

Cerebellar Contributions to Rapid Cross-Modal Attention in Visual-Tactile Processing

by

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Author's Declaration

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

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Abstract

Clinical, functional connectivity, and behavioral studies have provided growing evidence for the involvement of the right lateral cerebellar hemisphere in cognition, especially attention. The presence of contralateral connections between the cerebellum and cerebrum via the thalamus provides the groundwork for cerebellar involvement in cognition and lateralization of function. At any given time, the brain is subjected to multiple relevant stimuli. While we cannot divide our attention between these stimuli, we can rapidly shift our focus. If these rapid attentional shifts occur in close temporal proximity between two target stimuli (T1 and T2), there is a decrease in accurately reporting the second target (T2). This phenomenon is termed attentional blink (AB). Studies combining continuous theta burst stimulation (cTBS) with visual AB tasks have shown that inhibiting the right cerebellar hemisphere enhances visual attentional blink. However, the exact physiological mechanisms underlying cerebellar influence on attentional networks during sensory processing remain unclear. It is also uncertain whether the cerebellum impacts sensory processing when presented with two relevant targets in different sensory modalities compared to unimodal conditions, and whether lateralization of function is conserved in this process. The aim of this study was to investigate the cerebellar involvement in cross-modal attentional processes and its impact on rapid attentional shifts when integrating cross-modal information presented within short time intervals. Hypothesizing that cross-modal AB would be enhanced following right cerebellar stimulation, 26 healthy participants underwent two sessions consisting of pre and post-cTBS cross-modal AB tasks targeting either the left or right cerebellar hemisphere. The task involved presenting either a visual or tactile stimulus (T1), followed by a stimulus of the opposite modality (T2), and then a mask of the same modality as T2. After stimulus presentation, participants were prompted to indicate the perceived side for both stimuli. Our results

demonstrated that after transiently depressing the right cerebellar hemisphere, there was a significant reduction in extracting T2 tactile targets from the mask. Furthermore, there was an overall reduction in reporting T2 in the AB condition within the visual-tactile block type. There was no significant change in performance in either condition after stimulating the left cerebellar hemisphere. These results imply the cerebellum's role as a sensory modulator in a hemisphere-specific way. Given our results, we conjecture that during complex tasks which require attentional control, the right cerebellum is recruited to manage bottom-up processing of the mask (distractors) via sensory gating. This allows top-down processes to effectively integrate T2 (target) after processing T1. We put forward the “Sensory Balance Model”, offering insights into the neurophysiological mechanisms underlying cerebellar involvement in attentional modulation.

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List of Abbreviations

AB: Attentional Blink
ADHD: Attention Deficit Hyperactivity Disorder
AMT: Active Motor Threshold
ANOVA: Analysis of Variance
CCAS: Cerebellar Cognitive Affective Syndrome
CNS: Central Nervous System
cTBS: Continuous Theta Burst Stimulation
CPC: Cortico-Ponto-Cerebellar
CTC: Cerebello-Thalamo-Cortical
DAN: Dorsal Attention Network
DCN: Deep Cerebellar Nuclei
DLPFC: Dorsolateral Prefrontal Cortex
EEG: Electroencephalography
EMG: Electromyography
ERP: Event-Related Potential
FDI: First Dorsal Interosseous
FEF: Frontal Eye Fields
fMRI: Functional Magnetic Resonance Imaging
IPS: Intraparietal Sulcus
ISI: Inter Stimulus Interval
iTBS: Intermittent Theta Burst Stimulation
LTD: Long-Term Depression
LTP: Long-Term Potentiation
MD: Mediodorsal Nucleus
MEP: Motor Evoked Potential
MRI: Magnetic Resonance Imaging
SE: Standard Error
TBS: Theta Burst Stimulation
tDCS: Transcranial Direct Current Stimulation
TMS: Transcranial Magnetic Stimulation

TRN: Thalamic Reticular Nucleus

TV: Tactile-Visual

VIP: Ventral Intraparietal

VT: Visual-Tactile

1. Introduction

To achieve a unified perception of the external world and execute correct behaviours and or movements, it is important to process different types of sensory inputs in near unison to achieve maximal information about the environment. This is termed cross-modal integration of information (Lalanne & Lorenceau, 2004). At any given time, the brain is exposed to a plethora of sensory stimuli and thus, relies on selection and task-relevance of information for successful integration (Talsma et al., 2010).

Attentional control plays a critical role in determining task relevancy by guiding the brain's selective attention towards specific sensory inputs, influenced by both bottom-up factors (such as the saliency of stimuli) and top-down factors (including cognitive goals) (Corbetta & Shulman, 2002). The concept of attention is not a singular system, but rather a collection of mechanisms and significant attributes within various perceptual and cognitive processes that enable the regulation of information processing (Talsma et al., 2010). Interestingly, selection is one of the significant attributes of attentional control, through which the cognitive system determines pertinent information for ongoing behaviors (Talsma et al., 2010). According to current literature, there is evidence for the involvement of sub regions in attentional processing, such as the cerebellum (Brissenden et al., 2016).

Traditionally, the cerebellum has been termed as an accessory motor structure and has been linked to motor control and coordination (Manto et al., 2011). Nevertheless, emerging evidence indicates that the cerebellar cortex possesses considerable heterogeneity in its anatomical and functional connections with regions outside the cerebellum (Buckner et al., 2011). Several studies have provided evidence that a significant portion of the cerebellum demonstrates connections with cerebral cortex regions associated with non-motor functions,

including attention, perception and working memory (Brissenden et al., 2016; Schmahmann et al., 2019).

The primary objective of this research is to probe the attentional system during a cross-modal attentional blink task and investigate cerebellar contribution to this phenomenon. Specifically, this study aims to understand whether transiently depressing cerebellar activity influences rapid attentional shifts when integrating cross-modal information between vision and touch within short intervals ($< 500\text{ms}$). This research serves as an avenue to understand how the anatomical and functional connectivity of the cerebellum to non-motor cerebral areas translates to normal function or dysfunction in cases of cerebellar damage. Additionally, it will contribute to understanding the physiological mechanism through which the cerebellum influences sensory information processing through attentional networks. This could provide an updated therapeutic approach for targeting the cerebellum to treat sensory deficits observed in various abnormalities.

2. Literature Review

The following sections provide a review of the current literature that will aid in developing this thesis and research goals. An overview of the cerebellum's anatomy and functional connectivity will be provided along with evidence to support the influence of the cerebellum on non-motor functions. This will be followed by a discussion on concepts related to cross-modal integration, attention, and attentional networks. Lastly, research techniques related to the study will be explained.

2.1 Overview of Cerebellum

The cerebellum is a subcortical region of the brain, comprising about 10% of the total brain volume in adults. However, it contains more than half of the brain's total neurons (Klein et

al., 2016). Traditionally, the cerebellum has been classified as a motor structure responsible for maintaining balance and posture, coordinating voluntary movements, and facilitating motor learning (Manto et al., 2011). During motor coordination, the cerebellum integrates sensory input with motor commands to fine-tune and coordinate movements (Manto et al., 2011). It compares the motor command with the actual movement, making necessary adjustments for smooth and accurate execution (Manto & Bastian, 2007). According to the current framework, the cerebellum influences motor learning and adaptation by storing internal models of movement. These models allow for predictions of specific motor outcomes and adjustments of future movements to achieve desired goals (Manto & Bastian, 2007). Thus, the cerebellum can be classified as a comparator. It receives a copy of the motor command from the motor cortex, representing the intended movement, and compares this information with the sensory feedback (actual movement) received from the periphery (Welniarz et al., 2021). If there is a discrepancy between the intended and actual movements, the cerebellum sends corrective signals back to the motor cortex and other motor areas to adjust the movement in real-time (Welniarz et al., 2021).

Recently, functional, and behavioural studies have provided compelling evidence for cerebellar activation in tasks beyond motor control and coordination. These include cognitive functions such as working memory, attention, and language along with influences on sensory integration (Arasanz et al., 2012a; Brissenden et al., 2016; Schmahmann et al., 2019). Furthermore, clinical studies conducted on individuals suffering from cerebellar lesions and deficits have demonstrated that patients don't exhibit compromised primary sensory functions (Therrien & Bastian, 2015). Rather, there is a loss of execution of complex tasks which require sensory input to form perceptions (Therrien & Bastian, 2015). Lastly, anatomical studies have demonstrated richer and more widespread cerebellar projections to various thalamic nuclei some

of which are involved in cognitive functions. These include the mediodorsal nucleus (MD) which is involved in higher-order cognitive processes such as attention and working memory as well as the lateral posterior nucleus which is involved in processing somatosensory information (Pisano et al., 2021). Finally, projections to the lateral and medial geniculate nuclei have also been reported, which play a role in processing visual and auditory information respectively (Pisano et al., 2021). Hence, this collection of evidence has provided a stepping-stone to understand the role of the cerebellum beyond the motor domain and establish its role in sensory processing.

2.2 Gross Anatomy of Cerebellum

The cerebellum is a hindbrain structure located in the posterior fossa and is inferior to the tentorium cerebelli (Roostaei et al., 2014). Roughly ovoid-shaped, it is grossly divided into two lateral cerebellar hemispheres by the vermis (Roostaei et al., 2014). The cerebellar hemispheres are divided into three lobes by two large fissures: the anterior lobe and the posterior lobe, which are separated by the primary fissure, and the flocculonodular lobe, which is separated from the posterior lobe via the posterolateral fissure (Jimshelishvili & Dididze, 2020). These lobes in the cerebellum work together to execute various tasks including the integration of sensory information, monitor ongoing movements, and make precise adjustments to motor commands.

On the cerebellar surface, numerous fine, parallel folds called folia are present. These folia greatly increase the surface area of the cerebellum, allowing for a higher density of neurons and enhanced processing capabilities. The folia are further divided into smaller ridges known as lobules (Stoodley & Limperopoulos, 2016). These lobules further subdivide the lobes into more specific functional regions. The anterior lobe consists of lobules I to V, the posterior lobe comprises lobules VI to IX and lobule X is part of the flocculonodular lobe, which is located at the most inferior part of the cerebellum (Stoodley & Limperopoulos, 2016).

The cerebellar peduncles are bundles of afferent and efferent nerve fibres that serve as pathways connecting the cerebellum with other parts of the central nervous system (CNS). Together these bundles form three peduncles on each side namely, the superior, the inferior, and the middle cerebellar peduncle. The superior cerebellar peduncle consists primarily of efferent fibres which reach the cerebrum through the thalamus (Stoodley & Limperopoulos, 2016). The middle cerebellar peduncle is located at the pontine level and is composed of afferent fibres originating from the contralateral cerebral cortex to the cerebellum via the pontine nuclei (Stoodley & Limperopoulos, 2016). Lastly, the inferior cerebellar peduncle consists of afferent and efferent fibres. This allows the spinal cord, vestibular nuclei, and inferior olive, to form connections with the cerebellum (Stoodley & Limperopoulos, 2016).

There are four sets of deep cerebellar nuclei (DCN) located in the white matter of the cerebellum: dentate nuclei, fastigial nuclei, the emboliform nucleus, and the globose nucleus (the last two form the interposed nuclei). These cerebellar output areas utilize the superior peduncle to communicate with the CNS. The projections from the cerebellar cortex to the DCN are structured such that projections from the vermis are directed towards the fastigial nuclei, the paravermal regions of the hemispheres project to the interposed nuclei while the cortex in the lateral hemispheres project to the dentate nuclei (Manto & Oulad Ben Taib, 2010). Subsequently, the DCN transmit projections to the cerebral cortex through the thalamus and to the spinal cord via nuclei in the brainstem. These connections form closed-loop circuits between the cerebellum, spinal cord, and cerebral cortex. For example, the cerebellum projects information to sensorimotor cortices via the thalamus, and reciprocally, these cortical areas relay inputs back to the cerebellum through the pons (Manto & Oulad Ben Taib, 2010). These intricate anatomical connections within the cerebellum form the foundation of its functional topography, where

distinct cerebellar regions process information originating from diverse zones of the cerebral cortex and spinal cord.

