INVESTIGATING ATTENTIONAL DEMANDS OF A CONTINUOUS MOTOR TASK USING PROBE REACTION TIME AND MEASURES OF CORTICOSPINAL EXCITABILITY

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Statement of Contribution of Collaborators

I, Christin Sadler, hereby declare that I am the sole author of this document. The conception and design of the experiment, data collection and analysis, statistical analyses, and production of this document were completed in collaboration with my thesis supervisor, Dr. Anthony Carlsen, and supported by my committee members, Dr. Erin Cressman and Dr. Dana Maslovat.

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Table of Contents

Abstract

The performance of a second motor task during an ongoing motor task requires attention. Currently, it is unclear how the attentional demands of a primary continuous motor task affect the preparation and execution of a second motor task. The purpose of the present experiment was to investigate whether the attentional demands of a cyclical primary motor task vary with location within a movement cycle, and whether these variations impact response preparation of a second motor task reflected as differences in premotor reaction time (RT) and/or measures of corticospinal excitability. Participants (N=20) performed a continuous tracking task that involved cycles of wrist flexion and extension with their left hand. A probe RT task involving isometric wrist extension was performed with the right hand in response to auditory stimuli (80 dB and 120 dB) that were triggered as the left hand cycled through one of five locations. On separate trials, transcranial magnetic stimulation (TMS) was applied over the left primary motor cortex to assess corticospinal excitability associated with the probe RT task. The results revealed that probe RT latencies were significantly longer and motor evoked potential (MEP) amplitudes were significant larger when the RT task was probed when the left hand was in the middle of a movement cycle. Together, these results suggest that there are moments within a continuous motor task that have larger attentional demands, and these variations have an impact on advance response preparation of a second motor task as measured by differences in premotor RT and measures of corticospinal excitability.

Glossary of Terms

AMT: Active motor threshold

CNS: Central nervous system

CSP: Cortical silent period

ECR: Extensor carpi radialis (muscle)

EMG: Electromyography

FCR: Flexor carpi radialis (muscle)

HSD: Honestly significant differences

IS: Imperative stimulus

M1: Primary motor cortex

MEP: Motor evoked potential

MVF: Maximum voluntary force

RM-ANOVA: Repeated measures analysis of variance

RMSE: Root mean square error

RT: Reaction time

SAS: Startling acoustic stimulus

SCM: Sternocleidomastoid muscle

SCM+: SAS trials with confirmed startle reflex activity

SCM-: SAS trials without startle reflex activity

TMS: Transcranial magnetic stimulation

List of Figures and Tables

Chapter I: Literature Review

1. Introduction

A major aim of motor control research involves investigating how humans prepare, execute, and control our voluntary movements. For many individuals, activities that require dual tasking (performing two tasks simultaneously) occur frequently throughout the day and are usually performed without much difficulty. For example, a driver may control the steering wheel of a car with one hand while shifting gears with the other, or a parent may compose a text message on their phone while simultaneously carrying their child.

Interestingly, although actions involving upper limb dual tasking are common throughout our activities of daily living, bimanual movement is studied less frequently than unimanual movement (Swinnen, 2004). From a neuromotor perspective, dual tasking is an interesting construct, for it is quite complex and involves the communication and coordination of many sensory and motor structures, circuits, and processes within the central nervous system (CNS). Indeed, the central capacity required to successfully complete these actions are quite involved, and thus require further investigation. Specifically, the central processes underlying motor response preparation in dual-task conditions are not completely understood.

In a laboratory environment, it is possible for researchers to gain some insight into these complex CNS functions by studying the performance of a simple reaction time (RT) task probed within a dual-task paradigm; a method referred to as probe RT (Schmidt & Lee, 2011). In these paradigms, RT latencies are recorded and used as a proxy measure of neural activation, as shorter RT latencies have been associated with higher levels of response preparation (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004a; Hanes & Schall, 1996; Maslovat, Carlsen, & Franks, 2012). In a simple RT testing paradigm, the RT latencies measured are usually quite short because the required action is known in advance of the imperative stimulus (IS) and thus can be well prepared in advance, or “preprogrammed,” for quick performance upon stimulus detection

(Carlsen et al., 2009; Donders, 1969). Interestingly, when a startling acoustic stimulus (SAS) is presented as the IS for a preprogrammed action, the RT latencies for these movements are even shorter than normal (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004b; Valls-Solé, Kumru, & Kofler, 2008). It is thought that the SAS produces an accelerated motor response by triggering a prepared motor program with the startle reflex response (Carlsen et al., 2004a). This phenomenon is referred to as the "StartReact effect", and, in a dual-task testing paradigm, this effect has been established as a reliable way to measure advance response preparation of a voluntary action (Begeman, Kumru, Leenders, & Valls-Sole, 2007; Maslovat et al., 2013; Maslovat, Drummond, Carter, & Carlsen, 2015).

Additionally, response preparation can be further understood by assessing corticospinal excitability via transcranial magnetic stimulation (TMS), a non-invasive neural stimulation technique (Corp, Lum, Tooley, & Pearce, 2014; Hannah, Cavanagh, Tremblay, Simeoni, & Rothwell, 2018; Kennefick, Burma, van Donkelaar, & McNeil, 2019). When TMS is coupled with electromyography (EMG), the neuromuscular activity measured at the time of application can provide insight into the activity occurring in the cerebral cortex (Alibiglou & MacKinnon, 2012; Pascual-Leone et al., 1992). Together, when used in a probe RT paradigm, measures of corticospinal excitability, premotor RT, and the StartReact effect can provide insight into the complex central processes of preparing for and performing two motor actions at the same time.

2. Response Preparation

The human brain has the potential to coordinate a seemingly unlimited amount of diverse bimanual motor activities. To do so, cortical neurons communicate in complex and integrated ways, forming functional areas within the brain. Generally, these areas can be split into three groups: sensory areas, motor areas, and integration areas (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2013). Neural activity increases within and between these functional areas when an action is planned and prepared, a procedure often referred to as "motor programming" (Schmidt & Lee, 2011). A motor program is a theoretical construct involving a set

of motor commands (neuronal signals) preprogrammed in the brain and temporarily stored until the decision to perform the action has been made (Keele, 1968). The neural structures and pathways underlying the concept of a motor program have been researched extensively within the field of motor control. Specifically, the primary motor cortex (M1), located within the precentral gyrus of the frontal lobe of the brain, has been identified as an important motor area involved in voluntary motor programming. M1 is organized into groups of cortical neurons clustered together to control specific regions of skeletal muscle. These neuronal groups act as command centers for most voluntary movements occurring at the different regions of the body (Kandel et al, 2013; Deecke, Scheid, & Kornhuber, 1969).

2.1. Information Processing Model

One approach to studying motor programming is through the Information Processing model, which involves three serial stages of central processing (Schmidt & Lee, 2011). The model begins with *Stimulus Identification*, where sensory information from the environment is detected and identified. The second stage is *Response Selection*, in which an appropriate action is determined in response to the identified stimulus. The third stage is *Response Programming*, in which a motor program is prepared (i.e., *response preparation*) and stored until the decision is made to perform the action (i.e., *response initiation*) (Schmidt & Lee, 2011).

2.2. Reaction Time

The neural processes involved throughout the stages of information processing occur within the CNS, so they can be difficult to measure directly. RT is often used as an indication of the duration for the central processes involved in information processing, with longer RT latencies associated with larger amounts of central processing (Schmidt & Lee, 2011; Klapp, 2010). Generally, any change in RT by an experimental variable can be explained by a change within one of the information processing stages (Schmidt & Lee, 2011; Donders, 1969). More specifically, premotor RT, defined as the time between the presentation of an IS and the

initiation of muscle activity, has been used as a measure of *Response Programming* as it represents the interval of time required by the CNS to complete the information processing required after stimulus presentation (Schmidt & Lee, 2011; Donders, 1969).

A simple RT paradigm is a standard experimental design used to test information processing. In these paradigms, a predetermined action is performed in response to the presentation of a stimulus. From the perspective of the information processing model, simple RT tasks typically record fast RTs because the majority of the central processing required during the *Response Selection* and *Response Programming* stages can be completed before the *Stimulus Identification* stage, resulting in significantly shorter RT latencies than when these processes are performed serially (Donders, 1969; Keele, 1968; Klapp, 2010). In other words, if directed to move quickly, an action that is known in advance of the stimulus can be highly prepared in anticipation of stimulus presentation and performed with a short (fast) RT.

