

Exploring the Benefits of Multisensory Exposure on Early Sensory-Specific Processing

by

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## Author's Declaration

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

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## **Abstract**

Multisensory training can improve perceptual learning, exhibited by changes in accuracy, precision and response time (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Forster, Sambo, & Pavone, 2009; Giard & Peronnet, 1999; Murray et al., 2005; Pasalar, Ro, & Beauchamp, 2010; Teder-Sälejärvi, Russo, McDonald, & Hillyard, 2005). Recently, researchers have even demonstrated improvement in perceptual learning during a subsequent unisensory environment (Kim, Seitz, & Shams, 2008; Seitz, Kim, & Shams, 2006; Von Kriegstein & Giraud, 2006). This stems from increasing evidence supporting the involvement of unisensory structures during multisensory interactions. That said, it remains to be determined the exact role these areas play, and how they may be modulated during multisensory interactions. This thesis intends to further enrich the current understanding surrounding the influences of multisensory interactions, on the componentry low-level unisensory representations. It was hypothesized that a single session visual-somatosensory training intervention, would improve subsequent somatosensory perceptual performance; characterized as a decrease in reaction time. While mechanisms can only be speculated with the current knowledge, one plausible explanation could be the modulation of unisensory representations resulting from the multisensory exposure. Thus, it was proposed that evidence of early neuroplastic adaptation would be exhibited by the late stage of training. In an attempt to examine such modulations, electroencephalography was used to measure event-related potentials, time-locked to multisensory stimuli delivered during training. Subjects (n=12) were delivered faint, but above threshold vibrotactile stimuli to the fingertips of digits 2 or 5, or index and pinky fingers respectively. Baseline and post-intervention reaction time were tested by asking subjects to identify and discriminate which digit received a vibrotactile stimulus, and responded using a corresponding button press. During training, vibrotactile stimuli were accompanied by congruent visual light, delivered by light-emitting diodes. Once again, subjects trained to identify,

and discriminate stimuli delivered, responding as quickly and accurately as they could using a button press. Overall, a significant reduction in somatosensory reaction was displayed in post-intervention testing, compared to baseline measures. While no significant change in ERP amplitudes were exhibited across any of the examined components, a visual decrease from early-training amplitude was seen at the latency of N140, during late-training. This visual decrease could relate to a change in early somatosensory processing efficiency; whereby secondary somatosensory structures require less involvement. Without future investigations examining changes in early ERP components (ie. P50) during this paradigm, this interpretation remains purely speculation. It would also be strongly beneficial to examine changes in cortical excitability of early somatosensory representations prior to, and following the completion of multisensory training.

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## List of Abbreviations

RT -	Response Time
MFUL -	Multisensory Facilitation of Unisensory Learning
LED -	Light Emitting Diodes
EEG -	Electroencephalography
ERP -	Event-related Potentials
SI -	Primary Somatosensory Cortex
BA -	Brodmann Areas
V1 -	Primary Visual Cortex
LGN -	Lateral Geniculate Nucleus
HO -	Higher Order
SII -	Secondary Somatosensory Cortex
LOC -	Lateral Occipital Cortex
fMRI -	Functional Magnetic Resonance Imaging
LFP -	Local Field Potentials
D5 -	Fifth Digit
D2 -	Second Digit
Hz -	Hertz
V -	Volts
k $\Omega$ -	Kilo-ohms
ms -	Milliseconds
MOL -	Method of Limits
VT -	Visual-Tactile
ISI -	Inter-stimulus Interval
$\mu$ V -	Micro-volts
NHST -	Null-hypothesis Significance Testing
RM -	Repeated Measures
AV -	Analysis of Variance
BF -	Bayes Factor



## **1.0 Introduction: Thesis Overview**

This thesis intends to explore the behavioural and neurophysiological impact of a single session visual-tactile training intervention on early somatosensory perceptual processing. Perceptual learning is commonly defined as an improvement in discrimination of sensory stimuli following repetitive exposure or practice (Gilbert, Sigman, & Crist, 2001). These improvements can include reductions in response time (RT), and/or improved accuracy and precision on stimuli detectability and discrimination. Compared to a single modality (unisensory/unimodal), such improvements are greatly heightened when information is presented across two sensory domains (bimodal/multisensory) (Forster et al., 2002, 2009; Giard & Peronnet, 1999; Murray et al., 2005; Pasalar et al., 2010; Teder-Sälejärvi et al., 2005). This is often attributed to a redundancy effect taking place, particularly when RTs become faster (Mordkoff & Yantis, 1991). While it was once commonly believed that the sensory stimuli identified and analyzed first determines the response time (ie. race model) (Miller, 1982), increasingly more studies are finding violations to this model; supporting a more integrative approach (ie. coactivation model) (Molholm et al., 2002; Murray et al., 2005; Teder-Sälejärvi et al., 2005).

The concept of multisensory stimuli merging and interacting is not one of new conceptualization. It is well founded that, for humans and animals to efficiently and accurately interact with the surrounding world, stimuli from varying modalities must be combined (Stein & Meredith, 1993). Previous research would tell us that the merging of senses is a process limited to multisensory association areas. Recent evidence however, suggests that the interaction of bimodal stimuli does occur at low-level sensory structures; even those once deemed “sensory-specific” (Driver & Noesselt, 2008; Ghazanfar & Schroeder, 2006; Giard & Peronnet, 1999; Kayser & Logothetis, 2007; Martuzzi et al., 2007; Murray et al., 2005; Shams & Seitz, 2008; Shimojo &

Shams, 2001). Although the exact involvement of these idiosyncratic and unimodal association areas remains unclear, the addition of a secondary modality during training appears to modulate early sensory processing; and this is true across many modality combinations (Martuzzi et al., 2007; Murray et al., 2005; Staines, Popovich, Legon, & Adams, 2014; Zangaladze, Epstein, Grafton, & Sathian, 1999). Even more surprisingly, a small subset of studies have even demonstrated that congruent multisensory training produces a priming effect, promoting an enhancement of perceptual performance on subsequent unisensory tasks. For instance, subjects trained on simultaneous voice and face recognition showed subsequent improvements on voice recognition, when presented in isolation (Von Kriegstein & Giraud, 2006). Similarly, subjects demonstrated improvement in visual lip reading following vibrotactile and auditory training (Eberhardt, Auer, & Bernstein, 2014). This paradigm is described here as multisensory facilitation of unisensory learning (MFUL).

Although this paradigm appears to be newly discovered, studies have unknowingly shown evidence of MFUL for several decades. Phenomena such as the rubber hand illusion (Botvinich & Cohen, 1998) and ventriloquism aftereffect (Canon, 1970) are two such examples. Specifically, following exposure to temporally congruent, but spatially disparate multisensory input, a shift in unisensory perception is seen. In the rubber hand illusion, skewed visual input has participants perceiving a rubber limb as their own; an effect often described as “proprioceptive drift”. In the ventriloquist aftereffect, sound localization is negatively affected following repetitive exposure to spatially misaligned visual and auditory stimuli. Despite these findings, no conclusions have been made regarding what these effects may also suggest about the benefits of multisensory exposure on unisensory learning. Now with our current level of understanding, evidence from studies such

as the rubber hand illusion or ventriloquist aftereffect can be used as support to expand upon current findings.

Generalizations regarding MFUL are currently hindered due to two major factors. The first stems from the restrictive modality combinations used to-date during investigations. Although neurophysiological and behavioural benefits of multisensory exposure have been well investigated across modality combinations, the subsequent “carryover” effect on unisensory performance has been strongly confined to auditory-visual domains. To address this concern, this study expanded the current understanding into a novel domain, and evaluated interactions following visual-somatic training; specifically using light emitting diodes (LEDs) and vibrotactile stimulation. The second constraint surrounds the uncertainty surrounding the influence of multisensory training on the neural correlates of unisensory perceptual judgements. In an effort to further validate the influence of visual-somatic exposure on early sensory processing, electroencephalography (EEG) was acquired. Results may then provide a foundation for which mechanisms may begin to be explored further. Although there are several measures of perceptual learning, the current thesis examined changes in RT as a proxy for behavioural markers of facilitation. Alterations to early somatosensory event-related potentials (ERPs) were used to tap into underlying neurophysiological adaptations occurring.

## **2.0 Review of Relevant Research**

### *2.1 Overview of Primary Somatic Sensory Cortex*

It is worth noting that anatomical experimentations in this domain are commonly conducted on animals to maintain ethical and viable investigations. Nevertheless, functional imaging studies on humans have allowed researchers to confidently link properties found in animal models with those in humans (Driver & Noesselt, 2008; Gentile, Petkova, & Ehrsson, 2011; Pasalar et al., 2010). With that, animal experimentations will often be referenced in this thesis, however human models will be cited when possible.

Confined to the postcentral gyrus in the parietal lobe, the primary somatosensory cortex (SI) is the central recipient of ascending somatosensory information. Mechanical sensations, which includes touch and position sense, are delivered to SI via the dorsal column-medial lemniscal system. Vibrotactile stimulation of the fingertips is received via peripheral receptors, which open mechanically gated ion channels, resulting in the generation of an action potential. When discussing vibration, rapidly adapting receptor types are often discussed, which reside in Meissner and Pacinian corpuscles (Johnson, 2001; Johnson, Yoshioka, & Vega-Bermudez, 2000). Whereas Pacinian corpuscles are located deep in the dermis, and are most sensitive at high frequency (40-500Hz) vibration detection, Meissner corpuscles are found more superficial at the epidermis-dermis junction, and detect low frequency (2-40Hz) vibration or “flutter” (Johnson et al., 2000; McGlone & Reilly, 2010).

From the corresponding receptor, afferent information is transmitted through the dorsal root ganglion of the spinal nerve. First order neurons enter the white matter of the spinal cord, ascend the cuneate fascicle of the dorsal column, and synapse at the cuneate nucleus. Second order neurons then travel medially, decussating at the level of the medulla. Afferent fibers, now

travelling on the contralateral side, from the medial lemniscus as they ascend to the thalamus. A synapse then occurs in the ventroposterior nucleus; the chief thalamic nuclei for the somatosensory system. Finally, third order neurons travel through the posterior limb of the internal capsule before terminating in layer IV of SI. Efferent information can then travel upstream or downstream to unimodal association areas, as well as to heteromodal association areas for further processing (Mesulam, 1998).

The location of termination in SI is determined according to somatotopic representation and cytoarchitecture. Somatotopically, the hand forms a large representation on the dorsal aspect of SI. The size of the cortical representations is determined by the density of peripheral sensory receptor neurons, indicative of the level of sensitivity of that area (Hari et al., 1993). These maps are dynamic in nature however, with changes in cortical representations shown to occur following environmental manipulations (Jenkins, et al., 1990). Cortical representations within SI are also then divided according to neuronal architecture, or cytoarchitectonic divisions. Within SI, these are most commonly cited as: Brodmann areas (BA) 1, 2, 3a, 3b (Mesulam, 2000). Intracortical recordings in monkeys suggest these areas to be activated by varying receptor types (Mesulam, 2000). BA 1 and 3b activation derives from cutaneous external stimulation. Some researchers question the inclusion of areas 1 and 2 as valid components of the initial processing stage, as they possess several characteristics of upstream cortical processing (Mesulam, 2000; Garraghty et al., 1990). That said, common reference in literature is the inclusion of all four divisions; a practice that will be followed in this document.