2.3 Functional Anatomy of Cerebellum

There are three major functional divisions of the cerebellum which are differentiated by the types of input they receive from different regions. The vestibulocerebellum receives input from the vestibular labyrinth. The flocculonodular lobe is a critical component of the vestibulocerebellum and sends output signals to the vestibular nuclei located in the brain stem (Amore et al., 2021). It plays a crucial role in the integration of sensory information from the vestibular system, which contributes to balance control, coordination of eye movements, postural adjustments, and regulation of the vestibulo-ocular reflex (Amore et al., 2021). The spinocerebellum consists of the vermis and the intermediate zones of the cerebellar cortex, as well as the fastigial and interposed nuclei (Amore et al., 2021). It receives major inputs from the spinocerebellar tract. Its output projects to rubrospinal, vestibulospinal, and reticulospinal tracts. It is involved in the integration of sensory input with motor commands to produce adaptive motor coordination (Amore et al., 2021). The cerebrocerebellum is the largest functional subdivision of the cerebellum and consists of the lateral hemispheres of the anterior and posterior lobe and the dentate nuclei (Amore et al., 2021). The major input to this region originates in the contralateral cerebral cortex and forms connections to the cerebellum via the pontine nuclei (Stoodley & Schmahmann, 2009). The output projects from the dentate nuclei to the cerebrum via the thalamus. Functionally, the cerebrocerebellum is involved in planning movements and motor learning along with regulating coordination of muscle activation and visually guided movements (Manto et al., 2011). However, emerging evidence shows that input projections to the cerebellum via the pons is from several cerebral areas, including regions involved in

cognition and not just primary motor and motor association areas (Klein et al., 2016). Similarly, there is research to support presence of quite extensive output connections between DCN and the cerebral cortical area involved in cognitive functions (Heck et al., 2023).

2.4 Functional Connectivity of Cerebellum

Anatomical investigations in animal models and post-mortem human brains have established contralateral cerebro-cerebellar connections to each other which form the efferent cerebello-thalamo-cortical (CTC) and afferent cortico-ponto-cerebellar (CPC) pathways (Palesi et al., 2015; Palesi et al., 2017). These pathways form the functional connectivity between the cerebellum and cerebrum. Although there is a lack of comprehensive understanding of these network models, it is proposed that this connectivity facilitates the cerebellum's role in coordinating motor functions, sensory integration, and cognitive processes (Palesi et al., 2015; Palesi et al., 2017; Heck et al., 2023).

Anatomical and tracing studies about the CPC pathway have provided evidence showing projections to the pons from several cerebral areas and not just primary motor and motor association areas. According to Palesi and colleagues, major neural contributions to the CPC pathway originated from frontal cortex including motor areas, Broca's area, and frontal eye fields (FEF). However, 9% of the contributions were from the parietal lobe whereas 8% of the CPC connections stems from the prefrontal cortex. Thus, these results align with evidence from magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI) studies which have shown connections to the cerebellum from cognitive areas such as the prefrontal cortex and association cortices through the CPC pathway. As the parietal lobe is involved in tasks such as creation of cross-modal sensorial representations of objects, the result of the study supports the idea of cerebellar influences on such processes (Palesi et al., 2017). Furthermore,

evidence from mapping studies has highlighted bidirectional connections between the prefrontal cortex and the parietal cortex to the cerebellum (Ramnani, 2011).

As traditional views associate the cerebellum with exclusively sensorimotor and vestibular functions, the output CTC pathway from the cerebellum to thalamus was thought to be limited to the ventral or motor thalamus such as the contralateral ventrolateral thalamic nuclei, parvocellular red nucleus and parts of the ventral anterior nuclei (Palesi et al., 2017). However, recent tracing studies have shown quite extensive connections between the DCN and the thalamus, including thalamic nuclei involved in cognitive functions (Heck et al., 2023). To this end, studies using trans-synaptic tracing methods have shown DCN projections to MD, centrolateral nuclei and zona incerta (Pisano et al., 2021). Retrograde tracing studies have also found axons in the thalamic reticular nucleus (TRN) originating from the dentate nuclei (Pisano et al., 2021). Hence, the presence of these CPC and CTC pathways which connect the cerebellum with motor areas, non-motor association areas and paralimbic regions of the cerebrum provides compelling evidence for the widespread role of the cerebellum beyond motor functions.

The cerebellar functional laterality refers to the concept that each hemisphere of the cerebellum is associated with specialized roles in specific aspects of motor control and cognitive function (Starowicz-Filip et al., 2021). According to a study conducted on cerebellar stroke patients, it was observed that individuals did not suffer from motor deficits only (Schmahmann et al., 2009). These results led to the conclusion that the contralateral connections between the cerebellum and the cerebrum through the CTC pathway are functionally isolated (Schmahmann et al., 2009). Furthermore, in a study conducted on cerebellar lesion patients to assess the pattern of cognitive functions, it was observed that individuals suffering from right cerebellar lesions presented with a general deficit of cognitive functioning (Starowicz-Filip et al., 2021). This

included deficits in language and verbal fluency subscales and all Addenbrooke's Cognitive Examination III domains, including memory, attention, and visuospatial functions. However, patients suffering from left cerebellar lesions demonstrated only loss of visuospatial functions but not in language, memory, or attention (Starowicz-Filip et al., 2021). These findings provide a foundation for the presence of functional laterization in the cerebellum.

2.5 Current View of the Cerebellum in Non-motor Functions

One of the main questions posed in the literature is whether the cerebellum influences non-motor functions. This was initially addressed by Schmahmann and Sherman on cerebellar cognitive affective syndrome (CCAS) which is a condition that follows from lesions in the cerebellum (Schmahmann & Sherman, 1998). In this study, a variety of assessments involving neurological examinations, bedside evaluations of mental state, neuropsychological analyses, and anatomical neuroimaging were performed on 20 patients with specific cerebellar diseases. It was observed that individuals suffering from lesions affecting the posterior lobe of the cerebellum and the vermis exhibited impairment of executive functions. These included deficits in planning, verbal fluency, abstract reasoning and working memory. However, patients with lesions in the anterior lobe of the cerebellum experienced only minor modifications in executive and visual-spatial functions. Hence, it was concluded that these patterns of deficits suggest an interference with the cerebellum's modulation of neural circuits associated with cognitive functions.

A study conducted by Arasanj and co-workers, utilized continuous theta burst stimulation (cTBS) protocols to understand whether the cerebellum was involved in executive control of word generation using a phonemic and semantic fluency task (Arasanj et al., 2012a). Their results indicated that transient inhibition of the right posterior-lateral cerebellar hemisphere led to a significant decrease in the number of category switches during a word generation task.

Furthermore, neuroimaging studies have observed activation of the right lobule VI and Crus I/II during word generation (Stoodley & Schmahmann, 2009). Hence, it is theorized that the cerebellum plays a role in cognitively demanding tasks such as word generation and category switching (Arasanz et al., 2012a). This shows the involvement of the cerebellum in higher-order attentional processes.

One subtype of memory is working memory which is the ability to retain, process and analyze small amounts of information presented to convert it into a decision (Cowan, 2014). Previous research has identified the role of the cerebellum in working memory and decision-making tasks. For example, a transcranial magnetic stimulation (TMS) study utilizing a visual sequence task was performed to understand the influence of the cerebellum on short-term memory (Ferrari et al., 2018). The results demonstrated that TMS over the right cerebellar hemisphere impaired the participants' capacity to memorize and recall the order of appearance of a series of geometric shapes (Ferrari et al., 2018). Furthermore, during the process of decision-making, the brain must effectively and quickly convert sensory stimuli to goal-oriented behaviours. To determine if and how the cerebellum might influence this process, a novel evidence-accumulation task in mice was performed (Deverett et al., 2018). The results demonstrated inactivation of the lateral posterior cerebellum led to a reduction in the fraction of correct trials (Deverett et al., 2018). These results further enhance the notion of cerebellar involvement in higher order cognitive tasks which depend on accurate selection and processing of information.

2.6 Cross-modal Integration between Vision and Touch

Multisensory integration refers to the process whereby relevant stimuli presented in different sensory modalities are combined and integrated to form a unified sensory experience.

Furthermore, in cross-modal sensory processing, a stimulus in one sensory modality can influence the processing of another stimulus present in a different modality (Adams et al., 2017). This is termed as cross-modal integration and leads to a unique cortical response contrary to the case of a unimodal response.

A set of principles is commonly used in the literature to evaluate whether a specific neural activity can be classified as sensory integration. The first principle is related to spatial coincidence. For multisensory neurons, the receptive fields of the different modalities usually overlap and only stimuli falling within this overlap lead to an enhanced response (Stein & Rowland, 2011). The second principle is related to temporal coincidence. Only stimuli that occur in close temporal proximity (temporal binding window) cause response enhancement and stimuli that are well separated in time elicit their normal unimodal response (Stein & Rowland, 2011). The third principal deals with the concept of inverse effectiveness. It states that stimuli that individually elicit strong responses cause little cross-modal integration, while stimuli that elicit weak responses can cause strong interactions when presented simultaneously (Stein et al., 2009).

Recent work has indicated that multisensory integration can occur at various stages of the information processing stream (Talsma et al., 2010). Moreover, it can be modulated by cognitive mechanisms such as selective attention (Talsma et al., 2010). Selection can occur in a bottom-up manner which depends on the saliency of a stimulus. This has the potential to drive attentional shifts without conscious awareness. Selection can also occur in a top-down manner which is dependent on the relevance of the stimuli relating to the goals and intentions of the individual (Talsma et al., 2010). Sensory stimuli presented in different sensory modalities which are spatially and temporally aligned have a higher probability of capturing one's attention, which suggests that attention-related processes tend to orient towards stimuli that consist of

multisensory properties (Talsma et al., 2010). This framework provides a foundation for the relationship between attention and multisensory integration.

The encoding of visual and tactile stimuli displays similarities in their stimulus processing mechanisms (Lacey & Sathian, 2015). According to studies conducted in macaques, single neurons in visual (V4) and somatosensory (S2) cortex undergoing intermediate stimulus processing demonstrate similar tuning for curvature direction (Yau et al., 2009). This suggests that both modalities utilize analogous spatiotemporal coding strategies, thus offer a basis for the integration of multisensory inputs (Lacey & Sathian, 2015). Further evidence for this integration comes from studies in which the orientation of a tactile grating can resolve perceptual conflicts during binocular rivalry (Lunghi et al., 2010). In macaques, neurons within the ventral intraparietal areas (VIP) demonstrate response modulation to bimodal stimuli, even when their individual responses are limited to either visual or tactile stimuli (Avillac et al., 2007). In humans, the VIP homolog shows consistent topographic mappings for tactile and visual stimuli (Serenio & Huang, 2006). Interestingly, maximal cross-modal convergence evokes an inverse effectiveness pattern in human brain regions, especially in the lateral occipital complex and intraparietal sulcus (IPS) (Lacey & Sathian, 2015). According to TMS studies, repetitive TMS stimulation over the left anterior IPS disrupts visual-tactile shape matching using the right hand (Buelte et al., 2008). Collectively, these findings indicate the integration of visual and tactile information both behaviourally and anatomically.

2.7 Attention and Attentional Networks

Attention is a sum of various perceptual and cognitive mechanisms aimed at correctly allocating processing resources to relevant stimuli (Talsma et al., 2010). The need for attentional control is crucial for accurate execution of daily movement and behaviours (Esterman et al.,

2017). The dorsal fronto-parietal network also known as the dorsal attentional network (DAN) is a neural network which plays a crucial role in attentional control and cognitive processes related to goal-directed behavior and working memory (Brissenden et al., 2016). Research has shown the significance of this network in directing attention to relevant stimuli while filtering out distractors (Brissenden et al., 2016). Anatomically, the dorsal fronto-parietal network is comprised of regions primarily located in the frontal and parietal lobes. The frontal regions include the superior frontal gyrus and FEF (Brissenden et al., 2016). These areas are important for initiating and guiding attention (Brissenden et al., 2016). The parietal regions include the IPS and the superior parietal lobule, which are responsible for spatial processing, attentional shifts, and integrating sensory information (Brissenden et al., 2016).

Anatomical and physiological studies have provided corroborating evidence which suggests that communication between the high-order cortical areas such as the prefrontal cortex and the thalamus is important in attentional control and focus, especially during a complex task (Zikopoulos & Barbas, 2007). The current framework suggests that connections from the thalamus to the cortex can originate from the first-order thalamic nuclei as well as higher order thalamic nuclei. Information that must be relayed from the ascending pathways to the cortex involve first-order thalamic nuclei whereas the high-order thalamic nuclei play a role in the transmission of cortical-to-cortical information. One such example is the reciprocal projections between MD and TRN. MD is classified as a higher-order thalamic relay nucleus and 3D mapping studies have revealed an overlap between TRN neurons that project to MD and projections from dorsal area 46, which is involved in attention, working memory and polymodal association areas (Zikopoulos & Barbas, 2007). Furthermore, increased activity in networks connecting MD with area 46 have been observed in primates when they are required to internally

hold information to solve complex task (Funahashi & Takeda, 2002). Thus, these individual connections provide a potential framework for how the cerebellum can influence attentional networks.

A connection between the cerebellum and attention has started to emerge through various studies. Specifically, attentional deficits have been associated with abnormalities present in cerebellar morphology in patients suffering from cerebellar neurodegenerative disorders (Lupo et al., 2018). Furthermore, results from fMRI studies have indicated cerebellar and parietal influence on attention, particularly in coordinating attentional shifts and selective attention (Le et al., 1998). Lastly, data collected from non-invasive stimulation studies using the Attention Network Test demonstrated that the cerebellum influences the functioning of the executive attention network (Mannarelli et al., 2019). Thus, evidence from these studies provides a framework for the presence of cerebellar influence on attentional networks.