The fast execution of a prepared motor program can be explained using the neural accumulator model of movement preparation (Hanes & Schall, 1996). In this model, response preparation in advance of IS presentation increases the activation levels of cortical motor neurons responsible for controlling the prepared movement to an activation level just below their propagation threshold. This heightened level of activation allows for fast response initiation upon presentation of the IS, for the neurons are much closer to the neural activation threshold required for signal propagation and voluntary movement (Carlsen, Maslovat, & Franks, 2012). In a typical simple RT paradigm, an advanced state of response preparation is usually achieved during the foreperiod of the task, defined as the time between the “Get Ready” cue and the IS. In the foreperiod, the motor commands for the intended movement are stored in a “preprogrammed” state until neural activation surpasses the propagation threshold shortly after the presentation of the IS (Carlsen et al., 2012).

3. Transcranial Magnetic Stimulation

The preparatory processes for motor responses have an impact corticospinal excitability in the primary motor cortex (M1) and other cortical areas prior to performance (Kennefick et al., 2019). Transcranial magnetic stimulation (TMS), a non-invasive neural stimulation technique, has been used to investigate cortical contributions to motor response preparation (Davranche et al., 2007; Kennefick, Maslovat, & Carlsen, 2014; Smith, Maslovat, & Carlsen, 2019). TMS uses a copper coil to create a magnetic field over the skull to stimulate axons of cortical neurons (Di Lazzaro & Rothwell, 2014). Initially introduced by Barker et. al (1985) as a simpler, less painful alternative to transcranial electrical stimulation, this technique allows researchers to measure corticospinal activity (Day et al., 1989).

3.1. Motor Evoked Potentials

An important factor with TMS is identifying the motor threshold for a target muscle (Ah Sen et al., 2017). A motor threshold is defined as the minimum intensity of cortical stimulation required to elicit a motor response from a target muscle (Ah Sen et al., 2017; Di Lazzaro & Rothwell, 2014; Rossini et al., 2015). This motor response is referred to as a motor evoked potential (MEP) and is measured using surface electromyography (EMG). As an example, when TMS is applied over the M1 representation of the extensor carpi radialis (ECR) muscle, stimulation evokes an action potential within the cortex which propagates along the corticospinal tract towards the ECR where an MEP can be recorded with surface EMG (Barker, Jalinous, & Freeston, 1985; Rossini et al., 2015). The size (amplitude) of an MEP can be measured and used as an indicator of the level of corticospinal excitability in the cortex at the time and site of stimulation (Davranche et al., 2007; Ziemann, Tergau, Netz, & Hömberg, 1997). Larger MEPs have been associated with higher levels of cortical neuron activity and are typically seen when TMS is delivered during the RT interval (i.e., before movement but after an IS), and when delivered at supra-threshold intensities (i.e., a stimulation level higher than a muscle's motor

threshold) (Rossini et al., 2015; Ziemann et al., 1997). However, when TMS is applied in a short time window before the IS (i.e., during response preparation), there is evidence that MEPs are *smaller* than when measured at rest, indicative of a higher level of response preparation (Davranche et al., 2007; Hannah et al., 2018; Kennefick et al., 2014; Smith, Maslovat, & Carlsen, 2019). For example, Davranche and colleagues (2007) reported that when TMS was applied to M1 preceding an isometric button press, MEP amplitudes were smaller when stimulation was applied in a short foreperiod (500 ms) condition compared to a long foreperiod (2500 ms) condition. The authors argued that when IS presentation was associated with the short foreperiod, a high level of response preparation could be achieved because the timing of IS presentation is more predictable. Indeed, previous work has supported this result, and argue that the smaller RT latencies that are associated with smaller MEP amplitudes are a result of central inhibitory processes acting to suppress the highly prepared action until IS presentation (Davranche et al., 2007; Hannah et al., 2018; Smith, Maslovat, & Carlsen, 2019).

3.2. Cortical Silent Period

In most applications of TMS, particularly following supra-threshold stimulation, a cortical silent period (CSP) is present immediately following the MEP. The CSP is defined as a TMS-induced interruption in EMG activity recorded from the target muscle (Ziemann et al., 1997). When supra-threshold TMS is applied during an isometric contraction, a typical MEP occurs at approximately 20 ms following the TMS pulse, whereas the CSP will be present directly following the MEP and lasting for approximately 100 – 300 ms (Fuhr, Agostino, & Hallett, 1991).

Currently, it is unclear how MEPs and CSPs will present when TMS is applied to M1 during motor response preparation of a probe RT task performed in a bimanual dual-task paradigm (Corp et al., 2014). Generally, the duration of a CSP is associated with TMS intensity, in that a higher intensity of TMS is expected to produce a longer CSP (Terao & Ugawa, 2002). There are some reports of significantly shorter CSPs associated with highly prepared

movements in a simple RT tasks (Davranche et al., 2007). Thus, shorter CSPs and smaller MEPs may be an indication of advanced response preparation.

4. StartReact Paradigm

In addition to cortical structures, research suggests that subcortical structures and pathways may also be involved during advanced response preparation (Carlsen et al., 2004b; Valls-Solé, Rothwell, Goulart, Cossu, & Muñoz, 1999). This idea is often tested using a "StartReact" paradigm, in which the IS for a simple RT task is replaced with a loud acoustic stimulus capable of eliciting a startle reflex. RT latencies measured in response to a SAS are typically significantly shorter than in control trials (Carlsen et al., 2004b; Valls-Solé et al., 1999). Currently, this distinct decrease in RT is thought to occur due to subcortical startle reflex activity interacting with the cortical processes involved in advanced response preparation, and this interaction results in the early initiation of the preprogrammed motor response (Carlsen & Maslovat, 2019; Carlsen et al., 2012; Valls-Solé et al., 2008).

4.1. The Startle Reflex

Reflexes occur faster than voluntary actions because they do not require any voluntary motor commands and thus bypass the cerebral cortex (Kandel et al, 2013). A typical startle reflex is characterized by a generalized, involuntary flexion response, consisting primarily of cervical flexion, shoulder elevation, and bilateral blinking (Yeomans & Frankland, 1996). Startle reactions propagate along an involuntary, subcortical pathway that is thought to include the reticular formation and the reticulospinal tract (Brown et al., 1991; Davis, Gendelman, Tischler, & Gendelman, 1982; Yeomans & Frankland, 1996). Interestingly, when a SAS is presented as the IS for a voluntary movement that has been "preprogrammed", it appears to trigger the prepared action much quicker than with a control stimulus. In fact, startle-elicited RT latencies for upper limb movements are typically measured at < 80 ms, whereas RT latencies in response

to normal (control) auditory stimuli typically record at around 140 ms (Carlsen, Maslovat, et al., 2012; Valls-Solé et al., 1999).

4.2. StartReact Effect

When a startle reflex occurs in association with response initiation of a prepared action, the resulting motor phenomenon is called the "StartReact" effect (Carlsen et al., 2004b; Valls-Solé et al., 1999). A robust finding in the literature is that StartReact responses recorded in simple RT trials have shorter RT latencies than control trials, and the kinematic data collected from these movements are not different than the control performances (Carlsen et al., 2012). For example, Carlsen and colleagues (2004b) measured RT of different elbow extension movements (performed to 20°, 40°, and 60°) that were cued by either a normal auditory stimulus (82 dB) or a SAS (124 dB) and found no differences in mean peak displacement, time to peak displacement, peak velocity, final position, or movement time between the two conditions. Furthermore, the timing characteristics of the typical triphasic EMG pattern (agonist – antagonist – agonist) measured from concentric elbow extension movements were also not different between the two conditions (Carlsen et al., 2004b). Similar results have been reported in other experiments testing upper limb movements (Carlsen et al., 2009; Cressman, Carlsen, Chua, & Franks, 2006; Kumru & Valls-Solé, 2006; Maslovat et al., 2012; Valls-Solé et al., 1999), lower limb movements (MacKinnon et al., 2007; Valls-Solé et al., 1999), and in upper-limb dual-task conditions (Begeman et al., 2007). Collectively, these results provide strong evidence that the same voluntary movement is performed within SAS and control trials, yet in SAS trials the movement is initiated faster. The assumption from these results is that a highly prepared motor response is involuntarily triggered with the startle reflex in response to a SAS (Carlsen et al., 2004b; Carlsen et al., 2012; Kumru & Valls-Solé, 2006). This robust effect allows researchers to use a SAS as a tool to measure response preparation in a variety of testing paradigms.