## *2.2 Overview of Primary Visual Cortex*

The primary visual cortex (V1, BA17) is found on the medial surface of the occipital lobe, deep in the banks of the calcarine fissure. Visual information is projected to layer IV of the primary

visual cortex via the lateral geniculate nucleus (LGN) of the thalamus. Both V1 and LGN are retinotopically organized, mapping the contralateral peripheral and foveal visual field. Although the final destination is the same, the pathway to LGN differs according to the field of view. Visual information from the peripheral field of view lands on the nasal hemiretina of the eye, where via interneurons, information is passed to retinal ganglion cells. Axons then leave the eye through the optic nerve, decussate across the optic chiasm, travel along the optic tract and synapse in the contralateral LGN. Visual information from the central field of view lands on the contralateral temporal hemiretina, and remains ipsilateral as it travels to LGN. Once in V1, peripheral and foveal visual field is represented rostral to caudal, respectively. Retinotopic mapping is further subdivided according to the upper and lower visual field, represented in the inferior and superior banks of the fissure respectively.

While V1 is responsible for initial processing of visual information, the surrounding higher-order areas (BA 18-19) aid in the development of a complete visual percept. These higher order (HO) areas, collectively termed extrastriate cortex, can be divided according to cell structure into areas V2-V5. Work conducted by Hubel and Wiesel (1959;1977) demonstrated these areas to differ according to the size and specificity of the receptive fields; with the smallest and most precisely mapped topographies existing in V1. This encourages a high level of selectivity surrounding the processing of physical attributes of the stimulus during the early stages of visual processing; attributes such as orientation (Hubel & Wiesel, 1959) and position (Crist, Kapadia, Westheimer, & Gilber, 1997). The later stages of visual pathway contain larger and broader selectivity, allowing for more complex attributes to be processed (Gilbert et al., 2001). In short, the features of the visual stimulus looking to be processed helps guide efferent signals to the appropriate HO area. Object localization for example, is carried along the dorsal stream, which

travels through V2 and V5 on its journey to the parietal lobe for further spatial processing. Object recognition however, follows the ventral stream, is heavily connected with the medial temporal lobe, travelling first through V2 and V4.

### *2.3 Electroencephalography (EEG)*

EEG is an electrophysiological and neuroimaging technique which, through the placement of scalp electrodes, monitors the electrical neuronal activity of the brain. As information transmission and processing is represented by changes in electrical activity, EEG presents itself as an excellent proxy to monitor these processes. Specifically, the transmission of information across cortical areas is conducted through action potentials. The propagation of which, is controlled by graded- or postsynaptic- potentials, resulting in either depolarization or hyperpolarization of membrane potential. While intracranial recordings are best suited for monitoring of action potentials, non-invasive scalp recordings monitor postsynaptic potentials (Luck, 2005). By monitoring underlying cortical operations, EEG allows researchers to monitor changes in activity throughout all stages of processing; even before an action is observed. To monitor electrical responses time-locked to a stimulus or event, ERPs are analyzed. Specifically, ERP recordings monitor electrical activity of specialized neurons known as pyramidal cells. Pyramidal cells are arranged perpendicular to the skull surface, which ensures opposing dipole polarities of neighbouring neurons are not adjacent to one another (Luck, 2005; Woodman, 2010). This is important to ensure synchronous firing of these neurons does not result in a negated response. As electrical activity is strongly attenuated on its journey from the neuron to the scalp surface, synchronous firing of thousands or even millions of pyramidal cells is required in order to be detected by scalp electrodes. In summary, ERP recordings reflect summated postsynaptic potentials of pyramidal cells located below the scalp electrode (Luck, 2005; Woodman, 2010).

ERP recordings create a waveform pattern, with distinguishable peaks and troughs representing components- or stages of cortical processing (Luck, 2005; Woodman, 2010). By analyzing the different ERP components before, during and following an experimental manipulation, researchers can examine which cortical operations appear to be affected. For example, by monitoring changes in voltage amplitude and/or latency of these components, hypotheses can be made regarding which areas of the brain may be involved during a sensory event, and how baseline responses may be manipulated through training. When monitoring sensory ERPs, deflections are named according to their polarity and temporal latency; where P50 and N70 represent the first positive and negative deflections, occurring around 50 and 70ms, respectively (Luck, 2005; Woodman, 2010). It is important to note that polarity of the components is an important characteristic, however there appears to be a lack of continuity amongst researchers regarding how to represent this feature graphically. That is, some researchers display a negative polarity as a peak and positivity as a trough, while others take the opposing approach. For this thesis, positivity is demonstrated as a peak, with negativities as troughs.

As this thesis was interested in early somatosensory processing, components P50, and P100 were of high interest. While P50 is believed to represent initial somatosensory processing in SI, P100 represents the next stage of sensory processing, in the secondary somatosensory cortex (SII) (Truett, McCarthy, & Wood, 1992). Although representing a slightly longer latency response, N140 also remains an important component to discuss when examining earlier somatosensory processing; having both frontal and SII contributors (Garcia-Larrea, Lukaszewicz, & Mauguiere, 1995).



## *2.4 Convergence Zones and Hierarchical Organization*

Although the visual and somatosensory systems represent distinct sensory modalities, equipped with their respective specialized receptors and cortical representations, the perceptual world rarely presents a strictly unisensory experience. Rather, humans are constantly presented with sensory signals deriving from more than one modality. To create a unified and meaningful percept of the surrounding multisensory environment, the various sensory signals must converge and integrate. This convergence has been well demonstrated in both animal and human cerebrums, occurring in several cortical and subcortical structures; structures composed of bi-or trimodal neurons. The superior colliculus, posterior parietal, premotor cortex (Alex et al., 1987; Meredith & Stein, 1986b; Stein, Magalhaes-Castro, & Kruger, 1976; Wallace, Meredith, & Stein, 1992) and putamen (Graziano & Gross, 1993) are examples of well-established regions containing bimodal visual-tactile neurons.

Historically, multisensory processing was believed to follow a hierarchical organization, with interaction of multisensory input occurring only after low-level unisensory processing has occurred (Jones & Powell, 1970; Mesulam, 1998; Stein & Meredith, 1993). Meaning, processing of incoming visual-tactile input would remain segregated at early latencies; occurring first in their respective low-level sensory specific areas (Jones & Powell, 1970). Only after initial processing and analysis of stimulus features was complete, was it believed that multisensory processing would begin; marked by the convergence of the two sensory stimuli in multimodal areas, such as those listed above. This flow of information from the sensory to progressively higher-order areas is an anatomical representation of ‘bottom-up’ processing (Engel, Fries, & Singer, 2001). This classical bottom-up view suggests that multisensory interactions are limited to HO structures and

association areas, with little to no connections existing back to, or between, low-level sensory areas.

#### *2.4.1 Metamodal Organization*

Contrary to the beliefs of researchers in the late 90's, the neural correlates of multisensory interactions are now believed to include low-level sensory “specific” structures. Advances in electrophysiological and neuroimaging techniques over the last two decades have begun challenging this belief, proposing these “unimodal” areas may be involved in the processing of non-dominant sensory inputs. That is for example, the recruitment of visual areas during somatosensory tasks (Amedi, Malach, Hendler, Peled, & Zohary, 2001; Lucan, Foxe, Gomez-Ramirez, Sathian, & Molholm, 2010). Moreover, multisensory interactions appear to be far more ubiquitous than once suggested, occurring not only in subcortical and higher order multisensory areas, but also in primary sensory regions (Driver & Noesselt, 2008; Ghazanfar & Schroeder, 2006; Giard & Peronnet, 1999; Kayser & Logothetis, 2007; Martuzzi et al., 2007; Shams & Seitz, 2008; Shimojo & Shams, 2001). This defiance of classical hierarchical organization will be known here as the “metamodal organization”. This is supported by electrophysiological markers (Bieler, et al., 2017; Ghazanfar, et al., 2005; Giard & Peronnet, 1999; Molholm et al., 2002; Murray et al., 2005; Romei, Murray, Merabet, & Thut, 2007; Schicke, Bauer, & Röder, 2009; Schroeder et al., 2001; Taylor-Clarke, Kennett, & Haggard, 2002) and hemodynamic responses (Dionne, et al., 2010; Foxe et al., 2002; James et al., 2002; Kayser, et al., 2007; Lucan, et al., 2010; Martuzzi et al., 2007; Noesselt et al., 2007). Additionally, evidence arising from animal models advocates that connectivity may in fact exist between low-level sensory specific areas (Bieler et al., 2017; Falchier, et al., 2007).

From an electrophysiological point of view, evidence for a metamodal cortical organization has been demonstrated in several different ways, and across different modalities. For instance, evoked potentials measure through simultaneous audio-visual (Giard & Peronnet, 1999; Molholm et al., 2002), audio-somatosensory (Foxe et al., 2000; Murray et al., 2005), and visual-tactile (Dionne, Legon, & Staines, 2013; Staines, et al., 2014) stimuli have demonstrated supra-additive responses as early as ~40-50ms post-stimuli. Not only does this suggest an interaction effect to be occurring between the two stimuli, a latency of this magnitude suggests it may be occurring quite early in the processing stream; a latency arguably too short to represent feedback from associative multisensory areas. Furthermore, topographic mapping provides reason to believe that interactions such as these may be occurring outside of multisensory convergence zones, in areas once believed to be “unisensory” (Foxe et al., 2000; Molholm et al., 2002; Murray et al., 2005).

Hemodynamic evidence provides further validation for the involvement of early sensory areas beyond their “preferred” modality. Amedi and colleagues (2001) and Lucan and colleagues (2010) found recruitment of a lower-level visual area during somatosensory processing. Specifically, researchers were interested in investigating the response of the lateral occipital complex (LOC) during tactile shape discrimination. The LOC is an area heavily involved in the ventral visual stream, thereby believed to be responsible for early visual-based object recognition. Nevertheless, hemodynamic (Amedi et al., 2001) and electrophysiological measures have both demonstrated LOC involvement in tactile shape recognition; with timing occurring around ~150ms post-stimuli (Lucan et al., 2010). Martuzzi and colleagues (2007) also demonstrated activation of primary sensory representations during non-dominant sensory scenarios; in this case in the auditory-visual domains. Moreover, they demonstrated activation of these same early sensory representations during bimodal environments. Here, subjects performed a simple response time

task while undergoing functional magnetic resonance imaging (fMRI). Cues consisted of either congruent auditory-visual, auditory alone, or visual alone stimuli. In strong contrast to hierarchical belief, researchers demonstrated that both early visual and auditory “unisensory” structures were recruited during all three stimuli conditions. Once again, this calls into question the neurophysiology of these areas. Taylor-Clarke and colleagues raised an interesting hypothesis regarding this dilemma, stating that: “Brain areas traditionally thought of as unimodal, like SI and SII, may only be so in terms of their afferent projections” (Taylor-Clarke et al., 2002). That is, the idiomatic approach of classifying primary sensory areas as being strictly “unimodal” may be slightly too restrictive. While primary sensory areas surely have their “ideal” or principal sensory input, this may not be the only afferent type in which they respond to or are modulated by.

Anatomically, evidence from animal models demonstrate a possible means for how this may occur; sensory-sensory communication, or lateral connectivity. Retrograde tracings in anesthetized rats have demonstrated evidence of connectivity between SI and V1; feedforward mechanisms evolving even before multimodal experience (Bieler et al., 2017; Sieben, Roder, & Hanganu-Opatz, 2013). Similarly, lateral connectivity has been found in the macaque monkey between auditory and visual cortices (Falchier et al., 2002). Under the assumption that similar lateral connections exist in humans, it is then plausible for low-level sensory areas to communicate with one another ‘directly’ during unimodal, as well as multisensory experiences. This idea of lateral connectivity allows early communication between sensory “specific” regions, without the need to follow the hierarchical stepwise processing. Subcortical contributions may also play an important role in early cortical modulations following both unimodal and multisensory exposure; particularly the thalamus (Kayser & Logothetis, 2007; Sieben et al., 2013). Conventional depictions of the role of thalamic nuclei place a strong focus on the unidirectional relay of sensory

information from peripheral receptors to the cortex, via ‘first-order’ nuclei such as LGN (Guillery, 1995; Sherman, 2012). Far less discussed is the importance of transthalamic pathways, involving a bidirectional flow of information between the cortex and ‘higher-order’ nuclei and the thalamic reticular nucleus. This is despite the fact that these nuclei comprise the majority of those found in the thalamus (Sherman & Guillery, 2002). Consequently, it is then plausible that sensory-sensory communication could occur via transthalamic pathways; where one sensory system relays input to another via the thalamus (Noesselt et al., 2010; Sieben et al., 2013).