2.8 Research Methods

2.8.1 Attentional Blink

An attentional blink (AB) can be measured by recording the accuracy in the reporting of a second target (T2) when two targets are presented closely in time (200-500ms) at the cost of detecting and reporting the first target (Soto-Faraco et al., 2002). There are multiple frameworks which aim to explain the underlying mechanisms of AB.

One idea is related to the limited processing capacity which suggests that the occurrence of AB is related to transient interference between T1 and T2 processing (Martens & Wyble, 2010). When attention is required to process two relevant stimuli presented in close temporal proximity, attending to, and processing the first target can lead to delayed processing of the second target (Martens & Wyble, 2010). This is because T2 must wait to access a central

‘processor’ and during this wait time, the associated impulse is subject to degradation (Martens & Wyble, 2010). Thus, there is a cost of selectively attending to T1 which can interfere in the accurate processing of T2 and potentially lead to the stored representations of T2 to degrade and be unavailable for recall.

Studies using cross-modal AB task between vision and touch have proposed that visual and tactile stimuli compete for a common limited capacity processor (Soto-Faraco et al., 2002). Furthermore, event-related potential (ERP) data from electroencephalography (EEG) and visual AB studies have concluded that when a T2 is presented within a short interval after T1, it produces a normal pattern of neural correlates for at least the first 150ms of perceptual processing (Vogel et al., 1998). This is represented in the P1 and N1 components (Vogel et al., 1998). However, the ERP analyses associated with these studies exhibit a complete absence of the P300 ERP component (generally considered to reflect updates in working memory and attention). These results suggest that AB is associated with a deficit in the post-perceptual stages of information processing (Luck et al., 1996; Vogel et al., 1998; Vogel and Luck, 2002). Moreover, fMRI and EEG studies have been used to demonstrate that networks distributed across occipital, parietal, and frontal regions are involved in AB (Martens & Wyble, 2010). Specifically, reduced activity has been observed in the fronto-parietal cortex when T2 cannot be reported (Williams et al., 2008). Clinical evidence from lesion studies concluded individuals with lesions in the right inferior parietal cortex and lateral frontal cortex show a greater and enhanced AB effect (Husain and Rorden, 2003). In addition, TMS studies have indicated the involvement of IPS in visual AB due to its involvement in allocating visual attentional resources and directing attention for target reporting (Kihara et al., 2007).

Thus, the significance of using an AB experimental paradigm is that it can be viewed as a method to study the availability of attention across time. We believe that employing this technique will allow us to assess whether the cerebellum may be necessary for efficient and quick attentional shifts which are imperative for cross-modal integration.

2.8.2 Theta Burst Stimulation

Theta burst stimulation (TBS) is a pattern of TMS in the theta frequency range (around 5-7 Hz). The process involves delivering bursts of magnetic pulses to the different regions of the brain. One classification of TBS is continuous theta burst stimulation (cTBS). During cTBS, bursts of three stimuli are administered at 50 Hz and repeated at 5 Hz (theta frequency) for 40 seconds which amounts to a total of 600 pulses.

The neurophysiological mechanism of cTBS can be compared to long-term depression (LTD) (Barr et al., 1995; Di Lazzaro et al., 2011). This form of stimulation leads to transient depression of the cortical area which can then change the activity of an associated distributed network (Di Lazzaro et al., 2011). The benefit of this non-invasive brain technique is that it allows investigators to study the interactions between different cortical areas and understand the influence of the artificially depressed cortical areas on specific tasks. In the context of the cerebellum, it is conjectured that cTBS will result in a suppression of inhibitory GABAergic interneurons within the molecular layer of the cerebellum (Piochon et al., 2010). This will result in a reduction in the inhibition of Purkinje cells which would lead to an increase in their inhibitory output to DCN (Piochon et al., 2010). This increase in inhibition reduces the excitatory output of DCN to the thalamus and eventually the cerebral cortex.

Recent work has adopted the use of cTBS over the cerebellar cortex to better understand its influences on distal cortical networks. Studies have shown that cTBS over the right posterior-

lateral cerebellum decreases performance during a word generation task (Arasanz et al., 2012a). Furthermore, cTBS over the same area also leads to a decrease in accuracy when reporting the second target in a visual AB task when the two targets are presented within short time intervals (Arasanz et al., 2012b). Thus, TMS has been an effective tool to study the pattern of connectivity between the contralateral cerebral cortex and the cerebellum.

3. Rationale

The role of selection in attentional control is crucial for efficient information processing of relevant stimuli. Furthermore, Talsma and colleagues, recently put forward a framework to explain the influence of attentional control and selection in cross modal integration (Talsma et al., 2010). The role of attention in multimodal integration is dependent on the level of conflict between the interacting sensory modalities. In cases where there is minimal or no competition between multimodal stimuli, such as when tasks are simple or when one modality presents a highly salient stimulus that automatically captures attention, multisensory integration takes place effortlessly (Talsma et al., 2010). When stimuli from different modalities possess equal saliency, the processing and integration of information are influenced by attentional modulation due to an increase in cognitive load and limited structural and processing capacity (Talsma et al., 2010). Effective integration only occurs when observers' selective attention is directed towards the multimodal event. Furthermore, cross modal AB studies between vision and touch have demonstrated that AB is observed when visual stimulus is preceded by tactile stimulus and not vice versa (Soto-Faraco et al., 2002). This is because although the stimuli in the experiment are designed to be equally salient, the visual system naturally tends to be more dominant. This inherent salience means that visual stimuli more effectively capture and hold attentional resources compared to tactile stimuli (Soto-Faraco et al., 2002).

Current research has provided evidence for the involvement of cerebellar activity in rapid attentional shifts between attended visual stimuli (Arasanz et al., 2012a; Esterman et al., 2017). Anatomical and functional connectivity studies have also shown the presence of cerebellar nodes within the fronto-parietal attentional network (Brissenden et al., 2016). TMS studies coupled with visual AB tasks have demonstrated that transient inhibition of the right cerebellar hemisphere enhances visual AB, whereas stimulation over the left cerebellar hemisphere does not (Arasanz et al., 2012b). It has also been shown that transient excitation of the cerebellar nodes through intermittent theta burst stimulation (iTBS) protocols reduces the number of errors post-iTBS compared to the baseline (Esterman et al., 2017). However, it is not clear whether the cerebellum impacts sensory processing when presented with two relevant targets in different sensory modalities compared to the unimodal condition investigated in previous studies.

Thus, the aim of this study is to understand whether the cerebellum influences the fronto-parietal attentional networks during sensory processing of stimuli from different modalities. Specifically, does the transient inhibition of the cerebellum influence the attentional selection process of a stimulus in one modality, leading to a greater temporal interference in the ability to select a subsequent stimulus in another modality when presented in short intervals of time? Lastly, another research goal is to isolate the relevant cerebellar functional domains contributing to rapid attentional shifts during cross-modal integration of information between vision and touch. This will be examined by having the participants perform a cross-modal attentional blink task pre and post-cTBS to the left and right cerebellar hemispheres. We expect that the behavioural outputs will reflect the potential modulatory activity of the cerebellum on attentional networks.

4. Objective and Hypothesis

The main objective of this study is to understand whether the attentional selection of a stimulus in one modality leads to a temporal interference in the ability to select a subsequent stimulus in another modality. Furthermore, we aim to investigate whether the cerebellum influences attentional control during the sensory processing of stimuli from different modalities. Finally, we also seek to isolate the relevant cerebellar functional domains contributing to cross-modal AB. This will also allow us to assess whether lateralization of function is preserved within the cerebellum and cerebrum.

Hypothesis 1.1: We hypothesize that if attentional selection of the first target (T1) stimulus present in one sensory modality leads to a temporal interference in the ability to select the next target (T2) in a different modality, this would lead to a decrease in accurately reporting T2. This would be prevalent in trials when the visual target precedes the vibrotactile target within short time intervals (less than 500ms). Lastly, there should be no change in attentional blink performance pre-cTBS, regardless of whether cTBS is administered to the left or the right cerebellar hemisphere.

Hypothesis 1.2: We hypothesize that cTBS to the posterior right lateral cerebellum should enhance cross-modal AB in which the attended visual targets precede vibrotactile targets. This would result in a lower accuracy rate in reporting the second tactile target (T2) when it follows a visual target (T1) and is separated by a short time interval (<500ms). However, there should be no significant difference in T2 detection rates when cTBS is applied to the left lateral cerebellum compared to the baseline. This would also serve as an active control since evidence shows less association and influence of the left cerebellar hemisphere on AB performance.

5. Methods

5.1 Participants

Twenty-nine healthy participants (13 males and 16 females; mean age $\pm$ SD = 23 $\pm$ 3.6), with no history of neurological deficits, pathologies, or allergies to electrodes or adhesive gels, were recruited to participate in the study. Furthermore, they had no sensory or motor deficits. Three participants were excluded from the final analysis due to specific issues: one participant did not understand the instructions for the behavioral task, the other had an accuracy of less than 50% on baseline and control trials and for the last individual, we could not establish a satisfactory motor threshold. Therefore, the analysis included 26 participants (13 males and 13 females; mean age $\pm$ SD = 23 $\pm$ 3.6), of whom 24 were right-hand dominant and 2 were left-hand dominant.

The screening selected individuals with normal or corrected-to-normal vision. Each participant signed a consent form before the start of the experiment. Once written consent was obtained, the participants completed a TMS Safety Checklist Form to ensure they were eligible for the TMS study. Additionally, they completed the University of Waterloo Health History Questionnaire to record any history of concussions and exclude those currently experiencing concussion symptoms. Finally, the participants completed the Edinburgh Handedness Questionnaire to assess hand dominance.

5.2 Apparatus, Materials & Stimuli

A custom-made visuo-tactile device with two red LED lights and two vibrotactile sensors was used to deliver the stimuli (Figure 1). The experimental protocol was programmed using LabVIEW, which controlled the delivery and timing of the stimuli (National Instruments, Austin,

Texas, USA). The questions and fixation point appeared on a Dell color monitor, and participants recorded their responses using a mouse which acted as the response device. White noise was provided through headphones via Stim 2 to mask the noise from the vibrotactile sensors (Stim2, Compumedics Neuroscan, 2020).

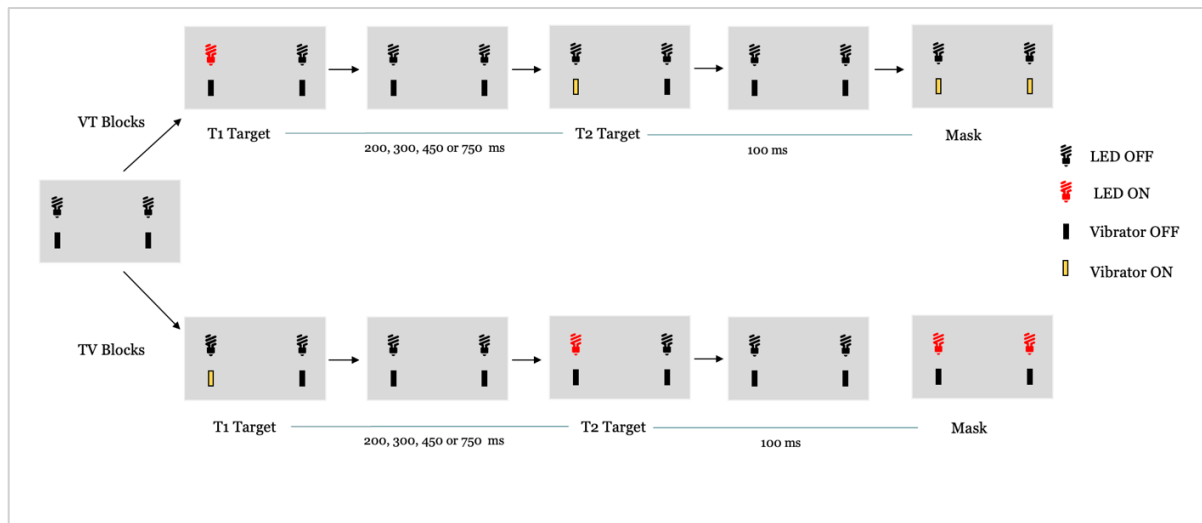


Figure 1. Temporal sequence of stimuli: The diagram displays the temporal sequence of VT (up) and TV (bottom) stimuli during a trial. Each box represents a configuration of LEDs and vibrators. Each trial started with the LEDs (black) and vibrators (black) turned off. Red LEDs and yellow vibrators indicate that they were activated.