5. Dual-Task Paradigm

In motor control research, a dual-task testing paradigm can be used to investigate different aspects of multi-tasking. Within these paradigms, response preparation can be investigated using a probe RT task, in which the IS for a simple RT task is presented during the performance of another motor task (Schmidt & Lee, 2011). Presently, it is understood that the RTs recorded in probe RT trials represent the level of response preparation achieved for the probe task, providing some insight into the complex nature of initiating an action while simultaneously performing a different motor response; and specifically addressing the questions of how an additional task impacts the stages of information processing (Schmidt & Lee, 2011). A slower RT may be indicative of our limited ability to prepare multiple concurrent motor responses to the same level of activation as when they are performed in isolation (Pashler, 1994). Another idea is that slower RTs are an indication of the greater allocation of cognitive resources towards the continued performance of the first motor task instead of focusing on motor preparation of the probe RT (Hanes & Schall, 1996; Maslovat et al., 2015).

5.1. Dual-Task Interference

It is widely understood that humans have a limited capacity to perform two motor tasks simultaneously as well as we can perform each task in isolation (Pashler, 1994). Indeed, when performing two tasks at once, we are more likely to perform movement errors, react slower, or fail to notice when a stimulus is presented compared to when we perform one task at a time (Begeman et al., 2007; Pashler, 1994). This reduction in motor performance in a dual-task paradigm is referred to as dual-task interference, which is usually investigated by evaluating the performance of each task independently before comparing concurrent motor performance to assess for differences in movement variables, such as RT (Schmidt & Lee, 2011; Pashler, 1994). There are many ideas proposed for the mechanisms contributing to dual-task interference; however, many of the proposed models still require further investigation since dual-task interference is a multi-factorial phenomenon (Pashler, 1994). Two of the main models

for dual-task interference discussed in motor control literature are presented below: the central bottleneck model, and the central capacity sharing model.

5.2. The Central Bottleneck Model

The central bottleneck model hypothesizes that the simultaneous preparation of multiple movements can create a central processing bottleneck. The effects of this phenomenon are typically identified by longer RT latencies recorded from the second (probed) motor task in a dual-task paradigm (Pashler, 1994). From an information processing perspective, longer response preparation has been identified as a possible contributor to the longer RT latencies measured for the second motor task. To test this idea, Maslovat and colleagues (2013) used a psychological refractory period (PRP) task to manipulate the time interval between the presentation of two stimuli in order to assess overlapping response preparation and response initiation for two ballistic movements. They found that RTs of the second motor task were not influenced when the stimuli for the two tasks were presented more than 500 ms apart; however, RT was significantly slower when the stimuli were presented in quick succession (100 – 200 ms). In other words, in a dual-task paradigm, two ballistic motor tasks can be prepared to the same level as when performed solo if there is sufficient time (> 500 ms) for adequate response preparation for each of the tasks. Interestingly, this same pattern in RT latencies was found when a SAS was presented as the second stimulus (Maslovat et al., 2013). The authors concluded that since the second response was delayed until the first task's response initiation processes were complete, and considering that the other stages of information processing are not measured in a simple RT paradigm, these results support the idea that the central bottleneck occurs during response preparation (Maslovat et al., 2013). Furthermore, this study also provides evidence that a SAS can be a useful tool to investigate response preparation bottlenecks in dual-task paradigms.

5.3. The Central Capacity Sharing Model

The second model under discussion is the central capacity sharing model, which operates on the idea that total information processing capacity is shared fluidly among two or more tasks (Pashler, 1994). In other words, the majority of processing capacity in a dual-task paradigm will be allocated to a primary motor task until the second task's stimulus is presented, in which the two tasks will then share the central processes involved in information processing of movement. As previously discussed, a comparison of RT latencies from two ballistic tasks performed close together (< 500 ms), and the use of a SAS as the stimulus for the second task presented evidence for a response preparation bottleneck (Maslovat et al., 2013). To investigate response preparation and the central capacity sharing model, a SAS can be presented as the stimulus for a probe RT task during the simultaneous performance of a continuous task (Maslovat et al., 2015).

There have only been a few studies using a SAS in a probe RT paradigm, yet a consistent finding in the literature is that SAS RTs are significantly slower in dual-task performances than when performed in single task paradigms; however, SAS trials are still faster than control trials tested in a dual-task paradigm (Begeman et al., 2007; Maslovat et al., 2015). In one study, participants performed a continuous "tremor-like" oscillation movement (~ 3 Hz) with one hand while responding to a probe RT with the contralateral hand. The authors reported that RT latencies for the probe RT task were longer in the dual-task conditions, regardless of the type of stimulus (control or SAS); a result they attributed to reduced response preparation of the probe RT task due to the simultaneous performance of the oscillatory movement (Begeman et al., 2007). The authors suggested that performing oscillatory movements with one hand interfered with the execution of a simple RT task by the other hand (Begeman et al., 2007). In a similar study, Maslovat and colleagues (2015) probed a simple RT task involving wrist extension with one hand while the contralateral hand performed either an easy or difficult continuous motor task for 6 seconds. The authors also reported that RT latencies in both control and SAS

trials of the dual-task paradigm were slower than in single task trials, and that RT latencies were significantly longer in the difficult condition than the easy condition (Maslovat et al., 2015). Together, these studies provide evidence for the idea that the performance of the continuous motor task interferes with the response preparation of the probe RT task, and these interferences are reflected as longer RT latencies.

5.4. Investigating Response Preparation in a Dual-Task Paradigm

Interestingly, the aforementioned studies presented the auditory stimuli randomly during the performances of the continuous tasks, so the timing or location of the probe RT stimuli in relation to each continuous task were not investigated for any effects on RT latencies. Not only could an investigation into the moment of probe RT stimulus presentation during continuous task performance provide further insight into how dual-task movements are prepared, it could also provide further insight into whether there are moments during the performance of a continuous task in which more central resources are required resulting in a reduction of response preparation capacity for the probe RT task.

A hallmark study investigating parallel information processing during a dual-task paradigm was conducted by Posner and Keele (1969). In a probe RT paradigm, participants twisted a handle 150° in order to move a pointer to a large (easy) or small (difficult) target in specific time period (700 ms), while probe stimuli were presented at either 0°, 15°, 45°, 75°, 105°, or 135° of the movement (as reported in Schmidt & Lee, 2011). The authors found that RT latencies were longest when the probe task was performed close to the beginning and end of the twisting movement than compared to the middle locations. Posner and Keele (1969) suggested that the start and finish positions of the twist movement required more central capacity to perform than the middle of the movement, and that these differences were reflected in the longer RT latencies for the probe RT task (Schmidt & Lee, 2011). Furthermore, the authors reported that RT latencies were longer in the difficult condition than the easy condition,

especially closer to the finish locations (i.e., where the target was positioned). The longer RT latencies measured in the difficult condition were also attributed to an increase in attentional demands required by the task (Schmidt & Lee, 2011).

Chapter II: Research Article

Investigating attentional demands of a continuous motor task using probe reaction time and measures of corticospinal excitability

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1. Introduction

Tasks that require the performance of two concurrent actions occur frequently throughout the day; however, these behaviours are studied less frequently than single action tasks (Swinnen, 2004). In a laboratory environment, it is possible to gain insight into the neuromotor functions associated with the simultaneous performance of two tasks by studying the performance of a simple reaction time (RT) task probed within a dual-task paradigm; a method referred to as probe RT (Pashler, 1994).

Response preparation has been identified as a possible contributor to the typical decreases in performance measured within dual-task performances compared to single task performances (Pashler, 1994; Maslovat et al., 2015). Typically, short RT latencies recorded for a highly prepared action are explained using the neural accumulator model of movement preparation (Hanes & Schall, 1996). In this model, advance response preparation increases the membrane potential of motor neurons in the cerebral cortex to a level just below their action propagation threshold. Upon presentation of an imperative stimulus (IS), this heightened level of activation results in faster RTs for a required movement as the neurons are already close to their activation thresholds (Carlsen, Maslovat, et al., 2012). Therefore, probe RT testing paradigms can provide some insight into the level of response preparation achieved for a secondary task during primary task performance (Schmidt & Lee, 2011).

One way to measure the level of response preparation for a task is by replacing the IS with a startling acoustic stimulus (SAS). When a SAS is presented as the Go-signal for a prepared movement, shorter than normal RT latencies are measured due to the involuntary triggering of the highly prepared action in association with the startle reflex (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004b; Valls-Solé, Kumru, & Kofler, 2008). This phenomenon is referred to as the “StartReact effect” which has been established as a reliable measure for advanced response preparation of voluntary actions (Carlsen et al., 2004b; Maslovat et al., 2013, 2015).