With all that said, it remains unclear under which circumstances, and exactly how these primary sensory areas are involved and/or modulated by multisensory processing. It is however clear that the classical hierarchical organization needs to be revisited, with strong evidence suggesting early sensory areas contribute to multisensory interactions in some capacity. Furthermore, the premise of “unisensory” representations may be too strict of a characterization of these areas. Further research is required to provide a more comprehensive understanding surrounding all sensory systems.

## *2.5 MFUL*

While more research is certainly required on the involvement of low-level sensory representations during multisensory environments, this is not to say that discoveries have not already begun with the current level of understanding. One such discovery is the priming effect that multisensory exposure may have on early sensory areas; characterized as a subsequent improvement in unisensory performance (MFUL) (Kim et al., 2008; Seitz et al., 2006; Shams, Wozny, Kim, & Seitz, 2011). Results from these studies showed that congruent visual and auditory training can have facilitatory effects on subsequent visual motion perception (Kim et al., 2008; Seitz et al., 2006). The preliminary study (Seitz et al., 2006) consisted of 10 subjects, evenly split

into two different training paradigm groups: visual-only or audiovisual (multisensory). Broadly, the task consisted of a two-interval forced-choice task, where subjects were asked to identify in which of two presented intervals a uniform directional stimulus was perceived. For the visual-only group, this consisted of a visual motion-detection task only. For the multisensory group however, responsibilities were far more diverse. That is, the stimulus type presented during training was evenly separated into three possible combinations: visual motion, congruent audiovisual motion, or auditory motion detection. Training was conducted across ten days, and performance was compared between the two groups on trials containing only visual motion. Performance was measured both within and across sessions, with the outcome measure being changes in percent correct detection. Not only did the multisensory group show evidence of visual sensitivity improvements, but they did so more efficiently and effectively than the unisensory group. This was characterized by faster and overall greater improvements in accuracy in visual motion detection; seen both within and across sessions. It is worth noting that the trials considered “visual-alone” for the multisensory group were not without sound, but rather without moving sound. Meaning, the audiovisual group received stationary sound on the visual motion trials; the trials experimenters were using to compare with the unisensory group which did not receive any sound. Furthermore, the multisensory group received an additional set of trials containing only auditory noise, which provided them with a longer, and more randomized training protocol as compared to unisensory group.

To address some of these concerns, as well as analyze the importance of multisensory stimulus congruency, Kim and colleagues (2008) conducted a follow-up study following a very similar protocol. To address the concerns previously mentioned, auditory only trials and the accompanying stationary noise previously provided on the visual only trials for the audiovisual

group, were both removed. Furthermore, an incongruent audiovisual group was added. Both congruent and incongruent multisensory groups followed the same protocol, except the congruency of the directionality of the auditory stimuli differed between the two groups. Meaning, in direct opposition with the congruent group, the incongruent multisensory group received visual and auditory stimuli of opposing direction of motion. Researchers also condensed the training days, from ten to five days. Consistent with the preliminary study, the congruent multisensory group showed highly significant ( $p < .0001$ ) improvements in their ability to correctly detect visual motion across sessions. The incongruent group however did not follow the same trend, with performance varying across sessions and only marginally reaching significance ( $p = .053$ ). Also consistent with the preliminary study, the visual-only group demonstrated consistent improvements in visual motion detection, however performance consistently remained below that of the congruent multisensory group.

Thus, it can be concluded that audiovisual training provides a sufficient learning environment to evoke improvements in unisensory visual motion detectability. Moreover, congruency in the multisensory stimuli appears to be an important contributor in the induction of learning effects seen. Lastly, it appears audiovisual training may in fact be a superior protocol than visual-alone training, in facilitating improvements in visual motion detection. With that said, one potential confounder exists in both studies, which may influence this interpretation. Specifically, Seitz and colleagues were interested solely in fast-learning effects; meaning only the trials delivered within the first third of each training session were included in the cross-session analysis. This is important to note, as results from within-session analysis showed that performance from the unisensory group, did not match that of the multisensory group until approximately 70% of the way through the session. It is then possible that the greater amount of improvements seen between

sessions in the audiovisual versus visual-alone group, may be biased more heavily because only the first ~33% was examined. It would be worth investigating whether the same conclusions could be made if performance was compared following the entire completion of the training day.

## *2.6 Neuroplasticity*

The brain is known to have a remarkable ability to rapidly modify and adapt to its surroundings through cortical plasticity (Feldman, 2009). Cortical plasticity is the ability of the brain to reorganize itself to allow for optimal performance and learning (Buonomano & Merzenich, 1998). These changes can result from growth and development, sensory loss, cortical lesion, or of particular interest in this thesis- perceptual learning. Although the exact cellular mechanism to explain cortical plasticity is still under debate, several physiological and structural modifications have been identified as important correlates; manifesting differently according to duration of exposure (Feldman, 2009). Whereas changes in receptive fields (Recanzone, Allard, Jenkins, & Merzenich, 1990) or oscillatory activity (Bauer, Oostenveld, & Fries, 2009) may appear within hours, structural changes to individualized neurons or gross cortical thickness manifests more slowly, following multi-day exposure (Rosenzweig & Bennett, 1996). Due to the speed in which changes appear, short-term plasticity is often believed to be the result of potentiation of existing connectivity (Butler & Wolf, 2007; Kaas, 1991). That is, improvements in synaptic efficacy of previously existing networks; some of which may have been previously dormant. This is contrary to long-term morphological changes, believed to be the product of processes such as the formation of new synapses and neurons (Butler & Wolf, 2007; Kaas, 1991). Although these changes occur more rapidly and even to a greater extent in young animal brains, use-and learning-related plasticity still remains well into adulthood (Feldman, 2009; Rosenzweig & Bennett, 1996).



### *2.6.1 Ways Multisensory Exposure May Induce Plastic Change*

As researchers are still trying to understand exactly how multisensory exposure benefits learning, and which cortical areas are influenced, a consensus has not yet been reached on where the learning effects and resulting plasticity takes place. With the classical hierarchical organization in mind, HO multisensory areas appeared to be critical structures in promoting multisensory performance. The posterior parietal cortex for example, appears to play a critical role in visual-tactile environments, as a transient disruption here results in worsened performance (Pasalar et al., 2010). However, at first glance, this fails to explain how then improvements in perceptual learning remain once the multisensory environment is removed; as displayed by the paradigm of MFUL. Now that multisensory processing is believed to occur almost immediately upon reaching the cortex, learning may instead occur within and/or between unisensory structures. Although researchers have yet to demonstrate such effects under the paradigm of MFUL, countless evidence does exist supporting multisensory enhancements of unisensory structures during the multisensory environment itself. Moreover, as neurophysiological evidence of learning takes on several different forms, there is no one way to demonstrate these effects. Nevertheless, despite their different forms, the following examples all support evidence of multisensory enhancement of unisensory structures.

Shams and colleagues (2011) suspect MFUL may represent evidence of ‘associative learning’, and that alterations are occurring in the connectivity between sensory representations. In this scenario, repetitive visual and tactile activation creates an association between their respective representations. Following Hebbian’s law that “neurons that fire together, wire together” (Hebb, 1949) , further repetitive presentation strengthens this association further; so much so that even the presence of an uninformative secondary stimulus improves sensory processing (Wonzy, Seitz,

& Shams, 2008). With a strong association now created, communication between these sensory modalities intensifies, creating a shift in the representations of the underlying unisensory areas. Hypothetically, this shift could cause unisensory representations to act in a multisensory fashion, where both visual and auditory areas are activated upon unimodal visual or auditory presentation (Shams et al., 2011). This model similarly reflects the ‘dynamicist’ variant of top-down processing, where already synchronized neuronal populations recruit other unassociated neurons through lateral connectivity; creating a change in the corresponding representation (Engel et al., 2001). This creates a larger cortical network activated during the subsequent unisensory task, thereby improving the signal-to-noise ratio due to increased number of cells available to access the stimuli (Gilbert et al., 2001).

Alternatively, sensory-sensory communication may modulate the unisensory representations themselves. Once again, these multisensory enhancements could take on several different forms; one being transformations to oscillation patterns. Multisensory training appears to modulate long-range communication between visual and somatosensory, by creating a phase-shift in oscillatory activity (Bauer et al., 2009; Sieben et al., 2013). Oscillation patterns reflect electrical activity put forth by action potentials, and local field potentials (LFPs) during neuronal communication; which can be both short and long-range in nature (Schnitzler & Gross, 2005). This was believed to be occurring in rat models, where researchers demonstrated a phase-reset of S1 oscillatory activity, through the addition of a visual stimuli (Sieben et al., 2013). Researchers argue that the addition of secondary stimuli can create a phase-shift in oscillatory patterns, such that subsequent processing of a sensory input occurs during an optimal state of excitability (Lakatos, Chen, O’Connell, Mills, & Schroeder, 2007; Schroeder & Lakatos, 2009). This is to say that the secondary stimulus is not responsible for the processing of its non-preferred input, but rather

provides background support to shift the opposing sensory area into an ideal phase for sensory processing. Although yet to be investigated, so long as the modulatory effects remain for a period of time beyond the multisensory training, this phase shift could facilitate subsequent unisensory processing; providing a plausible explanation for the MFUL.

While measuring changes in LFPs and action potentials directly provide strong evidence of underlying neurophysiology, it comes not without some risks. In their study, Sieben and colleagues recorded electrical activity through extracellular recordings inserted into the cortex of the rats; providing high spatial and temporal resolution. Ethically and feasibility wise, this procedure is far less realistic to perform on human subjects. Luckily, non-invasive techniques such as EEG allow researchers to measure electrical activity of post-synaptic potentials on humans. When examining changes to early sensory processing, electrode CP3/CP4 are commonly examined as it is believed to overlay the left and right sensory-motor cortex, respectively. Furthermore, as previously mentioned, components P50, N70, P100, and even N140 are of interest when discussing somatosensory processing, as they are believed to be generated by SI and SII electrical activity (Garcia-Larrea et al., 1995; Truett et al., 1992).

Dionne and colleagues (2013) and Staines and colleagues (2014) demonstrated an increase in early (P50) somatosensory activity at electrode CP4, through the addition of a task relevant visual stimulus. An increase in early somatosensory ERP components, was supported by behavioural markers of change as well in a study by Taylor-Clarke and colleagues (2002). During their study, researchers demonstrated improved tactile spatial acuity, masked as a reduced two-point discrimination threshold, through the addition of task relevant visual information. Compared to viewing an inanimate object, visual cues of the arm being stimulated resulted in a greater electrical response for both the N80 and N140 components. Thus, it was interpreted that a change

in excitability in SI may have occurred due to the addition of a task relevant visual stimulus. Just as did Dionne (2013) and Staines (2014) and colleagues, this increase in ERP amplitude was interpreted as a change in early somatosensory processing, following the addition of relevant visual input. This change in amplitude can then be viewed as evidence of increases in cortical excitability in that area (Dionne et al., 2013). If this is the case, this increase in excitability during multisensory training should then warrant improved perceptual processing, when presented with subsequent unisensory somatosensory stimuli. Due to the critical nature of task relevance in these studies, this change in SI and SII processing was believed to be aided by top-down feedback mechanisms, from multisensory association areas (Dionne et al., 2013; Taylor-Clarke et al., 2002). These effects (particularly surrounding N140) do strongly support frontal contributions due to the relevancy effects (Popovich & Staines, 2014). Nevertheless, as previously mentioned, modulations as early as ~50ms post-stimuli seems too short a latency to be solely the doing of multisensory association areas. As such the roles of early sensory-sensory communication cannot remain out of the realm of possibilities.