As depicted in Figure 1, each trial started with both vibrators and LED lights switched off. This was followed by one of the LED lights turning on visual T1 and tactile T2 (VT condition) for approximately 18ms and then turning off. After a lag of either 200, 300, 450, or 750ms, one of the vibrators turned on for 35ms and then turned off. After 100ms, both vibrators switched on as part of the masking condition. Finally, both vibrators switched off, and the participant was prompted to answer questions relating to T1 and T2. Conversely, in the tactile T1, and visual T2 (TV condition), the trial began with both vibrators and LED lights switched off. This was followed by one of the vibrators turning on for 35ms and then turning off. After a lag of either 200, 300, 450, or 750ms, one of the LED lights turned on for 18ms and then turned off. Lastly, to

induce the visual mask, both LED lights switched 100ms after T2 and then switched off, followed by questions relating to T1 and T2 as explained below.

5.3 Experimental Design

The study adopted a repeated measures design with the following independent variables: Session (cTBS left, cTBS right), Time (pre-cTBS, post-cTBS), Block type (VT and TV), and ISI (200, 300, 450 and 750ms).

Each participant took part in two sessions administered in a randomized and counter-balanced order. In one session (experimental session), individuals received cTBS to the right posterior lateral cerebellum, whereas during the other session (active control session), they received cTBS to the left posterior lateral cerebellum. The study used a cross-modal visuo-tactile paradigm in which a masked T2 was presented at variable ISIs.

All participants were presented with a total of 18 blocks throughout the experiment, with each block consisting of 64 experimental trials and 16 control trials for a total of 80 trials. The first 9 blocks were completed pre-cTBS, while the remaining 9 blocks were completed post-cTBS. The 9 blocks were broken down as follows and are displayed in Table 1:

1. 2 baseline blocks which consisted of unimodal stimuli, with each block exclusively featuring either visual or tactile stimuli. One of the two blocks consisted of 20 trials where only the visual stimulus was presented, while the other block included 20 trials with only tactile stimulus presented. These stimuli were masked meaning that if the target stimulus was visual, both lights were switched on simultaneously 100ms after the target stimulus was administered. Similarly, if the target stimulus was tactile, both vibrotactile sensors were activated concurrently 100ms after the target tactile stimulation as part of the masking protocol. The purpose of these baseline blocks was to assess participants' proficiency in

extracting the relevant T2 target from the mask. This assessment was crucial for understanding participants' perceptual capabilities and AB performance in subsequent experimental conditions.

2. 3 experimental blocks in which the visual stimulus (T1) preceded the tactile stimulus (T2) separated by variable ISI values of 200, 300, 450, or 750ms. The two stimuli were presented in four possible modality combinations: visual-tactile stimuli on the left side (VTL), visual-tactile stimuli on the right side (VTR), visual stimulus on the left and tactile stimulus on the right (VLTR), or visual stimulus on the right and tactile stimulus on the left (VRTL). The ISI variable was randomly selected for each trial in a single block with the constraint that each of the 4 possible combinations of factors occurred 16 times for each ISI value in every block (64 trials). In each block, 16 additional trials served as controls in which the participants were only presented with either T1 (8 trials) or T2 (8 masked trials). The T1 control trials acted as 'catch' trials to ensure that individuals were engaged in the task and were reporting stimulus location to the best of their understanding rather than randomly pressing the response buttons. In total each block consisted of 80 trials.
3. 1 experimental block in which the visual stimulus (T1) preceded the tactile stimulus (T2) separated by variable ISI values of 200 or 750ms only. The stimuli were randomly presented in four possible combinations: VTL, VTR, VLTR, or VRTL. The purpose of this block was to maximize the number of trials that could be used for relevant ERP extraction.
4. 3 experimental blocks in which the tactile stimulus (T1) preceded the visual stimulus (T2) separated by variable ISI values of 200, 300, 450, or 750ms. The two stimuli were presented in four possible combinations: tactile-visual stimuli on the left (TVL), tactile-visual stimuli on the right (TVR), tactile stimulus on the left and visual stimulus on the right (TLVR), or

tactile stimulus on the right and visual stimulus on the left (TRVL). The ISI variable was randomly selected for each trial in a single block with the constraint that 4 possible combinations of factors occurred 16 times for each ISI value in every block (64 trials). In each block, 16 additional trials served as controls in which the participants were only presented with either T1 or T2. In total each block consisted of 80 trials.

<i>Block Repeats</i>	<i>Stimulus Order</i>	<i>ISI (ms)</i>	<i>Modality Combination</i>	<i>Experimental Trials</i>	<i>Control Trials</i>
1	VT (Baseline)	NA	TR or TL followed by masking	20	NA
1	TV (Baseline)	NA	VL or VR followed by masking	20	NA
3	VT	200, 300, 450, 750	VTL, VTR, VLTR, VRTL	64	16
1	VT	200, 750	VTL, VTR, VLTR, VRTL	80	NA
3	TV	200, 300, 450, 750	TVL, TVR, TLVR, TRVL	64	16

Table 1. Overview of stimuli frequency and combination: In the experiment, each block type (VT and TV) contained stimuli presented in four modality combinations, separated by four ISI values. These also included additional control trials, which served as catch trials. Baseline blocks consisted solely of unimodal stimulus targets followed by a mask of the same modality. Each participant completed 9 blocks before stimulation and 9 blocks after stimulation, totaling 18 blocks.

After the completion of each trial, the participants answered two questions. The first question pertained to the T1 stimulus in which the individuals had to indicate the side on which they saw the light blink (VT block) or the side on which they felt the vibration (TV block) by pressing either the left or right button on the response device. Following their response, they were presented with the second question in relation to (T2) where they had to indicate the side on which they either saw the light (TV block) or felt the vibration (VT block) depending on the experimental conditions by pressing either the left or right button on the mouse. For the

experimental control trial questions where participants only received either the T1 or T2 stimulus, they were asked to indicate the side on which they saw/felt the stimulus. Similarly, during the baseline control trials where participants only received unimodal masked stimuli, they were also asked to indicate the side on which they saw/felt the stimulus. The presentation of experimental and baseline blocks was randomized.

5.4 Experimental Protocols

5.4.1 Active Motor Threshold (AMT) Protocol

The Active Motor Threshold (AMT) Protocol was implemented to establish the AMT. The index finger of the dominant hand was prepped along with the ulnar styloid of the same wrist as the ground. These areas were prepped by using abrasive gel and alcohol to clean and remove any unwanted particles. Subsequently, two surface electromyographic (EMG) electrodes were attached over the first dorsal interossei (FDI) muscle and one over the ulnar styloid. The AMT value was then established using the MagPro R30 stimulator (MagVenture, GA, USA) and the MCF-B65 coil. The coil was placed over the scalp's upper left or right surface (depending on hand dominance) to find the optimal position of the primary motor cortex to evoke a motor threshold potential (MEPs) FDI. The MEP was established when the MEP value was greater than 200 μ V in the muscle in 5 out of 10 consecutive trials while maintaining a 10% isometric contraction.

5.4.2 cTBS Protocol

The cTBS Protocol was administered using the MagPro R30 stimulator (MagVenture, GA, USA) and the MCF-B65 coil. The participant was seated with their head resting on the table in a U-shaped pillow, and the arm of the coil was positioned such that it was in the correct

location for the duration of the stimulation. During cTBS, bursts of three stimuli were administered at 50 Hz and repeated at 5 Hz (theta frequency) for 40 seconds, amounting to 600 pulses (Huang et al., 2007). The intensity of the stimulation was set at 80% of the active motor threshold of the participant. To stimulate the right lateral cerebellar hemisphere, the center of the TMS coil was placed 1 cm below and 3 cm lateral to the right of the inion. To stimulate the left lateral cerebellar hemisphere, the center of the coil was placed 1 cm below and 3 cm lateral to the left of the inion (Arasanz et al., 2012b)

5.5 Procedure

Each session began by establishing the motor threshold of the participant using the AMT protocol. This was followed by preparing a 32-channel electroencephalography (EEG) cap on the individual before the start of the behavioural task. The cap was placed on the participant's head, and the conductive gel was inserted into each electrode using a syringe to decrease the impedance between the recording electrodes and the living skin tissue (to ensure noise reduction in the recordings). The cap preparation was completed once each electrode had an impedance value of ≤ 5 k Ω . To measure electrical activity, data was recorded using a 32-channel EEG cap (Quick-Cap, Neuroscan 2, Compumedics, NC USA).

The participant was then seated in a dim-lit section of the lab with the device and computer monitor placed within their spatial frame of reference as shown in Figure 2. During the trials, the participants received white noise at an intensity sufficient to mask the sound of the vibrators. They were instructed to place the second digit and fifth digit of their left hand onto the vibrotactile sensors while placing their right hand onto the response device as represented in Figure 2. Secondly, they were instructed to look at the fixation point represented by a rectangular symbol on the screen next to their left hand. This arrangement ensured that both stimuli were

represented in the same cerebellar hemisphere due to their spatial alignment. Before the start of the experiment, the participants were provided with a series of instructions on how to use the mouse to record responses when presented with the questions.

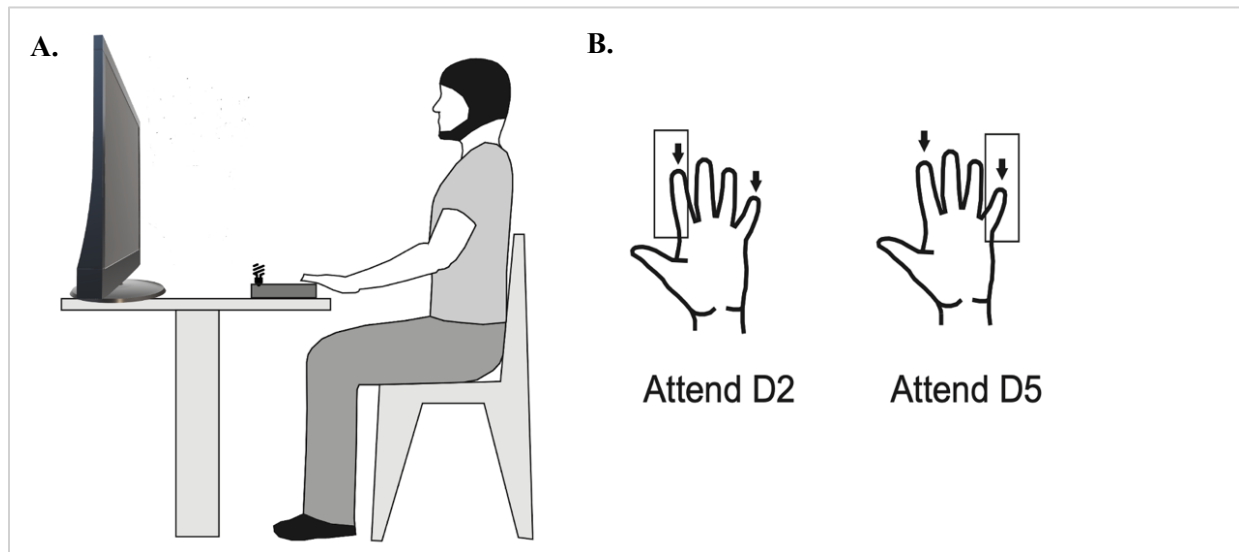


Figure 2. Experimental setup and paradigm: (A) Participants were seated in front of a monitor with the experimental and response devices. (B). Instructions were given for sensor placement: left-hand D2 and D5 to be placed on vibrotactile sensors.

This was followed by establishing stimuli intensities via thresholding. To determine the minimum level of stimulation needed to elicit a detectable response, the participant was exposed to gradually increasing intensities of the visual and tactile stimuli until they first perceived the stimulus. The initial detection points then represented the threshold for each type of stimulus. Furthermore, they were asked to identify the location of both targets on each trial, guessing if necessary. After completing the first 9 blocks with the inclusion of short breaks, the participant received cTBS to either the left or the right cerebellar hemisphere depending on the session. cTBS was administered according to the cTBS protocols discussed in section 5.4.2. Approximately 5-8 minutes post-cTBS, the participants re-performed the same behavioural task and paradigm as mentioned above. This concluded the first session, which lasted approximately 2–2.5 hours.

The participants were asked to return for the second session after a washout period of 5-7 days to avoid carry-over effects (Gamboa et al., 2010). During this session, step one was to establish the AMT followed by EEG cap preparation. The same behavioural task was then performed with the same set of instructions. After completing the first 9 blocks, the individual received cTBS either to the right or left lateral cerebellar hemisphere depending on the session. This was followed by performing the behavioural task for the remaining 9 blocks, ending the experimental procedure.

6. Behavioural Analysis

The behavioural data collected was processed using a custom-made Python script which takes the LabVIEW event codes from an experimental session and outputs a .csv file containing stimuli codes, response data, ISI values, and outcome classifications (no blink, blink, or T1 error). Error trials, where participants incorrectly responded to T1, were removed before analysis.

