latency, indicating that processing of unisensory visual information may be delayed with aging. In agreement with our behavioural data indicating a wider TBW for older adults compared to younger adults, the auditory N1 ERPs implicated in multisensory integration also showed a sustained higher amplitude across the SOAs in older adults. Our results provide evidence suggesting that simultaneity and temporal order perception are processed via different neural mechanisms and that simultaneity and temporal order perception change with age.

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