While none of these studies directly investigated the paradigm, they all provided plausible explanations for how the effects of MFUL may come to be. Specifically, demonstrating that the addition of a secondary sensory stimulus facilitates some form of acute neuroplastic change quite early on in the sensory processing stream. Future research on the neurophysiological adaptations of multisensory training is critical in understanding how effects like MFUL come to be. To the best of the researcher's knowledge, no neurophysiological investigations have been conducted tackling these proposed mechanisms within the paradigm of MFUL directly. This thesis intended to change this by providing the first known combined electrophysiological-behavioural

investigation directly interested in MFUL. As this is new territory, several questions remain unanswered, making the experimental setup one of discovery and exploration.

### **3.0 Experimental Design**

#### *3.1 Rationale*

Researchers have long been examining the benefits of multisensory training on perceptual learning. No matter the modality combination, multisensory training has been shown to facilitate a wide range of perceptual learning benefits including: reduced response latency (Bauer et al., 2009; Murray et al., 2005; Teder-Sälejärvi et al., 2005), improved accuracy (Ernst & Banks, 2002; Sumbly & Pollack, 1954) and improved precision (Alais & Burr, 2004); to name a few. However, focus has been placed primarily on the elicitation of these improvements during a multisensory task; a design which could create an unjustified bias in the interpretations. Specifically, it supports a notion that the facilitation of perceptual learning is confined to a multisensory environment, and that greater learning effects must then occur in longer-latency multisensory structures. This is despite the fact that a high level of specificity is often exhibited in perceptual learning; with improvements often being contained to tasks similar to those experienced during training. This high level of selectivity is consistent with neuronal responses in the early-stages of processing; where highly selective stimulus attributes are processed (Gilbert et al., 2001). Moreover, countless evidence now exists surrounding the involvement of early sensory structures during multisensory processing.

Combined, this has led to the discovery that the benefits of multisensory exposure go beyond the multisensory environment itself. Although current evidence is limited, multisensory training appears to prime subsequent unisensory perceptual processing as well. With its relative infancy, many questions remain however regarding the paradigm of MFUL. The primary objective of the present study was therefore to further develop the understanding surrounding this paradigm. One current limitation is the elicitation of subsequent unisensory performance beyond auditory-visual exposure. As we examined earlier, the benefits of multisensory exposure are not limited to

one combination of modalities, and thus similar effects should exist across other combinations, such as visual-somatosensory. Thus, the present study was interested in the modulations of somatosensory stimulus identification and discrimination following repetitive visual-vibrotactile exposure.

Secondly, while strong electrophysiological evidence exists surrounding the modulations of early sensory representations during multisensory versus unisensory training, the same cannot be said for MFUL. While Shams and colleague (2008) proposed several plausible mechanisms to explain the benefits of multisensory learning, the lack of accompanying neurophysiological evidence does not allow for robust interpretations to be made one way or another. While behavioural modulation was the primary outcome measure, EEG was used to guide an exploratory analysis. This was done in an attempt to further validate behavioural data, as well as to speculate regarding the neurophysiological correlates of MFUL.

### *3.2 Objectives and Hypotheses*

The objectives and corresponding hypotheses were as follows:

1. Examine whether a single session congruent visual-vibrotactile training intervention can modulate unimodal somatosensory processing.

*Hypothesis 1:* Multisensory training will modulate subsequent unimodal somatosensory processing. This will manifest as a significant reduction in RT to vibrotactile stimuli in post-testing, as compared to baseline measures.

2. Attempt to correlate behavioural evidence of somatosensory perceptual learning with electrophysiological markers of adaptation in early somatosensory processing

*Hypothesis:* Compared to baseline levels, post-testing early somatosensory ERP components (particularly at P50) will demonstrate an increase in amplitude following multisensory training.

*Modified Hypothesis:* Compared to early training (interventions 1 and 2), late training (interventions 5 and 6) earliest extractable somatosensory ERP components (P100, N140) will demonstrate a statistically significant increase in amplitude following multisensory training.

### *3.3 Methods*

#### *3.3.1 Subjects*

Twelve healthy participants were tested (7 Females; mean age 23.75; 3 self-reported left handed). Exclusion criteria were fluency in English, and free from any neurological or peripheral nerve damage. Furthermore, acuity and stereoacuity was tested to ensure all participants had clinically normal or corrected-to-normal vision. Visual acuity was measured using the Bailey Lovie Chart, where a score of at least 20/25 must have been achieved. The Randot Stereotest was used to measure stereoacuity, where clinically normal scores were characterized as 40 seconds of arc, or better. Participants were recruited from the University of Waterloo, as well as from the community. Experimental procedures were approved by the Office of Research Ethics, at the University of Waterloo. All participants gave written consent to participate in the study, and when necessary were given \$20 compensation for their time. Two participants were removed from EEG analysis due to excessive noise and blink artifacts.

#### *3.3.2 Apparatus and Stimuli*

Stimuli were delivered using a custom-made visual-vibrotactile stimulation device (see Appendix Figure 1). This device consisted of two adjustable piezo-electric actuators, which could



be moved left-right as well as up-down. The adjustability was designed to encourage maximum comfort for all participants, no matter the size of their hand or length of their fingers. Subjects were asked to place their second and fifth digits of their left hand on the two benders throughout the experiment. The actuators vibrated at a frequency of 25Hz for 500ms during each stimulus delivery. Directly behind each piezo-electric bender was a small red LED light, also presented for 500ms simultaneously with the vibration. This was chosen as paired touch and light on the hand is believed to be perceived as simultaneous when delivered truly simultaneously, opposed to accounting for the variance in neural processing time (Harrar & Harris, 2005) . Half way between the two LEDs (5cm apart) was a black cross, which was used as a fixation point throughout every component of the experiment. It is important to note that stimuli are described according to side, with the fifth digit (D5) and corresponding light representing the left side, and second digit (D2) and corresponding light representing the right side. Responses were performed with a right D2 button press. Specifically, participant's right D2 was placed on the response device, half way between the two buttons; known as neutral position (see Appendix Figure 1). When a response must be made, subjects pressed either the right (green) or left (red) button with their right D2, then returned back to neutral position.

Both visual and vibrotactile stimuli were delivered by custom LabView (National Instruments, Austin, Texas, USA) programs, which digitally generated waveforms, which were then converted to an analogue signal, and finally amplified (Bryston 2B-LP, Peterborough, ON, Canada). Visual stimulus amplitude (voltage) was set constant at 2 volts (V), while vibrotactile stimulus amplitude was adapted to each participant. As multisensory interaction is the strongest with weak stimuli (Meredith & Stein, 1983), the amplitude for vibrotactile stimuli was set low, yet distinguishable at two times perceptual threshold for each participant; calculated using an adapted

method of limits (MOL). Specifically, each participant completed three ascending and three descending protocols, resulting in six trials total from which an average stimulus intensity was calculated. For ascending runs, vibration began well below perceivable intensity, and progressively increased until participants detected a vibration on the glabrous surface of the skin; descending runs following the opposite protocol. MOL was chosen as the psychophysical method due to its efficiency and reliability in determining threshold in as few as five trials (Gerr & Letz, 1988). As arousal level and motivation are two areas of concern, efficiency should be strived for whenever possible. While this is true, there is still the tendency for variability between trials to be high in some participants. To control for this possible limitation, individual participant variability was calculated and was included in the calculation of vibrotactile stimulus intensity. A second limitation to this method is the tendency for subjects to anticipate when a “perceivable” stimulus will be presented, due to the starting amplitudes remaining constant across trials. To avoid bias through anticipation, starting levels varied each trial. As somatotopic representation and the number of peripheral receptors differs according to finger, this process was conducted separately for the second and fifth digit. Lastly, as the piezoelectric actuators are prone to creating noise when vibrating, participants listened to white noise delivered through earbuds throughout the study.

### *3.3.3 Procedure*

#### *Baseline Testing*

Participants’ baseline vibrotactile RT and ERPs were measured following threshold testing. RT testing consisted of a simple, choice response time task where a vibration was delivered to either the second or fifth digit. Subjects were asked to determine when, and to which side a vibration was felt, and to respond as quickly yet accurately as they could with a corresponding button press. RT testing consisted of 40 trials, evenly and randomly distributed between the two

sides, with an inter-stimulus interval (ISI) between 1.5-2.5 seconds. Somatosensory ERPs were then collected, with the second and fifth digit measured separately. 50 individual vibrations were passively delivered at four times perceptual threshold, to glabrous surface of the finger, with each stimulus separated by an ISI of 500ms. Subjects maintained visual fixation on the black cross throughout both RT and ERP testing.

### *Intervention*

The intervention consisted of six blocks, each containing 100 trials, with an ISI of 2 seconds; each block lasting approximately four minutes (see Appendix Figure 2). Throughout each block, subjects placed their left D2 and D5 on the piezoelectric benders and their visual fixation on the black cross. Right D2 was placed in neutral position, unless a response is being made.

Stimuli were delivered as one of three options:

1. Congruent VT (multisensory): light and vibration delivered simultaneously on the same side (can be either right or left). This represented 90% of the stimuli per block.
2. Visual alone (unisensory): a light on its own delivered on one side. This represented 4% of the stimuli delivered. These were considered the catch trials, thus no response was made.
3. Tactile alone (unisensory): a vibration on its own was delivered on one side. This represented 6% of the stimuli delivered

The percentage of each option remained the same across all six blocks, however the order in which subjects received the different stimuli type varied across the blocks. Subjects were instructed to respond whenever a multisensory or tactile alone stimulus was delivered. They were however, to remain in neutral position when a visual alone (catch) trial was presented. Thus, subjects were responsible for identifying the type, and location of the stimuli delivered. Once they had, they were

to respond as quickly yet accurately as they could by pressing the button corresponding to that side. A short break was taken half way through, in an attempt to maintain motivation and alertness.

### *Post-Intervention*

This third and final stage contained the same components described during baseline testing, and as such will not be further described.

#### *3.3.4 Data acquisition and Recording Parameters*

EEG was collected during baseline and post-intervention ERPs, as well as throughout the intervention. Unfortunately, due to excessive noise, somatosensory ERP components could not be extracted from baseline or post-intervention testing. As such, only somatosensory ERPs extracted during the training intervention will be discussed. Furthermore, cortical activity was only examined during the first and last third of the training. This corresponds to a comparison between training intervention blocks 1-2 versus 5-6, which will be referred to as early and late-training respectively. In order to gain a better understanding of the effects occurring, analysis was initially separated according to the finger that received vibrotactile stimulation, then combined.

EEG data was recorded using a 32-channel cap (Quik-Cap, Compumedics Neuroscan, NC, USA), with the main electrode of interest being CP4 (following to the International 10-20 system). Electrodes were referenced to linked mastoids, with all channel impedances kept below 5 k $\Omega$ . EEG data was filtered (DC-100 Hz) and digitized at 500 Hz (SynAmps<sup>2</sup> Compumedics Neuroscan, NC, USA), then saved for further analysis. Just as was done to blocks 5-6, event-related potentials from training blocks 1-2 were combined, epoched relative to a 100ms pre-stimulus onset, and band-pass filtered (1-50 Hz). Artifacts, characterized as deflections greater than 50  $\mu$ V, were manually inspected, and excluded from further analysis. An average of 5.2 and 7.8 trials were rejected for blocks 1-2 and 5-6, respectively. ERPs were averaged relative to a 100ms pre-stimulus interval,

with data from the second and fifth digit averaged separately. Components P100 (peak between 90-145ms), and N140 (trough between 145-190ms) were extracted for each subject individually; with distinct deflections required for inclusion. Due to minor noise remaining in the signal, each peak amplitude was averaged across a  $\pm 5$ ms latency window. This was conducted relative to each subjects' individual components, as well as per digit. Due to this process, any changes in latencies were not analyzed. Although analysis of earlier components (P50, N70) was desired to examine the earliest somatosensory processing, weak stimulus intensity delivered during training did not allow for clearly defined components to be extracted.