We analyzed the data by comparing the accuracy of reporting the second target (T2) in the presence of the first target (T1) at each ISI value and for each block type. These accuracy results will henceforth be called raw scores. T2 accuracy was calculated as the ratio of correct responses to total trials according to the following equation:

$$Accuracy (T_2) = \frac{N_{Correct}}{N_{Total}} \quad (1)$$

where $N_{Correct}$ is the number of trials where the participant correctly reported T2 and N_{Total} is the total number of trials.

To understand if there was a difference in the T2 recall rate at each ISI value in each block type pre-cTBS, and to ensure that the pre-cTBS performance was session agnostic, we

conducted a 3-way repeated measures analysis of variance (ANOVA) on raw scores. The within-subject factors were block type (VT/TV), ISI (200, 300, 450, and 750ms), and session (cTBS to the right hemisphere/cTBS to the left hemisphere). This analysis was performed in R, with statistical significance set at $p = 0.05$. To ensure that the assumptions of normality and homogeneity of variances were met, the Shapiro-Wilk test and Levene's test were conducted, respectively. Additionally, Mauchly's Test for sphericity was performed, and any observed violations were corrected using Huynh-Feldt Corrections.

We compared pre and post-cTBS accuracy for our experimental and control sessions to investigate the cerebellum's role in rapid cross-modal attentional shifts. Instead of using raw scores, we calculated a difference score (equation 2) to assess changes in AB performance. This correction was important due to the masking of all T2 stimuli. By subtracting baseline accuracy, we obtained a true representation of AB, allowing us to evaluate T2 reporting accuracy in the presence of T1 pre and post-cTBS for each ISI value without the confounding effect of masking. The difference score was determined using the following equation:

$$\Delta_{AB} = [(Pre_B - Pre_E) - (Pst_B - Pst_E)] \quad (2)$$

where Pre_B refers to the pre-cTBS baseline accuracy, Pre_E refers to pre-cTBS AB accuracy and Pst_B & Pst_E refer to post-cTBS baseline and experimental accuracy, respectively.

We conducted a three-way repeated measures ANOVA on the difference scores for the experimental trials, with within-subject factors of block type (VT/TV), ISI (200, 300, 450, and 750ms), and session (cTBS to the right hemisphere/cTBS to the left hemisphere) in R. Statistical significance was set at $p = 0.05$. The Shapiro-Wilk test and Levene's test were conducted to ensure the assumptions of normality and homogeneity of variances, respectively, were

maintained. Mauchly's Test for sphericity was also performed, and any observed violations were corrected using Huynh-Feldt corrections.

Additionally, the accuracy of extracting the target stimulus from the mask was assessed using equation 1. To determine whether there was a difference in extracting the target stimulus from the mask in baseline blocks before and after stimulation, we conducted pairwise t-tests. Furthermore, to ensure there was no difference in extracting the target in the baseline blocks before stimulation regardless of session, additional pairwise t-tests were conducted in R. Statistical significance was set at $p = 0.05$. Lastly, to assess the accuracy of detecting and reporting T1 control/catch trials, pairwise t-tests were conducted on the mean accuracy values pre- and post-cTBS. The ratio of accurate T1 control trials was assessed using a modified version of the equation 1:

$$Accuracy(T_1) = \frac{N_{Correct}}{N_{Total}} \quad (3)$$

7. Results

7.1 Pre-stimulation

Accuracy of detecting T2 (raw scores & AB condition): A 2 Block type x 2 Session x 4 ISI ANOVA of T2 accuracy was conducted. The test revealed no significant interaction or main effect involving session [$F_{1,25} = 0.65, p = 0.400, \eta p^2 = 0.028$]. Conversely, block type and ISI had a significant interaction effect [$F_{3,75} = 9.034, \epsilon = 0.82, p_{adj} < 0.001, \eta p^2 = 0.27$]. Thus, regardless of session, there was no difference in the individuals' ability to detect T2 at each ISI value for the two individual block types ([Appendix A](#)). However, post hoc analysis revealed a significant difference in the ability to detect T2 when it was either followed by a

visual or tactile stimulus at each ISI value regardless of the session ($p < 0.001$). These trends can be observed in Figure 3a and Figure 3b.

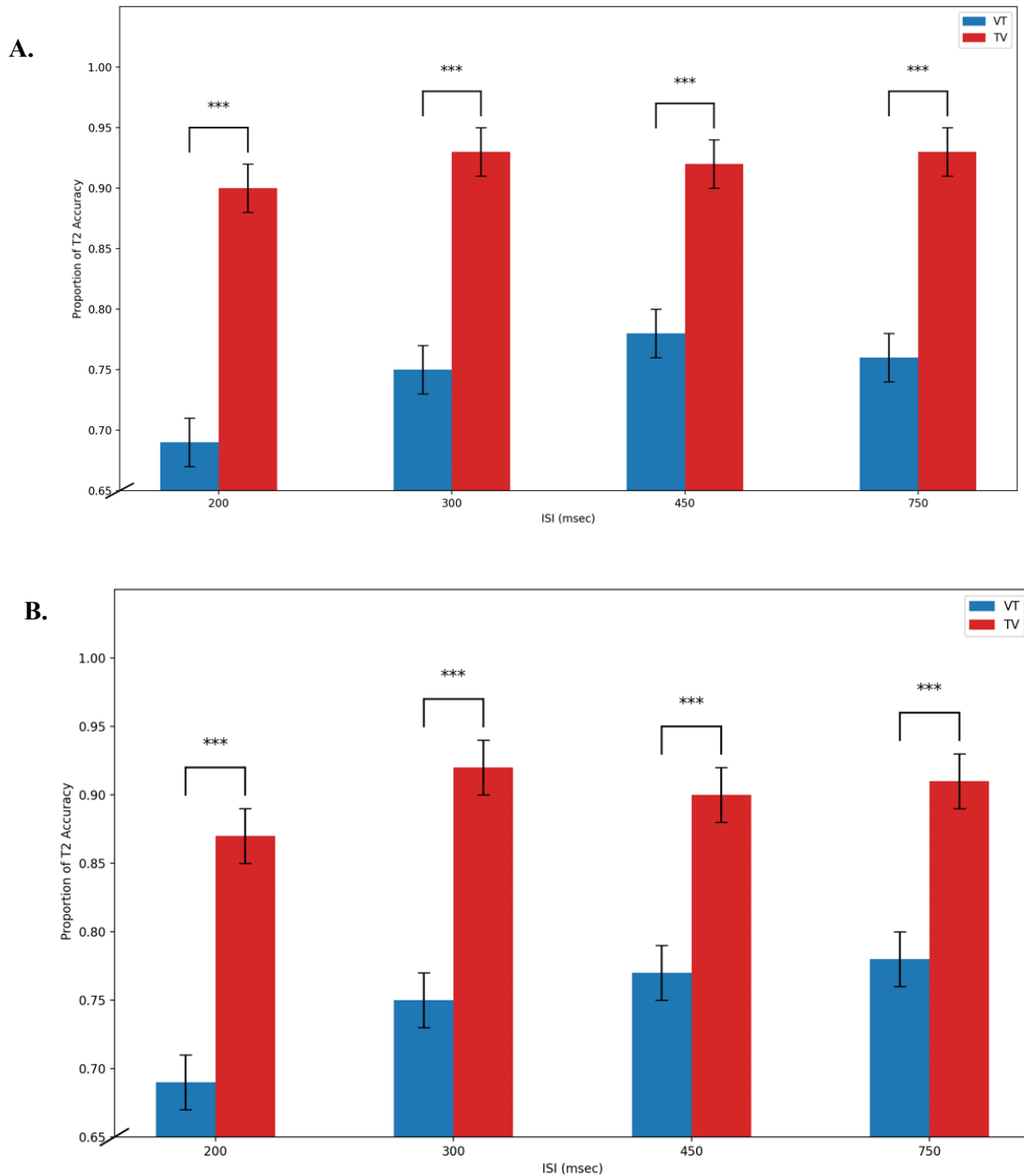


Figure 3. Attentional Blink Performance pre-cTBS: Figure (A). pre-right session. (B)pre-left session: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the VT (red) and TV (blue) condition before cTBS. There was a significant difference in performance between the two block types across all 4 ISI values. *** indicates $p < 0.001$. However, there was no significant difference in VT or TV performance pre-cTBS regardless of session.

Accuracy of detecting T2 from mask (baseline condition): For both sessions, individuals were engaged in extracting T2 from the mask. For both conditions, the t-tests indicated no significant difference between the means of the tactile or visual baseline values for the two sessions ($p_{tactile} = 0.55$ & $p_{visual} = 0.59$). See Table 2 for mean accuracy values.

	Tactile Right		Tactile Left		Visual Right		Visual Left	
	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>
Pre-stimulation	0.87	0.02	0.85	0.02	0.95	0.02	0.97	0.01
Post-stimulation	0.79	0.03	0.84	0.02	0.95	0.01	0.96	0.01

Table 2. Mean T2 Accuracy from Mask: Mean accuracy of T2 (tactile) and (visual) from the mask in baseline blocks before and after cTBS. SE denotes the standard error

Accuracy of detecting T1 (control condition): In each experimental block, participants were prompted to detect T1(either visual for VT blocks or tactile for TV blocks). The group accuracies for the control trials were high (Table 3), signifying that individuals were engaged in the task. The t-test results showed no significant difference in reporting T1 for the two different sessions within each block type ($p_{VT} = 0.34$ & $p_{TV} = 0.69$).

	VT Right		VT Left		TV Right		TV Left	
	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>	<i>Mean</i>	<i>SE</i>
Pre-stimulation	0.99	0.01	0.99	0.00	0.98	0.01	0.98	0.01
Post-stimulation	0.99	0.01	0.98	0.01	0.98	0.01	0.97	0.01

Table 3. Mean T1 Accuracy: Comparison of Mean accuracy of reporting T1 catch/control trials (visual in VT blocks) & (tactile in TV blocks) before and after cTBS. SE denotes the standard error.

7.2 Post-stimulation

Accuracy of detecting T2 (difference score & AB condition): A 2 Block type x 2 Session x 4 ISI ANOVA on change of scores revealed significant interaction effect between block type and ISI [$F_{3,75} = 2.76, \epsilon = 1.023, p_{adj} = 0.048, \eta^2 = 0.099$]. The analysis also revealed a significant interaction effect between block type and session [$F_{1,25} = 9.758, p = 0.004, \eta^2 = 0.281$]. To further explore the interactions observed and better understand how cerebellar

stimulation was impacting AB performance, two individual ANOVAs were conducted separated by session. For the right session, the ANOVA revealed a significant interaction between block type and ISI [$F_{3,75} = 4.81, \epsilon = 0.79, p_{adj} = 0.008, \eta p^2 = 0.16$] (Figure 4a). However, results from the left session showed no significant main or interaction effects as seen in Figure 5. Another set of ANOVAs separated by block type revealed that in the VT condition, there was a main effect of session [$F_{1,25} = 6.172, p = 0.02, \eta p^2 = 0.198$], whereas in the TV condition, there were no significant main or interaction effects as observed in Figure 4b and 5b. As observed in Figure 4a these findings suggest that after stimulation to the right lateral cerebellar hemisphere, there is a change in AB performance within the VT condition. However, it is interesting to note that within that experimental condition, there is also a decrease in the accuracy of extracting tactile T2 from the mask at baseline.

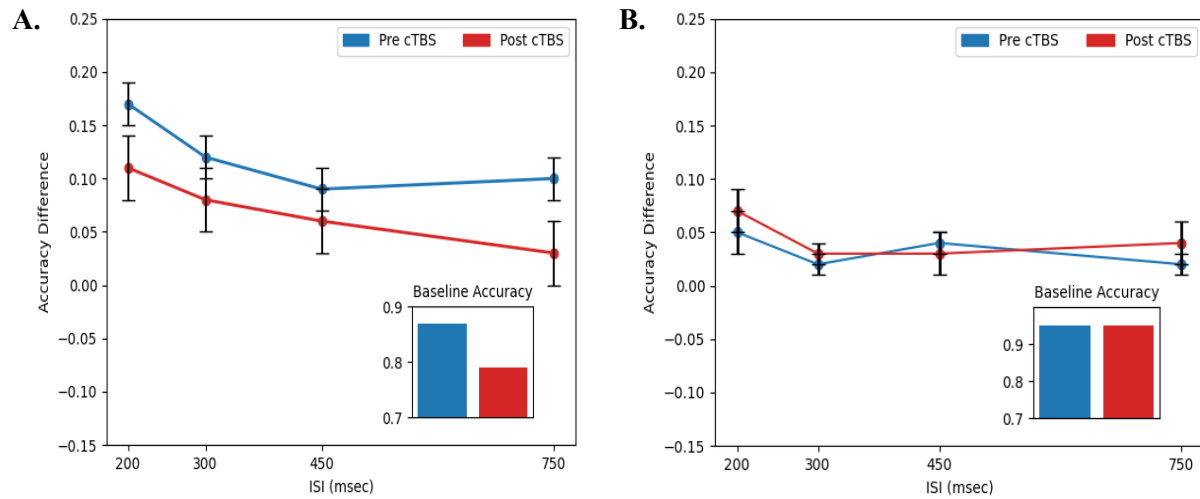


Figure 4. Right hemisphere cerebellar stimulation: (A). Performance (Change in AB $\pm$ S.E) pre vs post-cTBS in VT block type. T2 accuracy has been baseline corrected. An overall reduction in AB performance is observed. The subplot displays the extraction from the T2 from the mask only and there is a significant decrease in T2 extraction post-cTBS. (B). Performance (Change in AB $\pm$ S.E) pre vs post-cTBS in TV block type. There is no change in AB or T2 extraction pre and post-cTBS.