There are very few studies using a SAS in a dual-task testing paradigm, yet a consistent finding in the available literature is that SAS RT latencies are significant longer when recorded during dual-task conditions compared to single task conditions (Begeman et al., 2007; Maslovat et al., 2015). In one study, Maslovat and colleagues (2015) probed a simple RT task involving wrist extension with one hand while the contralateral hand performed a primary task involving wrist pronation and supination. The authors reported that the RT latencies in both control and SAS trials of the dual-task conditions were slower than in the single task condition, suggesting that the performance of a primary motor task interferes with the response preparation of a secondary RT task (Maslovat et al., 2015)

Another way to measure response preparation is by using a non-invasive neural stimulation technique called transcranial magnetic stimulation (TMS), (Davranche et al., 2007; Kennefick et al., 2014; Smith, Maslovat, & Carlsen, 2019). TMS uses a copper coil to create a magnetic field over the skull which stimulates cortical neurons (Day et al., 1989; Di Lazzaro & Rothwell, 2014). The size and length of the motor evoked potentials (MEPs) and cortical silent periods (CSPs) measured via EMG upon TMS application can be used as an indicator of the level of corticospinal excitability in the cortex at the time and site of stimulation (Davranche et al., 2007; Ziemann et al., 1997). Specifically, when TMS is applied during response preparation (i.e., before movement initiation), there is evidence that smaller MEPs and smaller CSPs are indicative of higher levels of response preparation for a tested action (Davranche et al., 2007; Hannah et al., 2018; Smith, Maslovat, & Carlsen, 2019).

Interestingly, there have been few investigations into how the characteristics of the primary task chosen for testing have an impact on response preparation of the secondary task. Posner and Keele (1969) looked into this question in their experiment when they had participants twist a handle in order to move a pointer to a target in 700 ms, while probe stimuli were presented at different predetermined locations throughout the movement (as reported in Schmidt & Lee, 2011). The authors found that RT latencies were longest when the probe task

was performed close to the beginning and end of the twist motion than compared to the middle locations, and suggested that this was due to the start and finish positions requiring more central capacity (i.e., demanded more attention) to perform (Schmidt & Lee, 2011).

However, there are many factors that remain unclear about how attentional demands of a primary motor task influence the advance response preparation of another motor task performed within a dual-task testing paradigm. A review of the literature revealed an apparent gap in the knowledge, in that there have been no investigations into how the (potentially variable) attentional demands of a continuous motor task affect response preparation of a concurrent RT task. Thus, our research questions for the present experiment were: are there moments during the performance of a continuous reciprocal task that require higher levels of information processing capacity (i.e., have larger attentional demands), and, if so, do these differences impact response preparation of a secondary motor task as measured by probe RT and measures of corticospinal excitability?

The following experiment was conducted to address these questions. Participants performed a continuous (primary) motor task with their left hand and a probe RT (secondary) task with their right hand. The continuous task involved repeating cycles of wrist flexion and extension, while the probe RT task involved transient isometric wrist extension in response to an auditory stimulus. The timing of the presentation of the auditory stimulus for the probe RT task was linked to the location of the left hand as it cycled through the continuous task. On a selection of trials, this IS was replaced with a SAS in order to measure response preparation for the probe RT task. Additionally, on a separate selection of trials, TMS was applied in place of the IS to assess corticospinal excitability associated with the performance of the secondary task.

We hypothesized that there would be moments within the continuous task that demanded higher amounts of attention (i.e., central capacity). Specifically - based on the results reported in Posner & Keele (1969) - we suspected that the locations associated with the largest

degrees of movement (i.e., end ranges of flexion and extension) would require more attention to perform compared to the middle of each movement. Furthermore, if these increases in attentional demands impacted response preparation of the secondary task, this would be evident by longer RT latencies measured in the control trials, longer RT latencies and lower levels of StartReact responses in the SAS trials, and larger MEP amplitudes and longer CSP durations in the TMS trials.

2. Methods

2.1. Participants

Twenty right-handed or ambidextrous adults (13 female; mean age = 26.6, SD = 5.6) were recruited for this study. All participants had normal or corrected-to-normal vision, were without known sensory or motor dysfunctions, and were naïve to the hypotheses under investigation. There was one testing session for each participant, which took approximately 90 minutes to complete. Prior to the start of a testing session, participants provided informed consent and completed a questionnaire to screen for contraindications to TMS (Rossi, Hallett, Rossini, & Pascual-Leone, 2011) (Appendix A). All aspects of the testing session were conducted in accordance with the ethical guidelines set by the University of Ottawa's Office of Research Ethics and Integrity.

2.2. Experimental Setup and Design

The experimental setup is depicted in Figure 1. Participants sat facing a computer screen with both forearms secured to armrests parallel to the floor, palms facing inwards. The left hand was held in a manipulandum that restricted movement to the wrist, allowing for only flexion and extension to be performed. The dorsum of the right hand rested in a neutral position against a fixed force transducer.

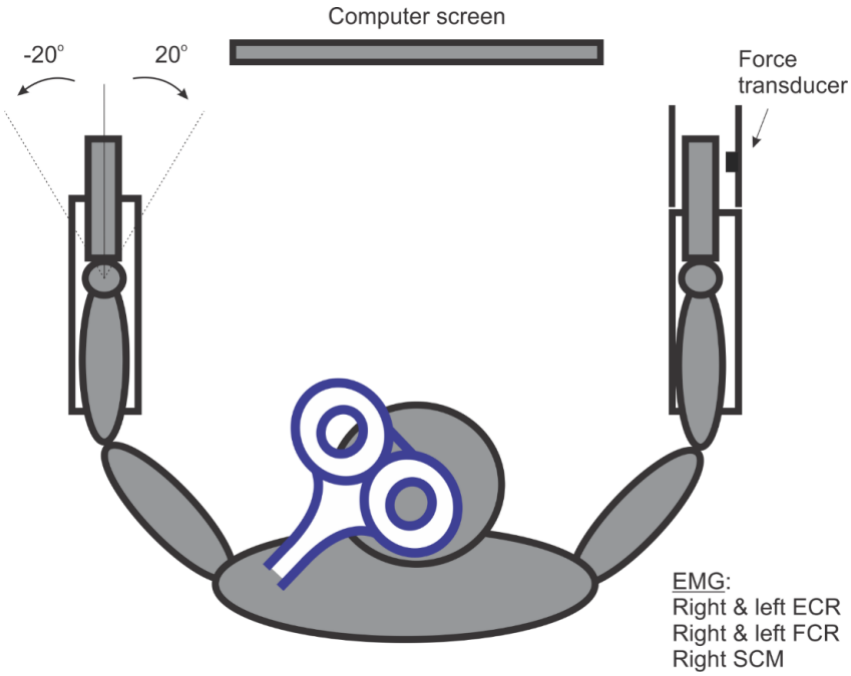

Figure 1. Experimental setup. Each arm was secured to a manipulandum that allowed for flexion and extension to occur at the wrist joint. The left hand performed a continuous tracking movement, alternating between 40° of flexion and 40° of extension. The right hand performed a brief increase in isometric wrist extension against a force transducer upon presentation of an auditory stimulus. EMG was collected from the right and left ECR muscles, right and left FCR muscles, and the right SCM muscle. TMS was applied over the M1 representation of the right ECR muscle located in the left cerebral cortex.

2.2.1. Continuous Tracking Task

Participants were instructed to flex and extend their left wrist to move the manipulandum in order to track the motion of a small circle (i.e., a “ball”) on the computer screen in front of them. Their wrist movement controlled a rectangular cursor on the screen that spanned +/-5° of wrist angle, and the goal was to move this cursor such that the ball was maintained within the extent of the rectangular cursor as long as possible throughout the experiment. The ball moved horizontally (extent +/- 10 cm from center) at 40 cm/s in a sinusoidal velocity pattern. To track the ball, participants completed 40° flexion (track right) and 40° extension (track left) in one second (one cycle), which corresponded to the wrist moving at 80 deg/s (1 Hz). The goal for the task was for participants to track the ball continuously and as accurately as possible throughout

each testing block. Real-time feedback regarding their tracking performance was provided on the computer screen and was continuously visible (Figure 2). In addition, red cursors were displayed at the ball's reversal points (-20° and +20°) in order to provide additional visual information about when the ball would be changing direction.