RT and threshold sensitivity testing were recorded using custom LabView programs (National Instruments, Austin, Texas, USA). Threshold was used to determine the amplitude of the vibrotactile stimuli delivered during training, and as previously described, was calculated as two times the threshold plus the variability. The mean stimulus amplitude for the second and fifth digit were 1.4V ( $\pm 0.40$ ; range 0.8-2.1V) and 1.3V ( $\pm 0.47$ ; range 0.75-2.4V), respectively. Response time was classified here as the absolute difference in time between the beginning of stimulus delivery, and the button being pressed (Pasalar et al., 2010). RTs faster than 200ms and slower than 1150ms, as well as incorrect responses were discarded in an attempt to remove spurious responses, which can greatly attenuate the true effects occurring (Pasalar et al., 2010; Whelan, 2008). Fast spurious responses are easily identifiable due to the minimum latency required to identify a stimulus and produce a response (minimum 100ms) (Luce, 1986). As a choice response time was conducted during this study, this latency increases even more, resulting in a minimum cut-off time of 200ms chosen. Slow spurious responses are far more difficult to identify, however are equally as important to remove. Pasalar and colleagues (2010) performed a study

using a very similar experimental design, and set its truncation value at 1150ms; a latency followed here.

Although still commonly reported, mean reaction time does not represent a robust measure of behavioural change due to its susceptibility of bias towards skewness. Furthermore, despite truncation performed, spurious responses are likely to still exist in the dataset. With these limitations in mind, subject median RT was used to describe the behavioural dataset. One strong contingency to the use of median RT however, is that the number of trials between conditions compared must remain constant (Miller, 1988; Whelan, 2008). This relates to the biased estimating nature of median responses, where absolute response times reported are often overestimated. This bias however becomes a negligible concern when interest lies in the relative RTs between conditions, as the predisposition to overestimate remains relatively equal between conditions. This assumption however, remains satisfied only when the degree of bias is in fact kept constant. When conditions with varying trial numbers are compared, there exists a differential median bias, leading to an even greater overestimation in the condition with fewer trials (Miller, 1988; Whelan, 2008). As such, the number of trials had to then be kept constant between baseline and post-intervention comparisons. For example, when a trial was removed due to error or truncation in baseline testing, the corresponding trial in post-intervention condition was also discarded; and vice versa. This was conducted separately per digit, per individual. Overall, 6.7% of trials were rejected (n=32). Once again, behavioural responses were analyzed first according to digit that received stimulation, then combined. RT was analyzed solely from these two conditions; intervention data is not included.

### *3.3.5 Statistical Analysis*

Differences between median baseline and post-intervention vibrotactile RTs were plotted, and a null hypothesis significance testing (NHST) one-way repeated measures (RM) analysis of

variance (ANOVA) was conducted; with condition as factor, containing four levels (ie. baseline-D5, post-D5, baseline-D2, post-D2). Orthogonal contrast between all baseline and post-intervention measures was then conducted. Bonferonni post-hoc tests were performed on the main effect to assess whether similar modulatory effects occurred, no matter the digit receiving stimulation. As excessive alpha-band activity contaminated baseline and post-intervention ERP testing, the second hypothesis could not be directly tested, and thus no statistical testing was conducted on these responses. That said, one-way RM ANOVAs were conducted on early ERP (P100, N140) amplitudes evoked during multisensory training, once again with condition as factor, with four levels. The only change however, is that condition represented early and late training, instead of pre- and post-intervention. To minimize the number of comparisons, only electrodes CP4 and FCZ were included; providing a contrast of activity between sensory-motor and frontal contributions, respectively. Statistical significance was set as  $p < 0.05$ .

To further supplement the statistical findings generated by NHST, a Bayesian approach was also conducted. Bayesian statistics provides further information about the strength of the evidence found during the study (Masson, 2011; Nuzzo, 2017). NHST uses the  $p$ -value to detail the probability of the results found given that the null hypothesis to be true. This relates to prior probability and is a uni-directional statement. Meaning, it does not allow for the involvement of posterior probability, which takes into consideration the likelihood of a result given the new information available. Furthermore, NHST allows only for the acceptance or rejection of the null hypothesis, allowing for no direct interpretations to be made regarding the alternative hypothesis. Bayesian statistics addresses these concerns by examining the bayes factor (BF), detailing the likelihood of the evidence under the null and the alternate hypotheses, given prior and posterior probability (Masson, 2011). Thus, the  $p$ -value and BF both represent the likelihood that the

observed results represent a significant change. However, BF simply provides more detail regarding the strength of the evidence, as well as providing a probability factor given posterior knowledge. RM Bayesian ANOVAs were conducted on both behavioural and electrophysiological data, once again with same factors and levels as NHST ANOVAs.  $BF_{10} > 1$  was set as supporting more evidence for the alternate hypothesis. This is contrasted to  $BF_{01} > 1$ , which signals more evidence in favour of the null hypothesis (Nuzzo, 2017).

### *3.4 Results*

#### *Response Time*

All twelve subjects were included in the analysis of behavioural data. Figure 1 depicts the average of all subjects' median response time to vibrotactile stimulation delivered to either D2 or D5. The one-way repeated measures ANOVA revealed a main effect of condition on RT ( $F_{3,33}=4.17$ ,  $p=0.013$ ,  $n^2_p=0.275$ ). This main effect was further confirmed by Bayesian statistics, which shows moderate evidence for the alternative hypothesis ( $BF_{10}=4.41$ ) that a significant difference exists between conditions. Upon further investigation, this effect is characterized as a mean 62.5ms reduction in response time between baseline and post-intervention testing (pre: 652.15ms  $\pm$ 12.90; post 589.73ms  $\pm$ 15.59). Pre-planned contrast of baseline versus post-intervention responses found this change to be statistically significant ( $F_{1,33}=9.52$ ,  $p<0.01$ ). Post hoc Bonferroni tests were then conducted to analyze whether the change in RT was similar based on the level of condition; specifically, the digit that received vibrotactile stimulation. Post hoc tests showed that while D5 failed to reach significance ( $p>0.05$ ), there was a significant effect of condition when D2 received stimulation ( $p<0.05$ ). These effects were confirmed using Bayesian statistics (D5:  $BF_{10}=0.595$ ; D2:  $BF_{10}=2.06$ ), and were characterized as a 40.8ms ( $\pm$ 30.43) and



84.2ms ( $\pm 35.65$ ) reduction in RT in post-intervention testing, as compared to baseline measures (see Fig.2).

### *Electrophysiology*

Ten out of twelve subjects were included in the EEG data analysis, with two subjects having been removed due to severe noise. Furthermore, baseline and post-intervention ERP testing data was not included due to excessive intrinsic artifacts, such as alpha-waves. Nevertheless, sensory ERPs were able to be extracted from the intervention tasks. Figure 3 depicts the grand average tracings for early and late training responses, at electrode CP4. Figure 4 and 5a provide a more in depth look at the mean differences in amplitude exhibited at the latency of P100 and N140, respectively (P100 early:  $2.81\mu\text{V} \pm 0.67$ , late:  $3.14\mu\text{V} \pm 0.73$ ; N140 early:  $-4.11\mu\text{V} \pm 0.506$ , late:  $-2.88\mu\text{V} \pm 0.757$ ). Identical one-way RM ANOVAs were conducted on both P100 and N140 amplitude, which revealed a main effect of condition on ERP amplitude for P100 ( $F_{3,27}=3.44$ ,  $p=0.03$ ,  $\eta^2_p=0.275$ ), but not for N140 ( $F_{3,27}=0.97$ ,  $p=0.423$ ,  $\eta^2_p=0.098$ ). This main effect on P100 amplitude may be further confirmed by Bayesian statistics, which suggests anecdotal evidence exists for the alternative hypothesis ( $\text{BF}_{10}=2.22$ ). Similarly, lack of evidence towards the main effect of time on N140, was also confirmed by Bayesian statistics ( $\text{BF}_{10}=0.843$ ). Upon further analysis, pre-planned contrast of early versus late training responses suggest the change in amplitude of P100, and N140 fail to reach significance ( $p>0.05$ ). It is suspected that the large variability exhibited across subjects, and the small ( $n=10$ ) sample size contributed to the failure to reach significance; particularly for the change at N140 (early:  $\text{SD}=\pm 2.261$ ; late:  $\text{SD}=\pm 3.386$ ).

### *3.5 Discussion*

Investigations conducted by Seitz and colleagues laid convincing groundwork for the notion of multisensory priming of unisensory processing, following as little as a single session of multisensory training (Kim et al., 2008; Seitz et al., 2006). The present experiment exploited this effect through modulations of somatosensory processing resulting from a single-session, congruent visual-vibrotactile training paradigm. The primary objective was to demonstrate a behavioural gain in somatosensory processing, characterized as improvements in response time; an objective successfully achieved. The main findings of this thesis largely support the original hypothesis, that a significant reduction in unimodal response time would be seen following multisensory training. Post-hoc investigations however, revealed that the digit which received vibrotactile stimulation had a significant effect on the degree of change exhibited. The secondary objective of the thesis was to explore electrophysiological correlates of adaptation occurring within early somatosensory processing. Due to external factors, the primary hypothesis that post-ERP testing would demonstrate modulations to the P50 amplitude could not be investigated. This resulted in a secondary hypothesis to be created, which although tackled the same question, addressed it in a new way. Meaning, the hypothesis that electrophysiological markers of adaptation would be present due to the multisensory training, remained. However, instead of testing this through pre-and post intervention ERPs, ERPs were extracted during early and late training instead. This slightly modified hypothesis suggested that markers of neuroplastic adaptation would be seen by late-training, characterized by a significant increase in amplitude in early somatosensory components. While neither change to P100 or N140 amplitudes reached statistical significance, a visible trend appeared at the latency of N140. This was exhibited by a decrease in amplitude by late training at central-parietal sites, with no visible change at frontal contributions (see fig. 5a/b).

While there are many ways to measure perceptual learning, in this study, response time was chosen. It was done so due to its popularity amongst researchers, providing it with strong validation as an appropriate dependent measure of perceptual judgment (Dawson, 1988; Rouder, Sun, Speckman, Lu, & Zhou, 2003). With that said, it remains not without its own limitations, with one of the more commonly discussed being how it is being examined. Specifically, while still commonly used, the analysis of mean RT is strongly disputed (Whelan, 2008). This is due to its distribution, in that it bears similarities to the ex-gaussian distribution; meaning it is often positively skewed. Furthermore, even within the same individual, RTs are inherently variable and thus, almost always contain outliers. This is because factors such as alertness, motivation, repetition, and anticipation can greatly affect variability across trials. Deviations such as these could then influence skew by contributing the infrequent, yet present density of responses of the right tail. When the mean is taken on data such as this, it is almost surely not capturing the true representation of the effects occurring; resulting in an average more heavily favoured in the direction of the skew (Whelan, 2008).