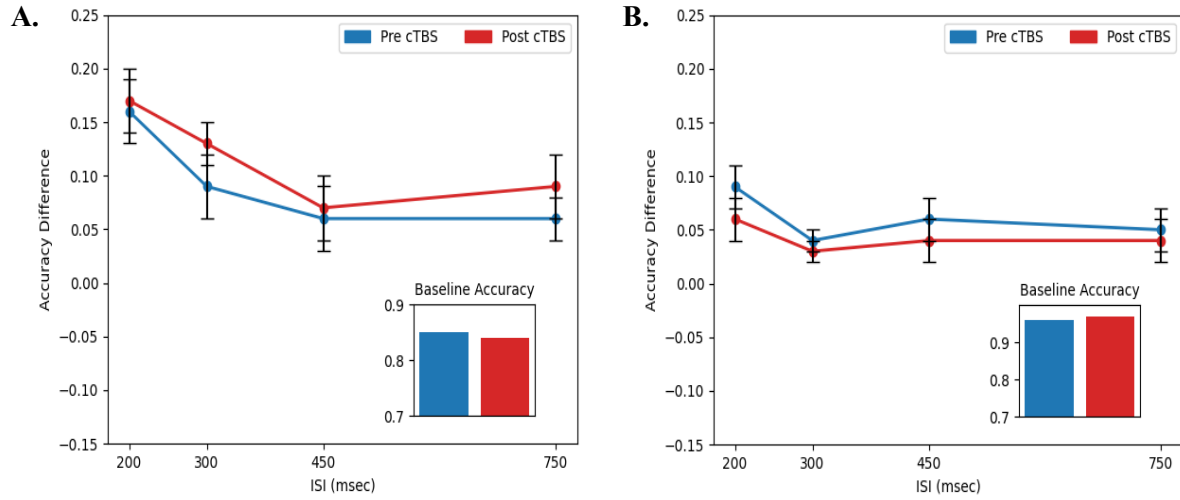


Figure 5. Left hemisphere cerebellar stimulation: (A). Performance (Change in $AB \pm S.E$) pre vs post-cTBS in VT block type. T2 accuracy has been baseline corrected. No change in observed in AB performance. The subplot displays the extraction from the T2 from the mask only and there is no change in T2 extraction post-cTBS (B). Performance (Change in $AB \pm S.E$) pre vs post-cTBS in TV block type. There is no change in AB or T2 extraction pre and post-cTBS.

Refer to [Appendix A](#) for raw score values detailing changes in AB performance without baseline corrections.

Accuracy of detecting T2 from mask (baseline condition): As observed in Table 2 and the subplots in Figure 4a, cTBS to the right lateral cerebellar hemisphere had an impact on extracting T2 tactile targets from the mask. The t-test revealed a significant difference in baseline performance pre and post-cTBS to the right lateral cerebellar hemisphere within the tactile modality ($p_{Tactile\ Right} = 0.004$). However, there was no significant impact on extracting visual targets from the mask regardless of the stimulation site ($p_{Visual\ Right} = 0.77$ & $p_{Visual\ Left} = 0.48$), nor was there a significant difference in extracting tactile targets from the mask when cTBS was applied to the left lateral cerebellar hemisphere ($p_{Tactile\ Left} = 0.63$).

Accuracy of detecting T1 (control condition): Irrespective of the stimulation site the t-test revealed no significant difference in detecting T1 in either block type ($p_{VT\ right} = 1.00$, $p_{VT\ left} = 0.58$, $p_{TV\ Right} = 0.91$ & $p_{TV\ Left} = 0.40$). The mean accuracy of reporting T1 after stimulation are noted in Table 3.

7.3 Right Cerebellar Stimulation & VT condition

Upon closer inspection, according to equation (2), which we re-iterate here:

$$\Delta_{AB} = [(Pre_B - Pre_E) - (Pst_B - Pst_E)]$$

there are two aspects which are driving the overall change in AB:

$$\Delta_B = (Pre_B - Pst_B) \quad (4)$$

$$\Delta_E = (Pre_E - Pst_E) \quad (5)$$

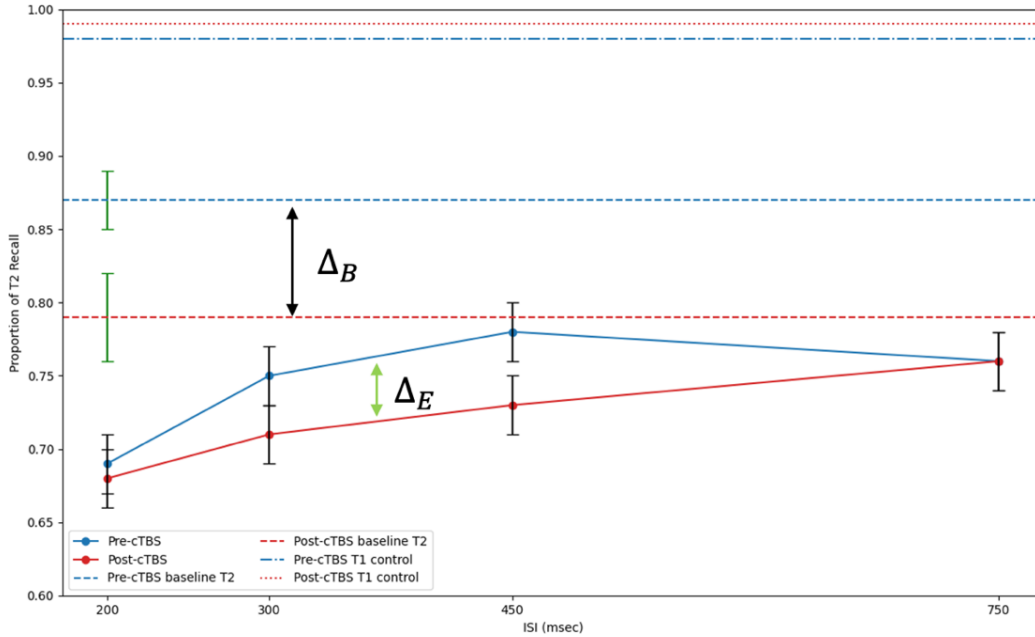


Figure 6. Comparison between extracting T2 from baseline and experimental VT-right condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the VT condition pre and post-cTBS. The dashed lines represent the performance (Mean ratio accuracy $\pm$ S.E) in extracting T2 from the mask pre and post-cTBS. The dotted lines represent mean accuracy of reporting T1 control targets. Δ_B represents the difference between accuracy of reporting T2 from the mask pre and post-cTBS. Δ_E represents the difference between accuracy of reporting T2 from T1 and mask across ISI values. $\Delta_B > \Delta_E(t)$ indicating a greater difference in extracting T2 from the mask post-cTBS. Blue represents pre-cTBS conditions, while red represents post-cTBS conditions.

Our analysis revealed that both $\Delta_B > 0$ and $\Delta_E(t) > 0$. Moreover, $\Delta_B > \Delta_E(t)$. t here is any ISI value. Thus, as observed in Figure 6, after stimulating the right lateral hemisphere there was significantly greater drop in extracting T2 from the mask compared to accurately reporting T2 within the AB condition across all ISI values.

8. Discussion

We administered cTBS to the posterior right and left lateral hemispheres of the cerebellum to transiently depress cerebellar activity and, by extension, influence attentional control. This was done to understand the role of the cerebellum in rapid attentional shifts during the integration of cross-modal information. We hypothesized that cTBS applied to the right cerebellar hemisphere would lead to a drop in the accuracy of T2 recall in the VT condition. Our results, however, demonstrate that right hemisphere-targeted cerebellar stimulation led to an increase in T2 recall compared to pre-cTBS performance after baseline corrections were applied. In contrast, for the VT condition, cTBS applied to the left cerebellar hemisphere did not modulate AB performance. Furthermore, contrary to our expectations, stimulation of the right lateral cerebellum influenced detecting tactile targets from the mask during the baseline blocks. Specifically, post-cTBS, there was a significant reduction in extracting tactile targets from the mask compared to baseline pre-cTBS performance. Interestingly, the change in the VT baseline condition was greater after stimulation, compared to the change in experimental condition [$\Delta_B > \Delta_E(t)$]. In comparison, there was no significant difference in extracting tactile targets from the mask after stimulating the left lateral cerebellar hemisphere.

Based on these outcomes, we propose that changes in AB performance following cTBS to the right cerebellar hemisphere can be attributed to the reduction in the extraction of T2 from the mask. As previously mentioned, AB is a phenomenon where the accurate detection of a

second target (T2) is reduced when it appears in close temporal proximity to the first target (T1) (Soto-Faraco et al., 2002). Previous studies and our pilot results have indicated that interruption masking is critical in producing the AB effect (Arnell & Jenkins, 2004). Interruption masking occurs when a mask of the same modality and saliency as T2 follows the second target, disrupting its processing which increases the likelihood of inducing AB (Arnell & Jenkins, 2004). This likely occurs due to "masking by object substitution," where the perception of a target object is impaired or interrupted by a masking stimulus that appears shortly after the target. This phenomenon is particularly evident under conditions of limited attentional resources, such as in a cross-modal attentional blink task (Arnell & Jenkins, 2004).

According to the central bottleneck theory, when a visual target (T1) and a tactile target (T2) are presented in close temporal proximity, they compete for a central processor with limited capacity. When the processor is engaged in processing T1, its capacity to simultaneously process T2 is diminished, causing T2 to "wait" to be processed (Soto-Faraco et al., 2002). During this waiting period, if a mask of equal saliency is presented approximately 100ms after T2, the bottom-up processing of the mask stimuli forms a strong tactile representation. Concurrently, the brain attempts to process T2 using top-down re-entrant processing, which relies on higher cognitive functions such as expectation, prediction, and prior knowledge. Due to limited attentional resources, the bottom-up processing of the mask competes with the top-down processing of T2. To manage the competition for attentional resources between these processes, our results indicate that the cerebellum is involved. Recent evidence from transsynaptic tracing studies has demonstrated the presence of synaptic pathways originating in the cerebellum and extending to the TRN (Pisano et al., 2021). Additionally, connections from the DCN, particularly

the dentate nucleus, to MD have been observed (Heck et al., 2023). We believe that the cerebellum influences the outcomes we observed through these cortical circuits.

In a cross-modal AB task, T2 can be considered a task-relevant stimulus, while the mask acts as a distractor. One neural process that ensures task-relevant stimuli are not overwhelmed by distractors is sensory gating. This process is the brain's intrinsic ability to filter irrelevant afferent stimuli, preventing an overload of information within higher cortical areas and occurring in the early stages of cortical processing. Mechanistically, when tactile stimuli are detected by mechanoreceptors, this information is sent to the CNS as afferent sensory information and relayed to the thalamus (McCormick & Bal, 1994). The thalamus acts as a compulsory relay station through which nearly all sensory information must pass before reaching the cerebral cortex (McCormick & Bal, 1994). One major function of the thalamus is the selective control of the flow of sensory information to the cerebral cortex via the TRN. The TRN is part of the ventral thalamus, composed of GABAergic (inhibitory) neurons projecting to most parts of the rostral, lateral, and ventral thalamus (McAlonan et al., 2000). According to the literature, the TRN regulates the flow of sensory information through thalamic-cortical and cortical-thalamic circuits (McAlonan et al., 2000). It receives excitatory inputs from both the cortex and the thalamus and sends inhibitory projections back to the thalamic relay nuclei, exerting feedback inhibition that helps control which sensory signals reach the cortex (McAlonan et al., 2000). We conjecture that the right lateral cerebellum is an input to this modulatory thalamocortical network via its connections to the TRN. During conditions of limited attentional resources, and competition between the top-down processing of T2 and bottom-up processing of the mask, the cerebellum attenuates the bottom-up processing via sensory gating such that the representation of the mask is weakened. This allows the top-down process to effectively process the T2 target.