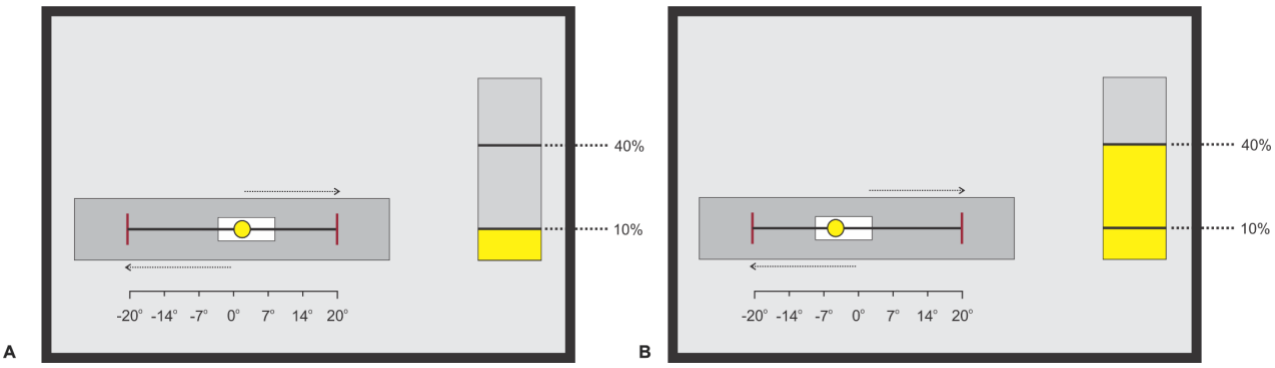

Figure 2. Representation of the visual feedback provided on the computer screen. Participants had continuous visual feedback of their performance for both the continuous task (horizontal bar) and probe RT task (vertical bar). **A**. Throughout the performance of the continuous task, participants maintained an isometric wrist extension contraction at 10% of their MVF with their right wrist (vertical bar; lower line). **B**. Upon presentation of an auditory stimulus, participants increased their force production to 40% MVF (vertical bar; upper line) before returning to the start position of 10% MVF.

2.2.2. Probe RT Task

During performance of the continuous tracking task, participants were asked to perform a light isometric wrist extension with their right wrist, and to increase their force production in response to auditory stimuli. A force transducer (Nano25, ATI Industrial Automation) was attached to the wall of the manipulandum to which their right wrist was secured. Throughout a testing block (i.e., while participants were performing the continuous tracking task with their left hand), participants were asked to maintain light isometric wrist extension with their right wrist measured at approximately 10% of their maximum voluntary force (MVF). Upon the presentation of an auditory stimulus, participants increased their wrist extension to 40% MVF as fast and as accurately as possible, and then returned to the 10% MVF start position.

Participants received online feedback of their force production (% of MVF) continuously throughout each testing block (Figure 2). The target force of 40% MVF has been used previously, as it provides sufficient activation in the target muscles without inducing fatigue (Carlsen, Almeida, & Franks, 2012; Drummond, Cressman, & Carlsen, 2017).

2.3. Maximum Voluntary Force

To determine individual MVF, participants completed three MVF trials prior to the start of testing. Here, participants pushed the dorsum of their right hand against the force transducer as forcefully as possible for 3 seconds. Each trial was followed by approximately 30 seconds of recovery time (Sahaly, Vandewalle, Driss, & Monod, 2001). A participant's MVF was determined as the average peak force across the three trials.

2.4. Auditory Stimuli

There were three different auditory stimuli presented to signal the performance of the probe RT task: a control auditory stimulus (80 dB, 25 ms, 1000 Hz), a SAS (white noise, 120 dB, 25 ms, equal power from 1 Hz to 22 kHz), and TMS (~ 69 – 75 dB; Magstim 200_2 stimulator, 70-mm figure-8 coil; Magstim Company Ltd., Whitland, UK). The control and SAS stimuli were delivered from a loudspeaker (MG Electronics M58-H, frequency response 300 Hz - 11 kHz, rise time <1 ms) positioned 30 cm behind the participant. One of the auditory stimuli was presented as the IS for each of the probe RT trials. The timing of the presentation of each stimulus was programmed to occur in association with the position of the left hand during the continuous tracking task (Figure 3). Within the 80° movement range, there were 5 locations that could prompt the presentation of a stimulus, and the hand moved through each location twice in a movement cycle: once as the hand moved through flexion (-14°, -7°, 0°, 7°, and 14°) and once has the hand moved through extension (14°, 7°, 0°, -7°, -14°).

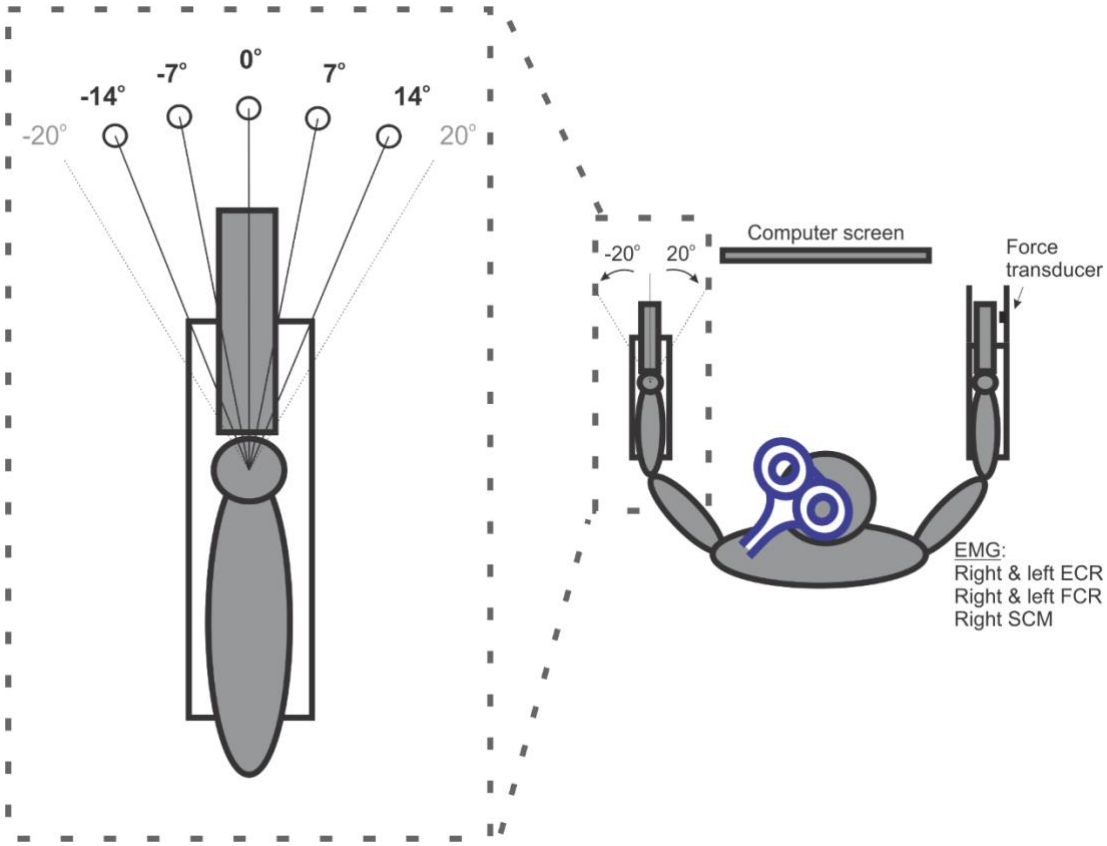

Figure 3. The locations (°) of the left hand probed for the RT task. As the left hand performed the continuous tracking task, the auditory stimuli (Control, SAS, TMS) were presented as the hand passed through one of the 5 locations. Participants moved through each location twice in a cycle (once through flexion and again in extension).

The IS for the probe RT task was presented at one location during each trial. In one testing block, there were 20 probe RT trials completed as 10 TMS trials, 5 SAS trials, and 5 control trials. A custom computer program written in LabView (National Instruments Inc.) controlled the presentation of each stimuli, and the order of presentation was pseudo-randomized so that SAS trials were not scheduled for consecutive presentation or as the first trial in a testing block.

2.5. Recording Equipment

Surface EMG was collected from the right and left ECR muscles and the right and left FCR muscles. EMG from the right SCM muscle was collected to assess for a startle reflex

response in the SAS trials (Carlsen, Maslovat, Lam, Chua, & Franks, 2011). A reference electrode for EMG was placed on the medial epicondyle of the right humerus. Bipolar pre-amplified surface electrodes (Delsys, Bagnoli DE-2.1) were used and placed parallel to the muscle fibers, attached to the skin via double-sided adhesive tape. All of the EMG recording sites were cleaned and prepared prior to application in order to decrease electrical impedance. The electrodes were connected with shielded cabling to an external amplifier system beside the testing location in the testing room. Raw band-passed (20-450 Hz) EMG was digitally sampled at 4 kHz (National Instruments PCIe-6321) using a custom program in LabVIEW (National Instruments Inc.).