While several analysis techniques have been identified to compensate for these characteristics, not one method works for all datasets. Factors such as where changes in RT are seen (ie. slower vs faster responses), number of trials conducted, or the commonality of trials between the conditions being compared, all play a role in deciding the best option for the dataset at hand (Whelan, 2008). Accordingly, while no one method is perfect, median RT was chosen as the best method for the present study. This is because the design of the study failed to satisfy the requirements of other methods; such as whole distribution analysis, which requires a large number of trials. As previously mentioned, median RT is only appropriate when the same number of trials are presented across the conditions being compared (Whelan, 2008). While equal trial numbers

existed originally, following data analysis and the removal of incorrect or spurious responses, this assumption no longer held true. To accommodate this, trials removed (due to error or set truncation boundaries) between baseline versus post-intervention conditions were compared. To correct for inconsistencies, whenever a trial was removed in baseline testing, the corresponding trial number was also then removed from post-intervention testing; and vice versa. This process was further detailed to the digit being analyzed, to ensure same number of trials existed in baseline and post-intervention testing, per digit.

The results suggest that MFUL may not be confined to auditory-visual experiences, but exists following visual-somatosensory training as well. Moreover, it appears this modulation of somatosensory processing is affected by the side in which stimuli are delivered (See fig.2). As a reminder, the right and left sides represented light and vibration delivered to D2 and D5, respectively. As the intensity of the light delivered to both sides was kept constant, visual stimulus intensity can be ruled out as a contributing factor. Furthermore, vibrotactile threshold testing was conducted on each digit individually, and stimulus intensity was increased by a factor of two times perceptual threshold. That said, to control for inconsistencies seen during threshold testing, vibrotactile intensity was chosen to also include a variability factor. This variability examined how inconsistent the participant was during the MOL procedure at identifying when a stimulus was presented, and when it disappeared. A paired t-test was conducted on the variability seen on D5 ( $\mu=0.0867V$ ) and D2 ( $\mu= 0.216V$ ) threshold testing; a difference which just reaches significance ( $p=0.049$ ). This suggests that this significant difference in the variability between the two digits at baseline could be contributing to the differences in response time seen. Research has suggested that multisensory perceptual learning may be dependent on the task difficulty, such that a more difficult task results in a greater degree of learning (De Nier, Koo, & Wallace, 2016). As the

variability in D2 was greater than D5, it is possible that subjects found it more difficult to identify the vibration delivered to D2 than D5; thereby making the task more difficult. Nevertheless, this difference in difficulty was controlled for, by applying this factor of variability to the stimulus intensity delivered during baseline, intervention and post-intervention testing. It is instead plausible that differences in the number of peripheral receptors present and/or the size of somatotopic representation between the two digits, could be playing a role in the greater degree of learning exhibited when D2 received stimulation. Examining the somatotopic representation for example, D2 has been demonstrated to occupy a larger area than D5 in the human somatosensory cortex (Sutherling, Levesque, & Baumgartner, 1992). This would be accompanied by more cells available to evaluate the stimuli, thereby leading to more pre- and postsynaptic activity. Overall, this leads to a greater number of connections available for improvement through training.

Interhemispheric communication may also be contributing to the differences displayed between the digits receiving stimulation. To explain, it is important to reconsider the visual and somatosensory pathways. During both the intervention, and baseline/post-testing, all subjects were instructed to maintain fixation directly between D2 and D5 (and corresponding LEDs). This means D2 and D5 (and corresponding LEDs) were in the right and left visual fields, respectively. As described above, visual information from the peripheral fields of view decussate at the optic chiasm, and thus travels to the contralateral visual cortex. Thus, the right and left LEDs would have therefore been represented in the left and right visual cortex, respectively. This is contrasted to the vibrotactile information, which was strictly delivered to the left hand, and as such is represented solely in the right somatosensory cortex. Furthermore, the motor responses were conducted with the right hand (D2 specifically), which is represented by the left motor cortex. In summary, while sensory-sensory binding required cross-hemispheric communication for D2, the

subsequent motor response did not relative to the visual input. On the other hand, interhemispheric communication was required for the motor responses surrounding D5, but not for sensory-sensory interactions. As the response to D2 stimulation displayed more than two times the amount of change than D5, it is possible that an important contributing factor is the commonality of hemispheric representation between the visual and motor representations during training. That is, to effectively facilitate a subsequent influence on unisensory perceptual performance following multisensory training, the additional sensory stimuli must share hemispheric properties with the outgoing motor response. The second digit also shares a commonality with the digit being used to perform the motor response. Future investigations should examine whether the digit used to execute a response affects the outcome based on the task setup. After all, as previously mentioned, perceptual learning maintains a high level of specificity; it is possible this relates as far as the digits being stimulated and corresponding motor response.

A significant reduction in unimodal somatosensory response time displayed here, supports the main hypothesis that visual-tactile training can modulate subsequent somatosensory processing. Due to the relatively short duration of training, structural modifications or changes in transduction times are likely not a contributor to the decrease in RT displayed. Consequently, a more likely explanation is that visual-tactile training facilitated potentiation of previously existing connectivity. Due to the subsequent improvements in unimodal somatosensory perceptual learning, it remains plausible that these adaptations are occurring within the early stages of sensory processing. More specifically, facilitating learning within early somatosensory representations. As described by the metamodal organization of sensory processing, low-level sensory structures play an important role in the processing and interaction of bimodal stimuli. Visual-tactile experiences are no exception, with studies such as Dionne and colleagues (2013) and Amedi and colleagues

(2001) demonstrating the activation and modulation of early somatosensory representations during visual-tactile environments. Assuming these structures are heavily involved in multisensory processing, then it is not out of the realm of possibilities that with repetitive exposure, learning can occur within these representations. After all, it has already been demonstrated that the addition of a relevant visual stimulus appears to increase the excitability within early somatosensory processing (Dionne et al., 2013). Evidence from the present thesis suggests that this modulation of somatosensory processing outlasts the bimodal environment in which it was induced, and facilitates subsequent somatosensory perceptual performance.

While behavioural evidence does provide strong support for claims such as these, it lacks the complexity to speak to the specific neurophysiological drivers of the potentiation of connectivity. As such, mechanistic understanding can remain purely speculative without the addition of such measures as EEG. Comparing activity between early and late training provided a proxy to monitor adaptations that may have occurred during training, and therefore would contribute to any changes in behavioural performance exhibited during post-intervention testing. The data fails to support the alternate hypotheses that late training ERPs would exhibit increases in amplitude, as compared to early training levels. Specifically, no statistically significant differences were shown at the latency of P100. This could be interpreted as a lack of modulation on neuronal activity at the earlier stages of SII processing. Therefore, it is possible that multisensory exposure may have more influence either at earlier or later stages of sensory processing, such as at the latency of P50, or N140.

While P50 could not be extracted in the present investigation due to weak stimulus intensity, the N140 component could; a component known to have frontal and SII contributors. Frontal contributions, which often relate to attentional or relevancy-based effects, are often displayed at

frontal electrodes such as FCZ (Dionne et al., 2013; Staines et al., 2014). As seen in Figure 5b, no change in amplitude is seen between early and late training at component N140, at electrode FCZ. Thus, this could be interpreted as no change in attentional state exhibited by the training paradigm. Furthermore, there appears to be no statistical difference in N140 amplitude at central-parietal sites. Examining Figure 7, one can see that a large level of variability existed in the dataset across all conditions and digits; particularly surrounding baseline D2 responses. This, combined with the low sample size, are likely two strong contributors to the lack of significance reached. Although failing to reach statistical significance, there visually appears to be evidence of a change occurring during training at central-parietal contributions of component N140 (See Fig. 5a). Due to its sensory-motor spatial representation, and contrasting effects to frontal areas, there is reason to believe activity here does in fact have SII generators. A reduction of amplitude ( $1.23 \mu\text{V} \pm 0.873$ ) by late training may be interpreted as early emerging evidence of change in sensory processing efficiency. Specifically, a reduction in activity by late training could suggest that less involvement of late SII processing. Nevertheless, the lack of statistical significance in the present study proves difficult to confirm these claims. Future research would be required to investigate changes surrounding not only late SII processing, but early SI as well. After all, should an efficiency effect be occurring, this would suggest sensory stimuli are being processed to a greater extent by earlier representations, such as SI. This would be represented by modulations of electrical activity at the latency of P50.

Without the ability to monitor changes at P50, this theory cannot be tested. Nevertheless, perceptual learning has been shown to maintain high levels of specificity; a quality strongly shared by neuron population of primary sensory areas, such as SI. This specificity could encourage learning to occur within these early representations, improving stimulus identification or synaptic



transmission of input here. Two plausible hypotheses could be made regarding how multisensory training may modulate early somatosensory representations. That is, theoretically the addition of visual stimuli may have upregulated somatosensory processing, enhancing the extraction of stimuli processing and improve synaptic efficiency. It has been proposed that a perceptual learning threshold exists, whereby without a sufficient activation of sensory structures, learning cannot occur (Seitz & Dinse, 2007). Shams and Seitz (2008) predicted that while a simple unimodal (visual) stimulus presented on its own may prove insufficient at reaching the threshold, following training, combined bimodal (auditory-visual) stimuli may change that. Applying that here, visual stimuli could boost somatosensory activation beyond the learning threshold, promoting processing and facilitating somatosensory learning (Shams & Seitz, 2008). With further multisensory presentation, somatosensory learning may only strengthen further, increasing neuronal synaptic efficacy and responsiveness within these representations.

Alternatively, a phase-shift in oscillation patterns may have promoted subsequent somatosensory processing, allowing signals to arrive during an optimal state of excitability. As previously mentioned, the addition of a stimulus in a secondary modality appears to increase excitability within early sensory-specific representations; such as SI (Dionne et al., 2013). Researchers have supported this claim in rat models as well, demonstrating an increase in neuronal response occurring during a bimodal task; be it visual-auditory (Lakatos et al., 2007) or visual-somatosensory (Bauer et al., 2009; Sieben et al., 2013). Here however, researchers predicted that the increase in electrical activity is related to a phase-shift in oscillation patterns within the early sensory-“specific” representations; a modulation that appears to be a consequence of the secondary sensory stimulus. This shift allows auditory (Lakatos et al., 2007) or somatosensory (Bauer et al., 2009; Sieben et al., 2013) input to arrive during an optimal state of excitability; thereby promoting

sensory processing. It is important to note that these effects have seemingly only been demonstrated in rat models. Furthermore, to the best of the researchers' knowledge, there is no information available on the duration of these effects. Meaning, we cannot confidently say that the same shift is occurring in humans, nor that the modulations of excitability would outlast the multisensory environment and facilitate subsequent unisensory perceptual performance. Nevertheless, this could provide a plausible explanation surrounding how bimodal training could modulate very early sensory processing, and thereby facilitating subsequent unisensory perceptual performance. Future investigations are greatly needed to explore these propositions.

With all that said, we cannot exclude the possibility that simply the repetitive nature of vibration delivered to the fingertips, resulted in a change in the receptive fields of somatosensory cortical neurons, thereby improving sensitivity and signal detection. It has been well documented that cortical representations are malleable structures, which can reorganize following experiences such as sensory loss or perceptual learning (Kaas, 1991). As displayed by Seitz and colleagues, both the unisensory and multisensory groups improved on visual motion detection despite their differences in training protocols; with the latter group simply demonstrating greater evidence of learning. Thus, it is plausible that it was merely the training of vibrotactile identification and discrimination that contributed to improvements in post-training; whereby the added visual light did not play a role. On this same topic, the factor of repetition also cannot allow practice effects to be discounted. While it is very likely that practice contributed to some degree towards improvements in RT displayed, the variability seen amongst the fingertips suggests there is likely something more driving the effects. Meaning, both the second and fifth digit received the same number of stimulations during training, and thus participants performed an equal amount of corresponding responses. If practice effects were the sole driver of the changes in RT seen, this

would then theoretically result in similar amounts of change in RT no matter the digit that received stimulation. Comparing the present results with a control group performing a similar task, with perhaps only one modality of stimuli delivered, would provide further confirmation of whether or not practice effects are playing a large role, and the particular contribution of the multisensory nature of the training.