Administration of cTBS can be thought to reduce the functional efficacy of the cerebellum by decreasing excitatory cerebellar output. Although we did not administer iTBS to the same hemisphere as a control to assess cTBS effects, our results show a negative change in behavior. This could be due to the introduction of noise into the system from the stimulation, making it harder for the cerebellum to modulate the cortical networks in question. Thus, when cTBS is applied to the right cerebellum, our results demonstrate that its ability to modulate bottom-up sensory gating is compromised. This explains why we observed a significant drop in extracting T2 targets from the mask in post-cTBS baseline blocks. However, as observed in Figure 4a. and Figure 6, before baseline corrections, there is an increase in AB between pre and post-cTBS results, but after baseline corrections there is an overall reduction in AB. To reconcile this increase in AB before baseline corrections with our view of the cerebellum as a bottom-up process attenuator, we will use the connections between the cerebellum and MD as our focal point.

The MD thalamic nucleus has projections to the pre-frontal cortex in mammals (Heck et al., 2023). During early cortical processing of sensory information, increased MD activity is observed (Heck et al., 2023). It is theorized that MD is responsible for coordinating the presentation of sensory information to higher cognitive areas which is relevant for goal-oriented behaviour (Heck et al., 2023). Furthermore, sustained, and timed MD activity is required for promoting coherence between principal neurons and interneurons (Heck et al., 2023). One mechanism employed in this processing is sensory weighting. This refers to the process by which the brain assigns different levels of importance or "weights" to various sensory inputs based on their relevance to current tasks, goals, or contexts. Sensory weighting is heavily influenced through top-down processing and is crucial for prioritizing sensory inputs based on their

relevance to the current context or task, thereby enhancing the processing of important stimuli while de-emphasizing less pertinent ones (Corbetta & Shulman, 2002; Macaluso & Driver, 2005). So, focusing on the differences observed in the experimental trials, we conjecture that the right cerebellum also modulates top-down processes via MD which re-weighs sensory information based on task relevance. However, after cTBS, the difference in T2 extraction pre and post cTBS from the mask (baseline blocks) is greater than the difference in T2 extraction pre and post cTBS from T1 in the presence of the mask (experimental blocks). Considering this, we conjecture that while the cerebellum's inhibition may reduce the incidence of AB, it also impairs the precise extraction of relevant stimuli, indicating a trade-off between these two aspects of attentional control. Finally, since after baseline corrections, we see an overall decrease in AB, we theorize that the cerebellar modulation of bottom-up processes is more significant than top-down processes. Focusing on these results, we propose the "Sensory Balance Model". In this model, output signals from structures like the cerebellum are combined with signals in the sensory processing circuits to control the input gain of sensory information by balancing attentional resources allocated to bottom-up and top-down processes. This adjustment ensures effective integration of sensory information, resulting in accurate behavioral outcomes.

Additionally, our results support the hypothesis that in the TV condition, which served as a control, there was no significant difference in extracting the visual T2 targets in either the experimental blocks or baseline blocks, regardless of stimulation site. This pattern of results can be attributed to the difference in neural processing time between tactile and visual stimuli, which prevents the bottleneck effect from occurring. As there is little to no competition between the two attentional processes in the TV condition, there is a lack of cerebellar involvement. This is in line with our sensory balance model which casts the cerebellum as a sensory modulator during

conditions of limited attention. Furthermore, cTBS to either site did not impact performance in detecting T1 catch/control trials. This outcome implies that the cerebellum is not involved in stimuli detection, irrespective of modality. It is involved in accurate target stimulus extraction from a series of target and non-target stimuli presented in close temporal proximity.

Lastly, our results contribute to the growing body of evidence that distinct functional domains exist within the cerebellum. Lateralization of functions refers to the idea that certain cognitive processes are more dominantly associated with one hemisphere. For example, language is typically lateralized to the left cerebral hemisphere. Interestingly, research suggests that the lateralization of function between the cerebellum and cerebrum is maintained via contralateral connections between these structures. Arasanz and colleagues demonstrated that cTBS to the right cerebellum led to a decrease in verbal fluency and word generation (Arasanz et al., 2012a). Evidence from studies on patients with cerebellar lesions indicates a general cognitive deficit in individuals with right cerebellar lesions, while those with left cerebellar lesions show deficits primarily in visuospatial functions and not language or attention (Starowicz-Filip et al., 2021). To understand the right cerebellar hemisphere dominance in our results, we can use the contralateral connections between the cerebrum and cerebellum, and results from clinical studies related to Attention Deficit Hyperactive Disorder (ADHD) as our foundation.

ADHD is a neurodevelopmental disorder characterized by symptoms of functional impairment, inattention, and/or hyperactivity-impulsivity (Coghill et al., 2018). Individuals with ADHD also exhibit deficits in higher-level cognitive functions essential for goal-oriented behaviors (Rubia, 2018). According to mechanistic studies, the underlying symptom of ADHD is a neuropsychological deficit. This results in anomalies in attention selection or maintenance and cognitive control (i.e., top-down goal-directed behavior) (Chan et al., 2021). Consequently,

individuals have difficulties responding to external stimuli, leading to response inhibition or delays.

Studies using transcranial direct current stimulation (tDCS) to observe changes in executive control and attention in patients with ADHD have shown improvements in reaction time on flanker tasks (Dubreuil-Vall et al., 2021). These improvements were more pronounced when the left DLPFC was stimulated compared to the right DLPFC (Dubreuil-Vall et al., 2021). This suggests a greater role for the left DLPFC in modulating attention and executive function. Furthermore, cerebellar volumetric studies involving 350 individuals diagnosed with ADHD, revealed that ADHD patients exhibited a 3.51% smaller right cerebellar cortex volume, a 2.94% smaller left cerebellar cortex volume, and a 3.18% smaller total cerebellar volume compared to healthy controls (Wyciszkiewicz et al., 2016). Meta-analyses of fMRI studies reveal diminished activation in the cerebrum, thalamus, and cerebellum. This under-activation affects fronto-striato-parietal and fronto-cerebellar networks in individuals with ADHD compared to healthy controls while performing tasks related to selective attention (Ivanov et al., 2010; Rubia, 2018). These findings along with our results demonstrate that during rapid attentional shifts and attentional modulation, the left cerebral hemisphere plays a more dominant role, which then translates to right cerebellar involvement in such processes.

9. Limitations and Future Directions

The current study was limited in assessing the complete lateralization effect of the cerebellum, as all stimuli were presented to the left hand and visual space. This approach was intended to ensure that sensory feedback was not received by the right cerebellar hemisphere and that stimuli processing occurred in the right cerebral hemisphere. This allowed us to assess its involvement without any confounding factors. Future research should investigate how cerebellar

hemisphere contributions may shift if the stimuli are presented to the right hand. This would help determine if there is a lateralization of function, especially if a similar pattern of results emerges with delivery of stimuli to the right hand and visual space.

Moreover, iTBS could be used as a control to assess the pattern of stimulation for cTBS. This would be valuable because iTBS is known to have excitatory effects on neural activity, whereas cTBS generally has inhibitory effects. By comparing the effects of these two patterns of stimulation, we can better understand the specific impact of inhibitory stimulation on attentional processes. This comparison can help isolate the effects of cTBS and provide insights into how different patterns of stimulation influence behavior. However, as one of the main questions of this research was to assess lateralization, it was imperative to stimulate the left hemisphere as an active control with the same type of stimulation. Furthermore, one of the notable limitations of this study is the inherent variability in the outcomes associated with non-invasive brain stimulation targeting cerebellar regions. As highlighted in the meta-analysis conducted the effects of non-invasive brain stimulation on cerebellar-associated cognitive processes exhibit considerable heterogeneity across studies (Pezzetta et al., 2023). This variability could be attributed to differences in stimulation parameters, individual anatomical and functional variability, and the complex interactions between cerebellar and cortical regions. However, despite this limitation, the data from this study, along with ongoing research using these stimulation techniques, are important for improving our understanding of how cerebellar non-invasive brain stimulation works.

Considering the links between ADHD, the cerebellum, and the frontoparietal network, it would be valuable to explore whether TMS over the cerebellum could provide new avenues for alternative interventions targeting the underlying neurobiology of the disorder. Specifically, it

would be interesting to assess whether AB performance or reaction time in the flanker task in individuals with ADHD before stimulation is comparable to that of healthy individuals following cTBS, and whether administering iTBS over the right cerebellar hemisphere can lead to improvements in AB performance or reaction time.

Lastly, we collected EEG data to assess attentional correlates, although this analysis is not part of the current thesis. Future analysis of this EEG data aims to provide evidence for whether there is a neurological marker or change that represents the perceptual reduction in cross-modal AB. We believe that this would be observed as either an increase in latency or a decrease in amplitude of the P300, or a difference in the N2pc components between blink and non-blink trials. The P300 component is related to attentional and working memory processes (Luck et al., 1996; Vogel et al., 1998; Vogel and Luck, 2002). An increase in latency or a decrease in amplitude of the P300 in blink trials would suggest that the processing of the target stimulus is delayed or less efficient. The N2pc component reflects the focusing of attention onto a target in the presence of distractors (Jolicœur et al., 2006). Differences in the N2pc between blink and non-blink trials would indicate variations in the allocation of attention and the ability to distinguish the target from distractors.

10. Conclusion

In conclusion, we found that the right lateral cerebellum is a key player in modulating sensory processes that compete for attentional resources during complex tasks. Based on our results, the thalamo-cortical and frontoparietal networks involved in managing relevant versus irrelevant information during attentional shifts recruit the cerebellum in a hemisphere-specific manner. This work provides further validation for cerebellar-targeted cTBS as a non-invasive tool to study cerebellar contributions to cognitive processes. Moreover, in this thesis, we propose

the "Sensory Balance Model" to emphasize physiological mechanisms by which the cerebellum is adjusting the signal-to-noise ratio of sensory processing driven by attention. Although more work is needed, this study lays the groundwork for understanding the physiological mechanisms and the role of the cerebellum in functional networks underlying attention.

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Appendix A: Supplementary Figures

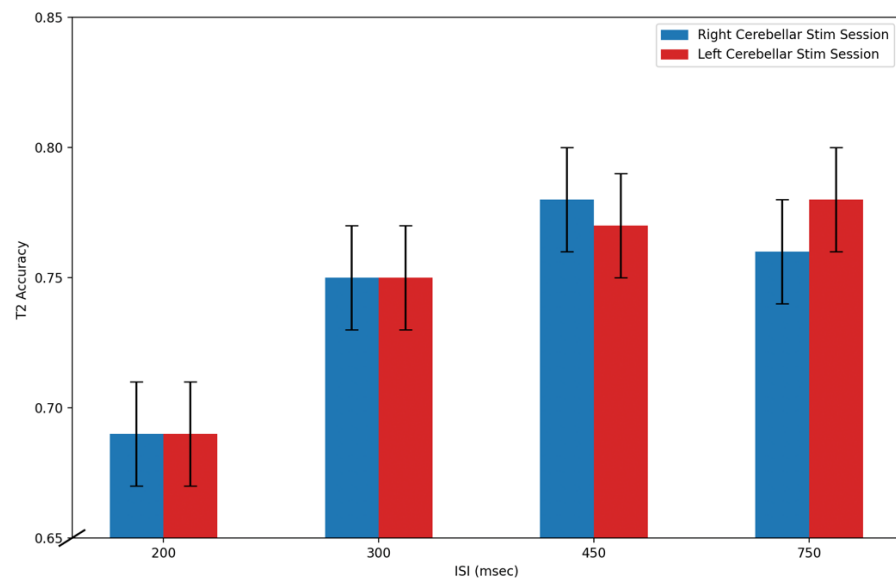


Figure 7. Attentional Blink Performance pre-cTBS in VT condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the VT condition before cTBS in session right (blue) or session left (red). There was no difference in performance between the two session days across all 4 ISI values.