2.6. Transcranial Magnetic Stimulation

TMS was delivered using a Magstim 200$_2$ stimulator with a 70-mm figure-8 coil (Magstim Company Ltd., Whitland, UK) over the M1 representation of the right ECR muscle. To locate this region of the left cerebral cortex, the midpoint between a participant's nasion and inion (midsagittal plane), and the left and right pre-auricular notches (horizontal plane) was found. The location 4 cm lateral and 1 cm anterior from this point was marked and used as a starting position to locate the spot over M1 that generated the largest MEPs in the right ECR muscle (Rossini et al., 2015). To do so, TMS pulses were delivered through the coil to areas around the mark in a posterior-anterior direction oriented at 45° towards the contralateral forehead. In order to determine and re-locate the location of this ECR hotspot as accurately as possible, neuro-navigation hardware and software (ANT Neuro Visor 2, Madison, WI) was used throughout hotspotting and throughout all TMS applications in the experimental trials (Rossini et al., 2015).

2.6.1. Active Motor Threshold

After the hotspot was located, the active motor threshold (AMT) for the right ECR muscle was determined. AMT was found while the target muscle held a slight isometric contraction during motor threshold discovery (Ah Sen et al., 2017; Rossini et al., 2015). In the present

study, TMS was pulsed over the ECR hotspot at 30% of maximum stimulator output, and it was gradually increased or decreased until right ECR MEPs had an amplitude of >50 μV on each pulse (Rossini et al., 2015). At this point, the stimulus intensity was gradually modified in stages (by 1%) until individual AMT was found. For the present study, individual AMT was defined as the minimum intensity required for TMS to elicit an MEP of 100 μV in 5 of 10 trials during the slight isometric contraction (approximately 10% of MVF) of the right ECR muscle (Ah Sen et al., 2017; Rossini et al., 2015).

In each TMS probe RT trial, monophasic TMS was delivered at 105% of individual AMT. The timing of TMS application was determined by a custom LabView program and delivered at one of the five predetermined locations the left hand passed through during continuous task performance (Figure 3).

2.7. Experimental Procedure

Each experimental session began with EMG electrode application and TMS hotspotting. Afterwards, individual MVF was determined in order to establish individual force goals for the performance of the probe RT task (40% of MVF), and to be used during AMT discovery (10% of MVF) for TMS application. Finally, individual AMT was established for each participant and their suprathreshold stimulation intensity was determined (105% of individual AMT).

To begin the experiment, participants performed 3 practice blocks to familiarize themselves with the experimental tasks. Each practice block took approximately 30 seconds to complete. In the first practice block, participants practiced the continuous tracking task with their left hand while their right hand rested passively in the right manipulandum. In the second practice block, participants completed 10 trials of the probe RT task with their right hand while their left hand rested passively in the manipulandum. Here, participants practiced moving from 10% to 40% of their MVF (wrist extension) in response to the auditory stimuli. In the third practice block, participants practiced performing the continuous tracking task with their left hand while preparing for and responding to 10 probe RT trials with their right hand. The IS for 8 of

these trials was the control auditory stimulus, and 2 trials involved the SAS. During each of the practice blocks, real-time feedback was constantly visible on screen for each task in order to help participants perform the tasks as accurately as possible.

The experimental blocks followed the practice blocks. There were 10 testing blocks, and each block consisted of 20 probe RT trials. Before each block began, a 15 second countdown was presented on the computer screen to allow the researcher to get into the correct position for the TMS application as guided by the Neuro Navigation program. Participants began each testing block by beginning to perform the continuous tracking task in the last 3 seconds of the countdown, which ensured they were already performing the continuous task at the start of the first trial of each block. In a testing block, a “trial” lasted approximately 4 seconds. The IS for the probe RT task was presented every 2 – 6 seconds; however, the exact length of the trial was dependent on the previous probe location and the next probe location.

The timeline for a “trial” is depicted in Figure 4. A new trial began immediately following the completion of the previous trial. A trial lasted no longer than 4 seconds and always followed the same series of actions. First, the trigger for the specific stimulus assigned to a trial was enabled at a random time point between 1 and 2 seconds. Next, the stimulus (TMS, SAS, or Control) for the trial was presented when the left hand passed through the specific target location randomly assigned to that trial while also moving in the appropriate direction (i.e., flexion or extension). Last, the participant performed the RT task in response to the stimulus. The next trial timeline began shortly after the presentation of the stimulus. The exact timing for stimulus presentation depended on the position of the hand when the trigger was enabled. For example, if the computer selected 1.5 seconds to enable the trigger, the stimulus would be presented sometime within the next second as the left hand moved to the location assigned to the trial.

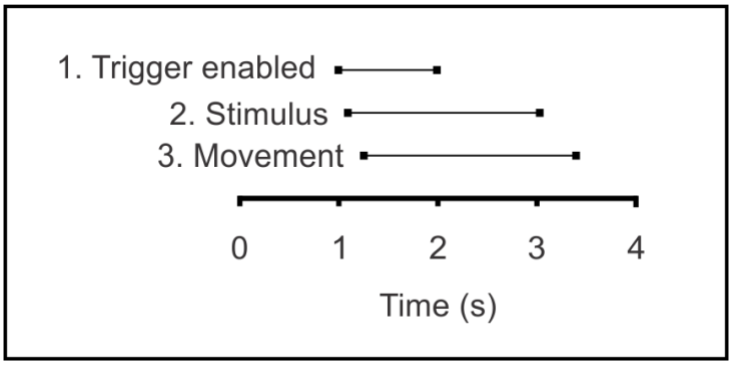

Figure 4. Sequence of events for a probe RT trial. Once the trigger was enabled, the stimulus was presented for the trial once the left hand passed through the assigned target location in the appropriate direction. The next trial began shortly after stimulus presentation.

There were 20 probe RT trials in each testing block (10 TMS, 5 SAS, 5 Control), thus an average testing block lasted approximately 80 seconds. The exact timing for the delivery of the TMS and auditory stimuli were dependent on the participant's left hand, as each trial was randomly linked to a different location of the hand during performance of the continuous tracking task. If the left hand failed to move through the location assigned to a specific trial (e.g., targets with the largest flexion / extension extent), the auditory stimulus was not presented for that trial. Real-time feedback was constantly visible on screen for each trial. Additionally, after each testing block, participants received their median RT performance for all trials within that block as a way to encourage participants to prepare to respond as fast as possible to the probe stimuli.

10 testing blocks were completed in the testing session for a total of 200 probe RT trials (100 TMS, 50 SAS, 50 Control). Participants were encouraged to take as much time as they wanted between testing blocks to ensure maximum engagement in the tasks. The average total testing time for each experimental session was 90 minutes.

3. Data Analysis

3.1. Electromyography

EMG data was collected from the right ECR and FCR muscles, the left ECR and FCR muscles, and the right SCM muscle. EMG onset for all muscles was defined as the moment

following the IS where the rectified and filtered EMG activity reached two standard deviations above baseline (defined as mean EMG activity in a 100 ms interval in the 1 second before IS presentation) and was maintained for at least 20 ms (Carlsen et al., 2011). The EMG data was analyzed using a customized program in LabView (National Instruments Inc.). Premotor reaction time for the probe RT task was defined as the time of EMG onset in the right ECR muscle.

For the SAS trials, EMG data from the SCM muscle was used to confirm a startle reflex response, which was defined as short latency (within 120 ms) EMG onset after the presentation of the SAS (Carlsen et al., 2011; Maslovat et al., 2015). SAS trials with confirmed startle reflex activity were categorized as SCM+ trials, whereas the SAS trials without startle reflex activity were categorized as SCM- trials.

For the TMS trials, EMG data collected from the right ECR muscle was analyzed in a customized LabView program (National Instruments Inc.), where the MEP amplitude and CSP duration for each trial was identified. MEP amplitude was defined as the greatest peak-to-peak amplitude recorded in a 30 ms window after the application of TMS, and CSP duration was defined as an apparent pause in ECR EMG activity between the TMS application and return to baseline (i.e., pre-stimulus) EMG activity (Fuhr et al., 1991; Orth & Rothwell, 2004).

3.2. Force and Reaction Time

Participants' raw force data was collected from the force transducer. Force onset was defined as the moment following IS presentation that force output reached at least 12% of individual MVF and exceeded two standard deviations above baseline levels. Peak force was defined as the highest force value within a trial and was expressed as a percentage of individual MVF.