Another limitation of the present investigation resolves around the inability to measure baseline and post-testing passive ERPs, as initially anticipated. The goal of this paradigm setup was to allow researchers to gain a better understanding of what, if any, changes in SI and SII processing could be displayed following training. Specifically, this design allowed for an unbiased analysis of cortical responses, without the contribution of visual input and motor responses. Unfortunately, the passive nature of the design resulted in a strong dissociation from the subjects and the ongoing stimuli. Meaning, motivation and alertness were no longer controlled, and ultimately played a large role in masking any effects that may have otherwise been visible. Specifically, alpha-band activity (8-12Hz) is a strong noise contaminator when participants are tired or disinterested (Woodman, 2010). Future directions should try and limit this effect by perhaps, having the participants count the number of stimuli delivered, or count the number of breaks between stimuli. This would encourage subject engagement.

Alpha waves were seemingly not the only limitation exhibited by the electrophysiological measures used. While steps were taken to remove the noise prior to data collection, post-hoc analysis clearly displays some remnants remained. These measures involved trial-and-error testing of potential cap damage, and the placement of a plastic nut overtop the piezoelectric benders to attenuate noise being picked up by the benders themselves. Furthermore, channel impedances were checked after each trial to ensure they were kept below 5 k $\Omega$ ; whereby actions were taken should

any have increased since the previous check. Despite these efforts, and the application of a bandpass filter (1-50Hz), some participants' averaged tracings still displayed noise. This resulted in small deflections ( $<1\mu\text{V}$ ) sometimes displayed across peaks and troughs. Following traditional EEG analysis measures, ERP components are chosen according to the largest, most defined deflection within a set time window. If these measures were solely followed, it could not be confidently ruled out that the amplitude value chosen, was not the doing of noise. To counteract any influences of noise, area sweep averaging was conducted on the components of interest. This involved locating the peak or trough according to the standard protocol, following which the mean amplitude across a  $\pm 5\text{ms}$  latency window was taken. This process was conducted separately according to each participants' tracings.

As ERPs were taken from multisensory stimuli delivered during the intervention itself, it cannot be discounted the potential contribution of motor preparation and visual activity. That is, it cannot be confidently stated that measurable electrical activity is solely representative of somatosensory processing. While earliest responses (ie. P50) occur prior to the arrival of visual input (Meredith et al., 1987), components such as P100 and N140 may not. If metamodal organization of sensory processing does reflect multisensory experiences, then it remains possible that visual representations may have feedforward input to somatosensory areas. Furthermore, motor learning can also occur following a single-session training protocol, where increases in cortical excitability has been exhibited at short latencies at central and parietal sites (Smith & Staines, 2006). Thus, longer latency components such as N140 may include top-down influences on sensory processing, from visual and/or motor regions. To avoid any confounding influences, future investigations should examine somatosensory ERPs evoked from passive somatosensory stimuli; as originally intended.

Along with feedforward influences, fast learning effects should also not be discounted. It was chosen to combine training blocks to ensure a sufficient number of trials were used for ERP analysis. Nevertheless, it may have been invalid to assume cortical activity would be similar between the blocks; particularly between blocks 1 and 2. This is due to the lack of trials necessary to initiate perceptual learning; displaying within minutes of training (Karni & Giuseppe, 1997). Qu and colleagues (2010) demonstrated significant decreases in the visual N1 component between the first and third block of training, with a visually evident decrease occurring even between blocks one and two. While a direct contrast cannot be made with this study, it raises the question of whether participants demonstrated evidence of learning following even the first block of training in the present investigation. If so, the early training amplitudes may not be an adequate representation of “baseline” sensory processing, but instead may already include early evidence of adaptation. This would result in the early training ERP amplitudes to be biasedly elevated, thereby influencing the contrast with late training.

In summary, the present study demonstrated first known evidence of visual-tactile modulation of somatosensory processing. Behavioural evidence displayed clear evidence of learning, with electrophysiological evidence hinting at modulations potentially occurring at the early stages of somatosensory processing. A small sample size and a large level in participant and EEG noise variability made interpretations of ERP data difficult. A visual N140 decrease at central-parietal, but not frontal areas could suggest a modulation occurring solely to sensory processing; not attentional state. More specifically, proposing a change in stimuli processing efficiency, with neuronal populations at later stages of SII processing requiring less involvement. Nevertheless, future investigations are required to confirm such claims, investigating not only changes in SII processing, but early SI as well. While neurophysiological mechanisms remain to be determined,

preliminary evidence from the present thesis supports the notion that multisensory training can induce learning in unisensory representations. Further investigations into MFUL will thereby support the new-age opinion that these areas are more involved in multisensory interactions than once perceived.

#### **4.0 Future Directions**

As detailed in the discussion, there are many areas that require future investigations. Of noteworthy mention is a more detailed look into the neurophysiological mechanisms occurring. While modulations to ERP amplitude is a good place to start and would benefit from further investigation, changes to oscillation patterns or hemodynamic responses should also be considered. Combining behavioural and neurophysiological measures would provide a more comprehensive understanding of any adaptations occurring, while controlling for confounders such as practice effects. Furthermore, reaction time represents only one measure of perceptual learning. Future investigations may consider expanding upon these outcome measures, as well as examine more closely the effects of fast learning, and multi-day training.

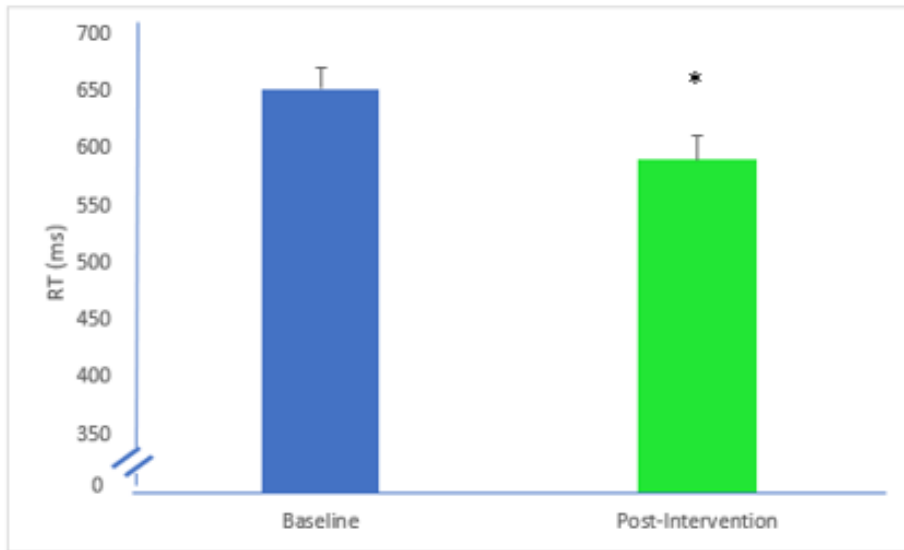


Figure 1. Unimodal somatosensory response time (RT) across condition (baseline and post-intervention). Group (n=12) means  $\pm$  SE. \* indicates  $p < 0.05$

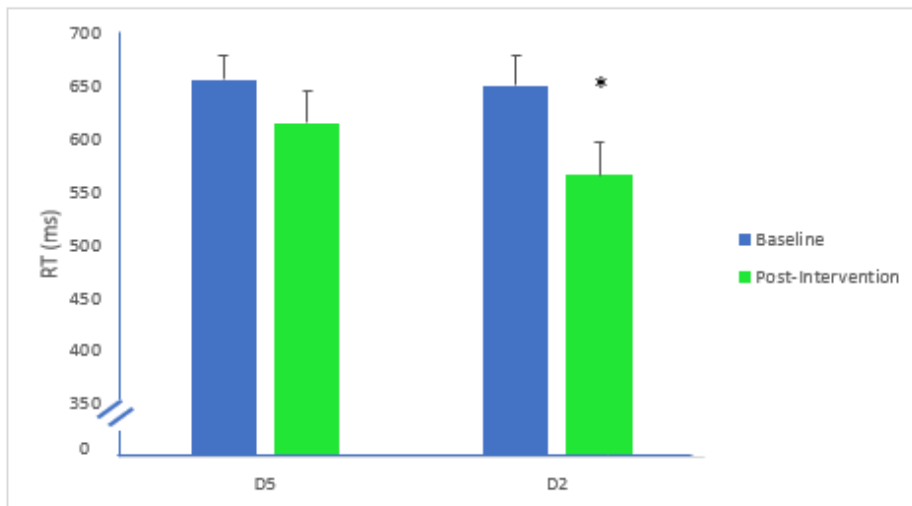


Figure 2. Unimodal somatosensory response time (RT) across condition (baseline and post-intervention), according to the digit (D2, D5) that received vibrotactile stimulation. Group (n=12) means  $\pm$  SE. \* indicates  $p < 0.05$

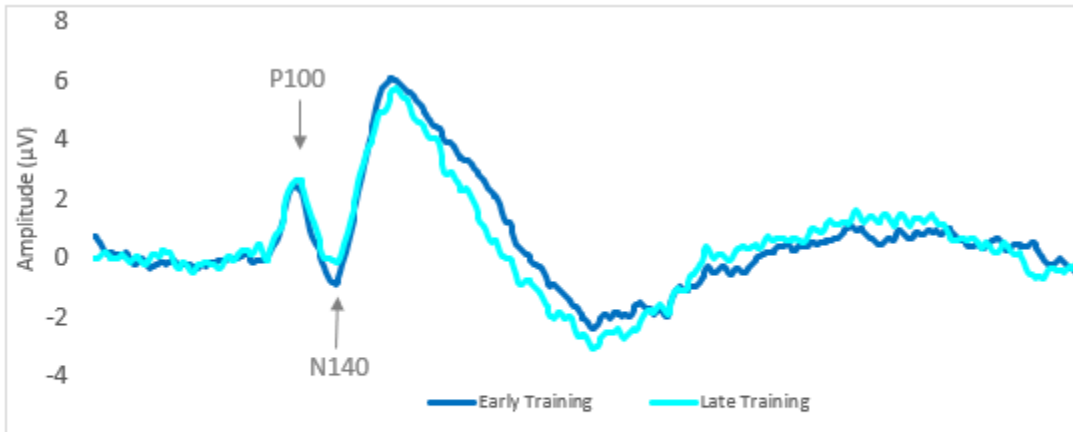


Figure 3. Grand average waveforms at central-parietal (CP4) sites. Grand averaging tracings in response to visual-tactile stimuli delivered during early (Int. 1/2) and late (Int. 5/6) training. ERP components of interest are labelled. Dark blue and teal represent early and late training, respectively.

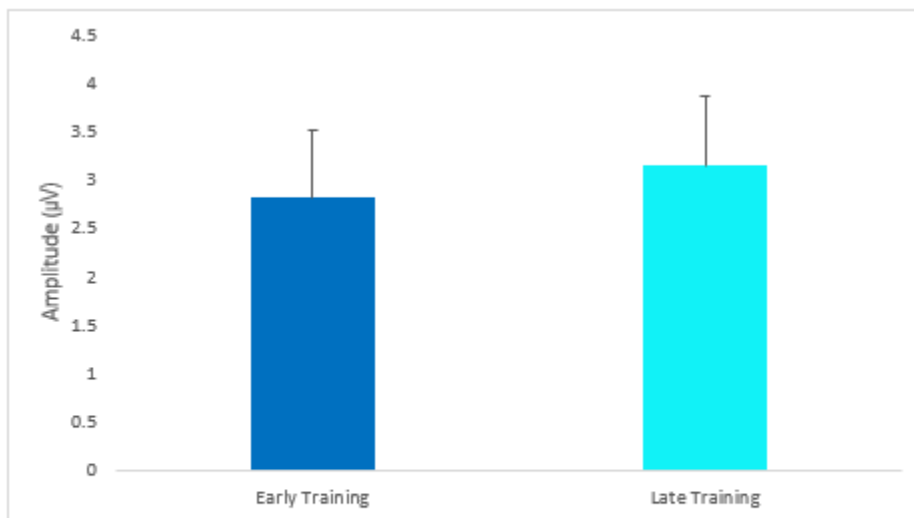


Figure 4. Group ERP means at the latency of P100 at electrode CP4. Group (n=10) ERP means  $\pm$ SE in response to multisensory (VT) stimuli delivered during training. Dark blue represents early training (Int. 1/2) and teal represents late training (Int. 5/6).