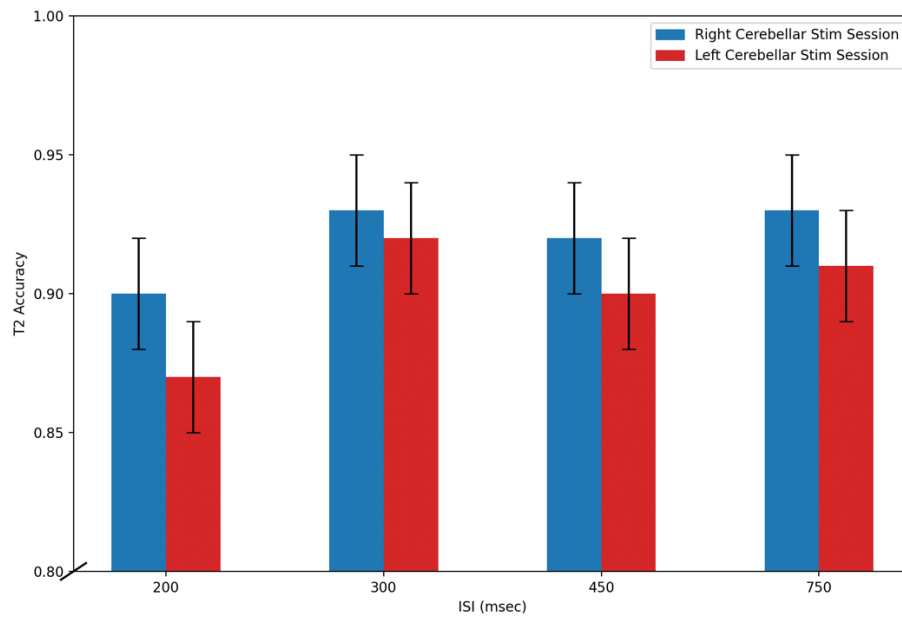


Figure 8. Attentional Blink Performance pre-cTBS in TV condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the TV condition before cTBS in session right (blue) or session left (red). There was no difference in performance between the two session days across all 4 ISI values.

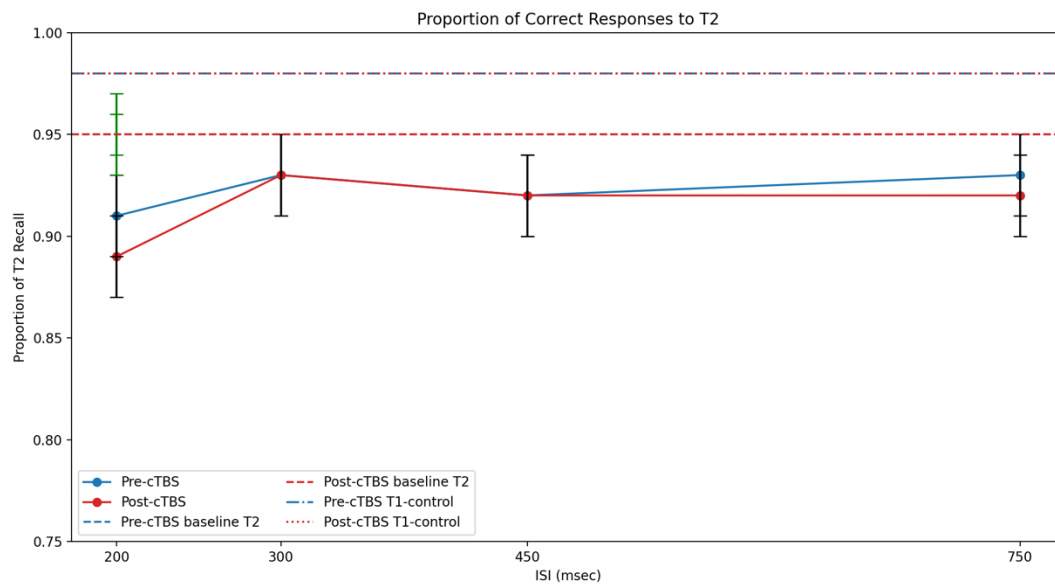


Figure 9. Proportion of accurate T2 response in TV-right condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the TV condition pre and post-cTBS to the right cerebellum. The dashed lines represent the performance (Mean ratio accuracy $\pm$ S.E) in extracting T2 from the mask pre and post-cTBS. The dotted lines represent mean accuracy of reporting T1 control targets. Blue represents pre-cTBS conditions, while red represents post-cTBS conditions.

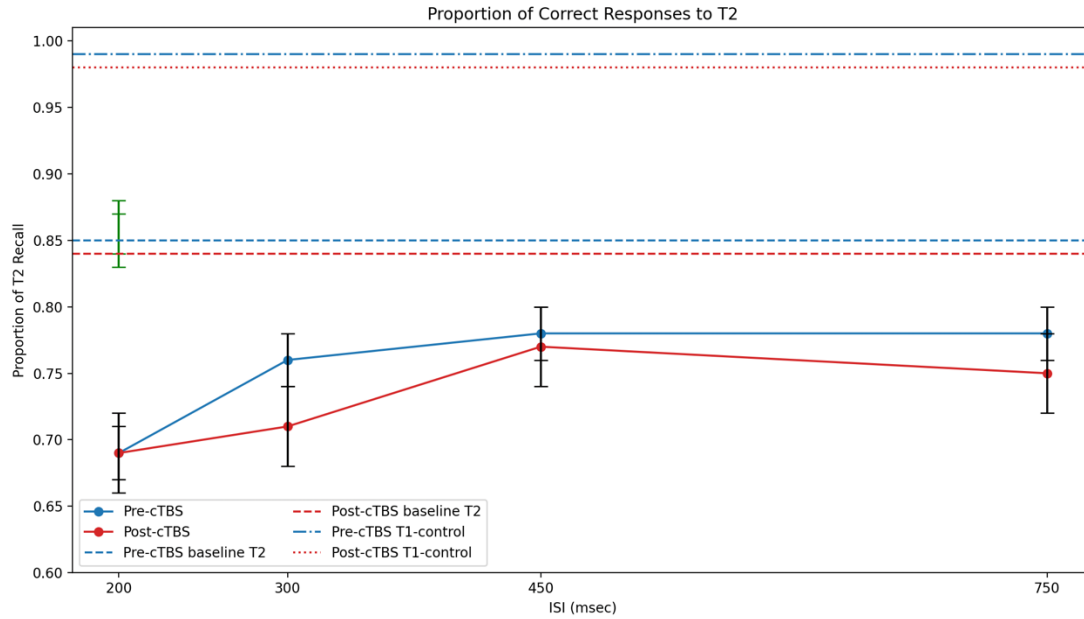


Figure 10. Proportion of accurate T2 response in VT-left condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the VT condition pre and post-cTBS to the left cerebellum. The dashed lines represent the performance (Mean ratio accuracy $\pm$ S.E) in extracting T2 from the mask pre and post-cTBS. The dotted lines represent mean accuracy of reporting T1 control targets. Blue represents pre-cTBS conditions, while red represents post-cTBS conditions

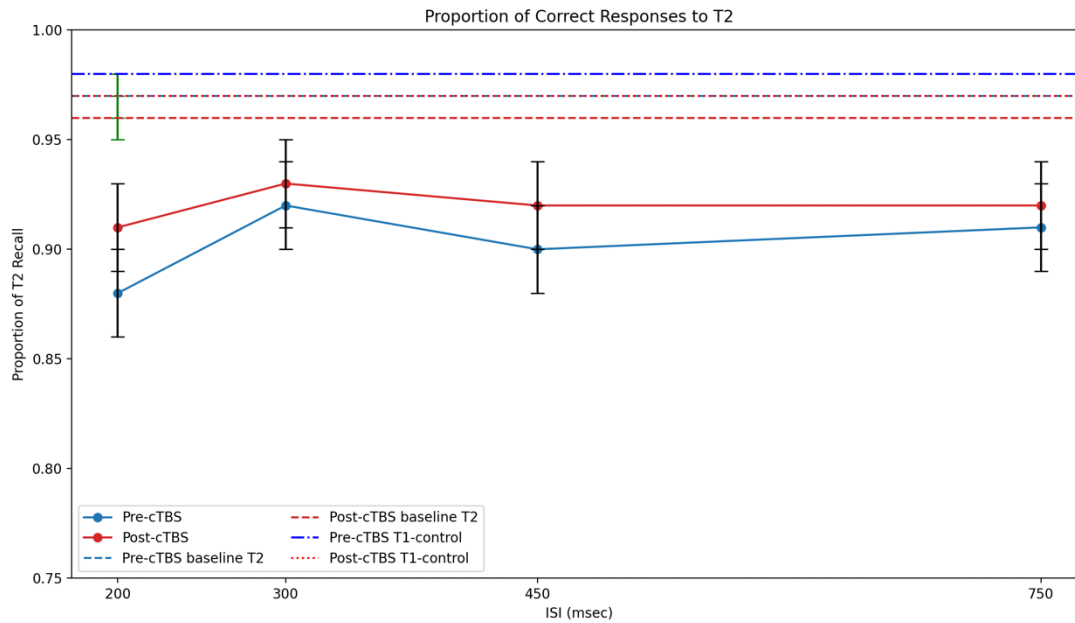


Figure 11. Proportion of accurate T2 response in TV-left condition: Performance (Mean ratio accuracy $\pm$ S.E) in detecting T2 in the TV condition pre and post-cTBS to the left cerebellum. The dashed lines represent the performance (Mean ratio accuracy $\pm$ S.E) in extracting T2 from the mask pre and post-cTBS. The dotted lines represent mean accuracy of reporting T1 control targets. Blue represents pre-cTBS conditions, while red represents post-cTBS conditions

Appendix B: Questionnaires

Modified University of Waterloo Health History Questionnaire

Participant ID _____ M/F
Age _____

Date _____
Sport/Position _____

1. Aside from concussion, have you been diagnosed with any other neurological conditions (ADHD, depression, anxiety, etc.)?

a) _____yes _____no

b) If yes, please list:

2. Have you sustained nerve damage to either of your upper limbs:

a) In the past 6 months?

_____yes _____no

b) That resulted in permanent damage?

_____yes _____no

3. At what age did you begin playing organized sport? _____

4. How many years have you played your sport? _____

5. Do you wear a mouth guard while playing?

_____yes _____no

If yes, what kind?

_____stock _____boil & bite
_____custom, front teeth _____custom, all

6. Have you suffered from neck pain within the past 6 months? _____yes _____no

7. Have you suffered a concussion?

_____yes _____no _____not sure

8. If yes to #7,

a) How many times total? _____

b) How many were clinically diagnosed?

c) How many while playing sport in the past 6 months? _____

d) Date of last concussion? _____

e) Have you been clinically cleared to return to full physical and cognitive activity since the most recent concussion? _____yes _____no

- f) How long did symptoms last (for most recent concussion)?

_____1-3 days _____4-7days

_____8-10 days _____11-14 days

_____more than 14 days

- g) After the most recent concussion, how long did you refrain from physical activity?

_____1-3 days _____4-7 days

_____8-10 days _____11-14 days

_____more than 14 days

9. Have you ever been knocked unconscious?

_____yes _____no

10. If yes to #9,

a) How many times in the past 6 months? _____

b) What is the longest duration you've been knocked unconscious? _____

11. In the past 6 months, after being hit in the head in, have you experienced any of the following symptoms?

_____confusion _____getting 'dinged'
_____headaches _____balance problems

_____nausea _____getting 'bell rung'

_____dizziness _____ringing in ears

_____blurry vision _____poor memory

_____other: _____

12. In regards, to how you feel NOW, please rate the following:

	None		Mild		Severe		
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck pain	0	1	2	3	4	5	6
Nausea/vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Hard to concentrate	0	1	2	3	4	5	6
Feeling "in a fog"	0	1	2	3	4	5	6
Trouble remembering	0	1	2	3	4	5	6
Fatigue/low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Nervous/anxious	0	1	2	3	4	5	6

13. Do the above symptoms get worse with physical activity? _____yes _____no
14. Do the above symptoms get worse with mental activity? _____yes _____no

Edinburgh Handedness Inventory¹

Your Participant ID: _____

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	$R = (D / CT) \square 100 =$	

¹ Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97-113.



TRANSCRANIAL MAGNETIC STIMULATION (TMS) SCREENING FORM

Below is a questionnaire used to exclude participants considered not suitable for transcranial magnetic stimulation (TMS). This information, as well as your identity, will be kept confidential in all future publications.

PLEASE COMPLETE FORM BELOW:

Participant's Name: _____ **Age:** _____

Please **CIRCLE ONE**:

Do you have epilepsy or have you ever had a convulsion or a seizure?	YES	NO
Have you ever had a fainting spell or syncope? If yes, please describe in which occasion(s)	YES	NO
Have you ever had severe (i.e., followed by loss of consciousness) head trauma?	YES	NO
Do you have any hearing problems or ringing in your ears?	YES	NO
Are you pregnant or is there any chance that you might be?	YES	NO
Do you have metal in the brain/skull (except titanium)? (e.g., splinters, fragments, clips, etc.)	YES	NO
Do you have cochlear implants?	YES	NO
Do you have an implanted neurostimulator? (e.g., DBS, epidural/ subdural, VNS)	YES	NO
Do you have a cardiac pacemaker or intracardiac lines or metal in your body?	YES	NO
Do you have a medication infusion device?	YES	NO
Are you taking any medications? (Please list)	YES	NO
Did you ever have a surgical procedure to your spinal cord?	YES	NO
Did you ever undergo TMS in the past?	YES	NO
Did you ever undergo MRI in the past?	YES	NO