3.3. Data Exclusion Criteria

All 20 participants were included in the analyses of this study. The performance within the practice trials was not analyzed. Each participant completed 200 experimental trials; thus,

4000 trials were considered for analysis (2000 TMS trials, 1000 Control trials, 1000 SAS trials). Experimental trials were excluded if an error was identified within a trial. TMS trial errors were categorized as either: “no stimulus” (TMS was not delivered) or “bad TMS” (data collected was insufficient; e.g., TMS pulse occurred very late in the recording window). RT errors included: “no movement performed” (failure to respond to the stimulus), “anticipation” (RT < 50 ms), “slow response” (RT > 350 ms), or “no stimulus” (no IS presentation). A summary of all the errors identified is presented in Table 1.

Table 1. *Summary of the trials excluded from data analysis.*

Error Type	Description	Number of Trials
TMS Trials		
No Stimulus	TMS was not delivered	146
Bad TMS	Data insufficient for analysis	89
	Total TMS Errors:	**235**
RT Trials		
Anticipation	RT < 50 ms	3
Slow RT	RT > 350 ms	87
No Stimulus	Auditory stimulus not presented	198
Movement Error	No movement performed	12
	Total RT Errors:	**300**
Total Errors:	**535/4000**	
% of collected trials:	13.4%	

3.4. Statistical Analysis

Analysis of the data was completed with Microsoft Excel and IBM SPSS Statistics. Mean values for each location (10) probed with each IS condition (3) were determined. Repeated measures analysis of variance (RM-ANOVA) statistical tests were used to investigate the results for statistically significant differences. The results of the RM-ANOVAs are described in the following Results section. Differences with a probability of less than 0.05 were considered

significant. Greenhouse-Geisser-corrected *p* values were reported if sphericity was violated. Post hoc analyses were conducted using Tukey's Honestly Significant Differences (HSD) post-hoc tests to further understand any significant interactions.

4. Results

4.1. Reaction Time

Premotor RT was collected on all control and SAS trials. Throughout the testing session, participants received their median RT for each testing block as feedback on their performance (Figure 5). The median RT for the first practice block consisting of only the probe RT task was 225.8 (SD = 53.6) ms, which increased to 279.0 (SD = 46.7) ms in the dual-task practice block. In the experimental trials, the median RT (control, SAS, and TMS trials) across all blocks was 222.8 (SD = 45.94) ms.

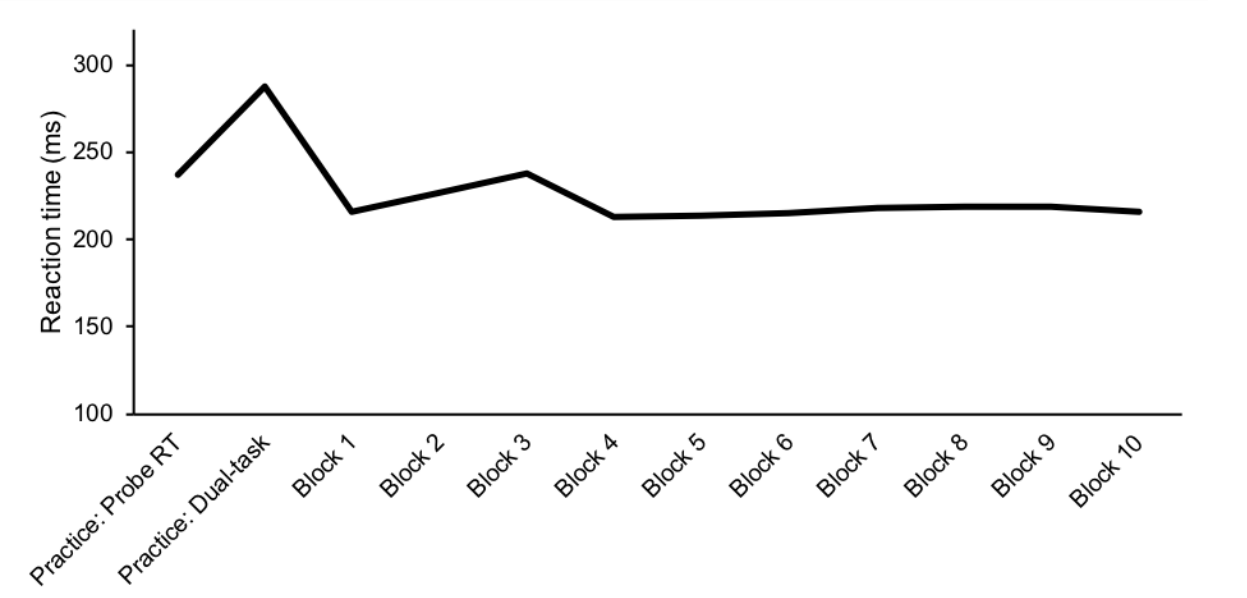

Figure 5. Median premotor RT by testing block. Participants received their median RT as feedback on their performance during testing at the completion of each testing block.

The timing for the presentation of the IS for the probe RT task was linked to 5 locations of the left hand (Figure 6A). Mean premotor RT for the probe RT task was recorded for the control and SAS trials. The mean probe RT (ms) for all the trials was 188.7 (SD = 42.1) ms. Mean RT for all the control trials was 219.0 (SD = 31.6) ms, and 158.4 (SD = 26.7) ms for all the SAS trials (Figure 6B). The mean RT for each participant was calculated for each of the 10 locations. A 2 Stimulus (Control, SAS) x 10 Location RM-ANOVA revealed a significant main effect of Stimulus ($F\ (1,19)$ = 380.215, P < 0.001), indicating that the mean RT in SAS trials was 61 ms faster than the control trials. The main effect of Location was not significant ($F\ (9,171)$ = 1.146, P = 0.333) and there were no significant interactions (P > 0.05).

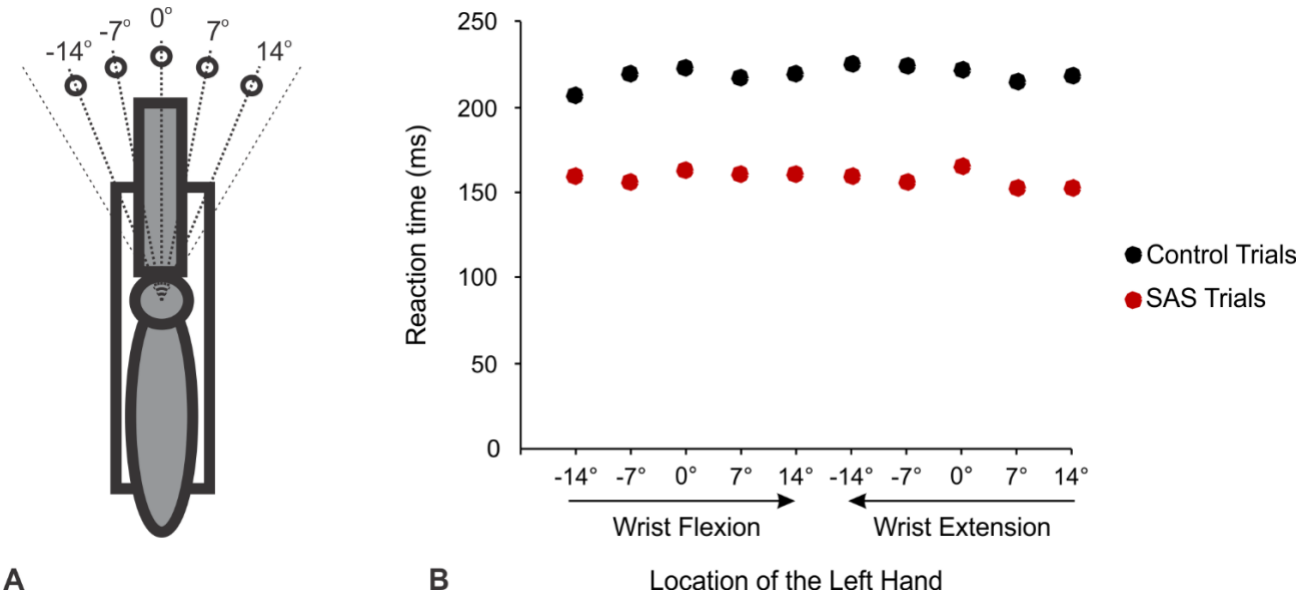

Figure 6. **6A.** Representation of the locations of the left hand. **6B.** Mean premotor RT for the two conditions at the 10 locations. There was a significant main effect of stimulus, indicating that premotor RT was faster in SAS trials compared to control trials. There were no significant differences in RT at the 10 locations, and there were no significant interactions.