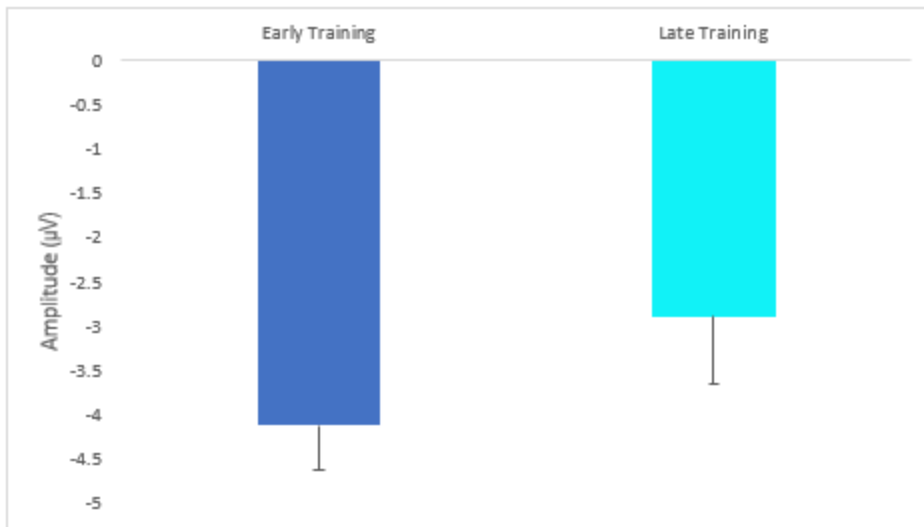


Figure 5a. Group ERP means at the latency of N140 at electrode CP4. Group (n=10) ERP means  $\pm$ SE in response to multisensory (VT) stimuli delivered during training. Dark blue represents early training (Int. 1/2) and teal represents late training (Int. 5/6).

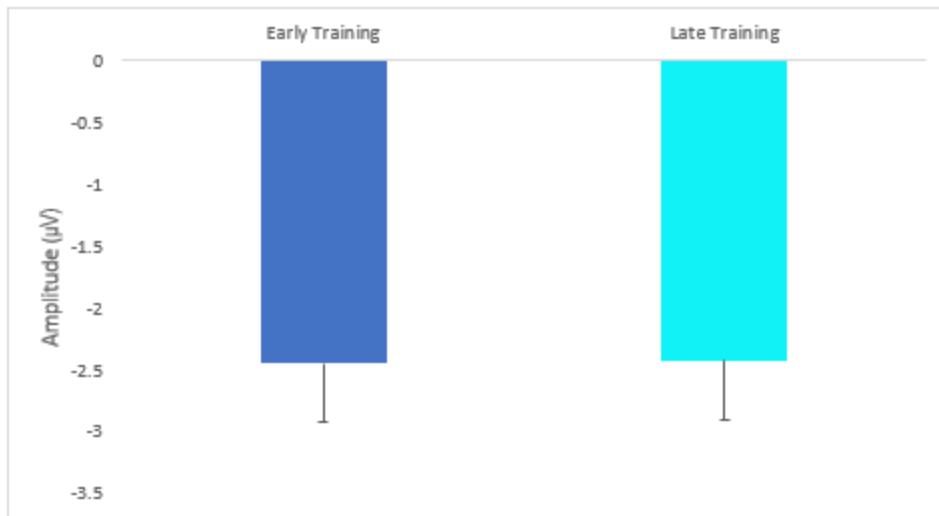


Figure 5b. Group ERP means at the latency of N140 at electrode FCZ. Group (n=9) ERP means  $\pm$ SE in response to multisensory (VT) stimuli delivered during training. Dark blue represents early training (Int. 1/2) and teal represents late training (Int. 5/6).

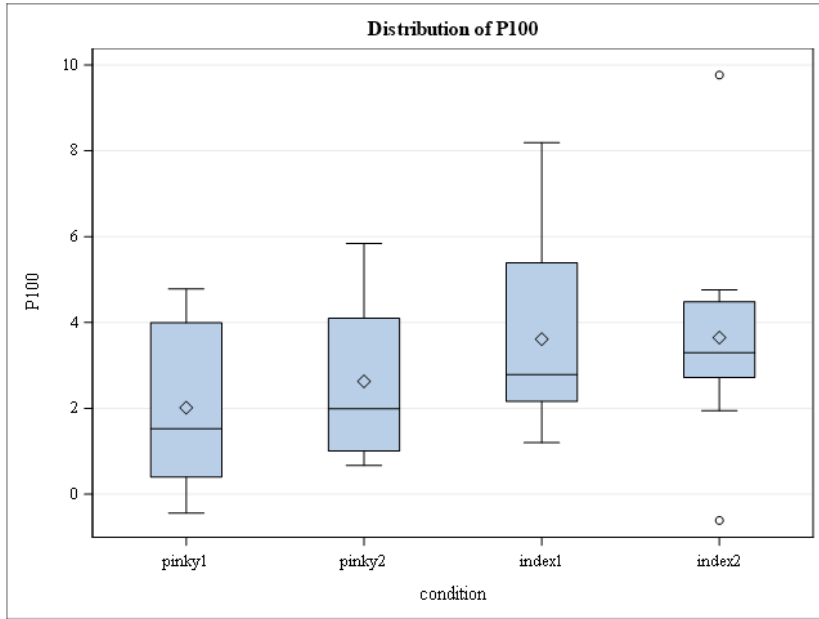


Figure 6: Distribution plots for component P100 at CP4. Distribution of subject ERP responses at the latency of P100, at electrode CP4. Separated according to the digit which received stimulation (pinky(D5), index(D2)), and condition (baseline (1), post-intervention (2)).

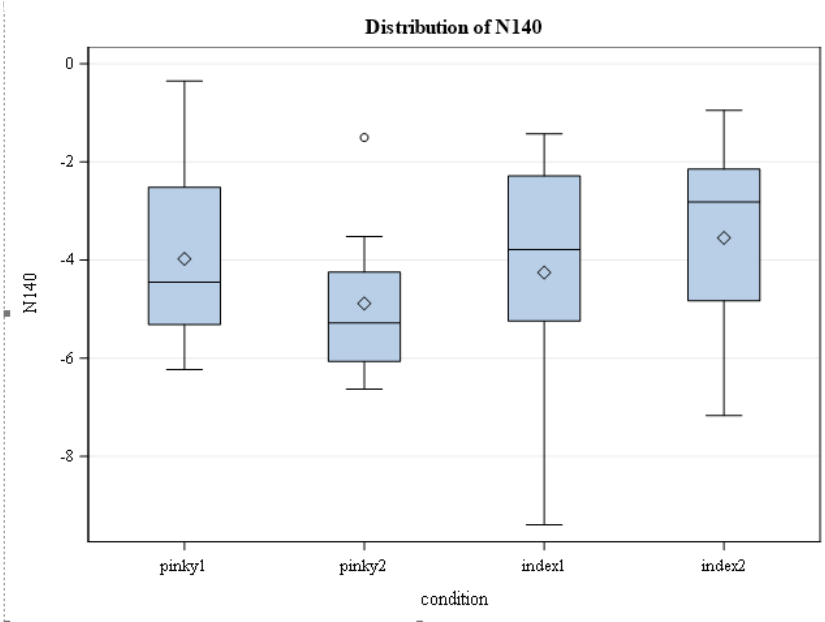


Figure 7: Distribution plots for component N140 at CP4. Distribution of subject ERP responses at the latency of N140, at electrode CP4. Separated according to the digit which received stimulation (pinky(D5), index(D2)), and condition (baseline (1), post-intervention (2)).

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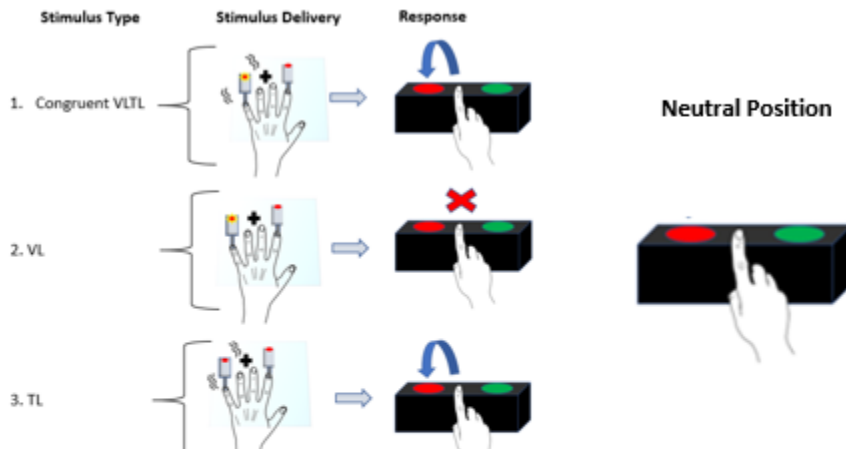
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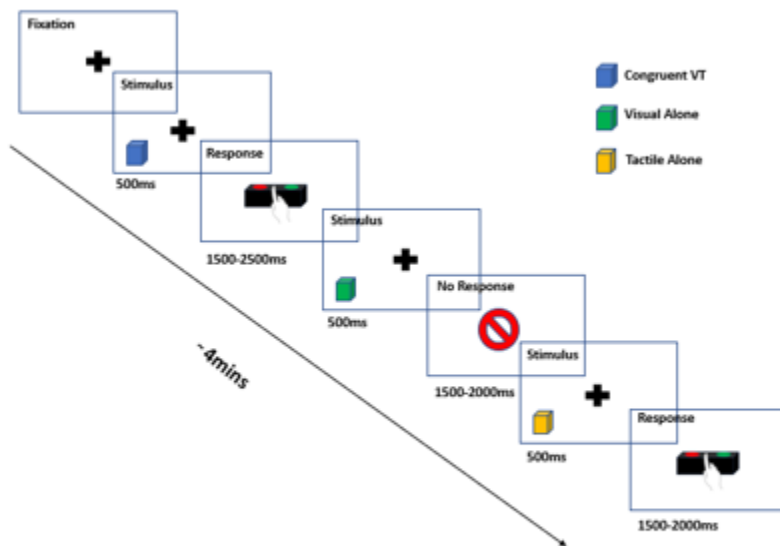
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## Appendix



*Appendix Figure 1.* Cartoon schematic of possible stimulus types, and corresponding responses delivered through one block of training. The small red circles displayed in the *Stimulus Delivery* column indicate non-illuminated LEDs, while the yellow and red circles represent an illuminated LED. The jagged accents represent vibration. The dark blue arrows in the third column represent the direction of response. Neutral position represents the position of right D2 before a response is made. VL= visual left, TL= tactile left. Only left sided examples are being displayed. TL also represents the setup for baseline and post-testing RT and ERPs.



*Appendix Figure 2.* Experimental sequence completed during each block of the Intervention. Order of stimulus delivery was randomized in each block but remained constant across subjects