In order to further understand the attentional demands within the continuous task, the 10 locations for the left hand were grouped according to different phases of the movement (Figure 7). First, the locations were grouped into direction, as either Flexion (-14°, -7°, 0°, 7°, 14°) or Extension (14°, 7°, 0°, -7°, -14°) (Figure 7A). A 2 Stimulus (Control, SAS) x 2 Direction (Flexion, Extension) RM-ANOVA was conducted and revealed a significant main effect of Stimulus, indicating that the mean RT in SAS trials was 62 ms faster than control trials ($F\ (1,19)$ = 448.385, $P < 0.001$); however, the main effect of Direction was not significant ($F\ (1,19)$ = 0.008, $P = 0.932$) and there were no significant interactions ($P > 0.05$) (Figure 8).

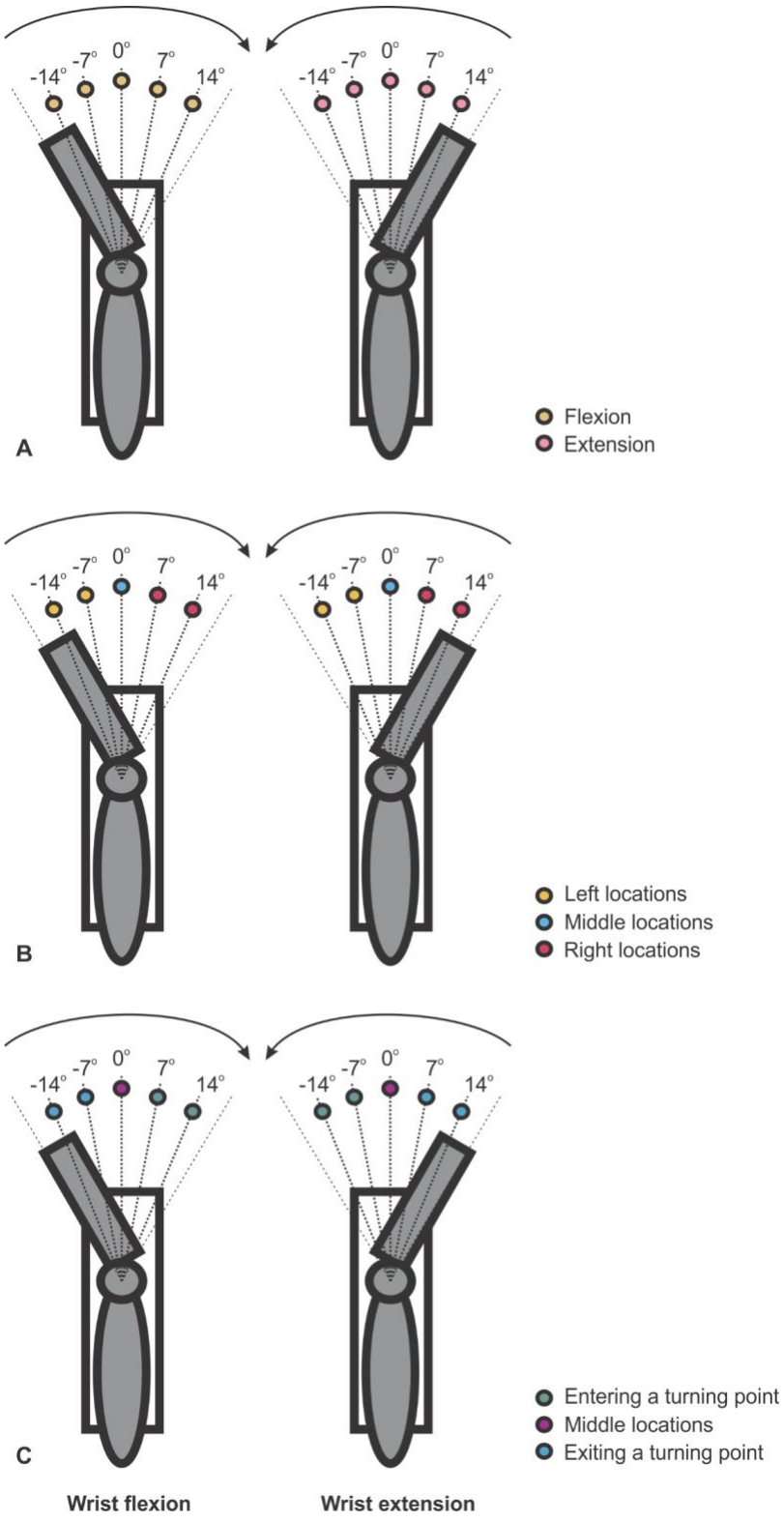

Figure 7. The locations of the left hand were grouped into 3 locations. **7A.** The locations grouped by Direction (Flexion and Extension). **7B.** The locations grouped by Location (Right, Middle, and Left). **7C.** The locations grouped by Turning Point (Entering a turning point, Middle locations, and Exiting a turning point).

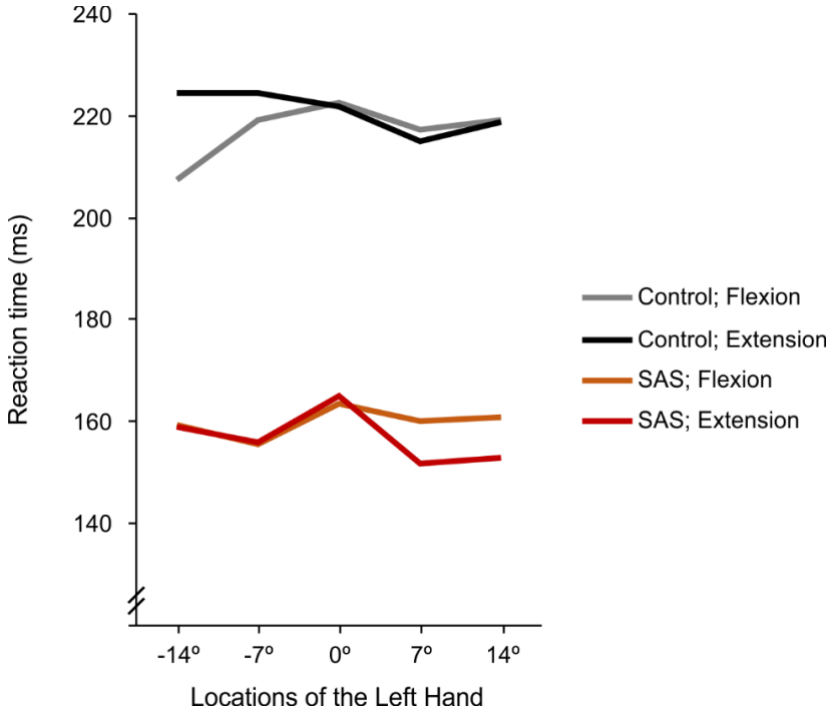

Figure 8. Mean premotor RT for the two conditions as a function of Direction. There were no significant differences between the locations in flexion or extension, and there were no significant interactions.

Next, the locations were grouped positionally as either “right” locations (i.e., closest to the midline), middle locations (i.e., neutral), and “left” locations (i.e., furthest from the midline) (Figure 7B). A 2 Stimulus (Control, SAS) x 3 Location (Right, Middle, Left) RM-ANOVA revealed the significant main effect of Stimulus ($F\ (1,19)$ = 453.021, P < 0.001), indicating that the mean RT in SAS trials was 61 ms faster than the control trials. The main effect of Location was not significant ($F\ (2,38)$ = 1.857, P = 0.170) and there were no significant interactions (P > 0.05).

Finally, the probed locations were grouped to describe the functional phase of the hand’s position as it changed direction during the continuous task (i.e., moved from flexion into extension), thus, the locations were grouped in association with the hand exiting a turning point (-14° and -7° in flexion and 14° and 7° in extension), the middle locations (0° in flexion and extension), and the locations associated with the hand entering a turning point (7° and 14° in

flexion and -7° and 14° in extension) (Figure 7C). Mean probe RT for each of the groups are presented in Figure 9. A 2 Stimulus (Control, SAS) x 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA revealed the significant main effect of Stimulus ($F\ (1,19)$ = 424.442, P < 0.001), indicating the mean RT in SAS trials was 61 ms faster than the control trials. There was also a significant main effect of TurningPoint ($F\ (2,38)$ = 3.527, P = 0.039), suggesting that participants were 7 ms faster in performing the probe RT task when the auditory stimuli were presented when the left hand exiting a turning point (i.e., beginning a movement in a new direction) than when the hand was in the middle of a movement, and 4 ms faster when exiting a turning point than entering a turning point (Figure 9). There were no significant interactions (P > 0.05).

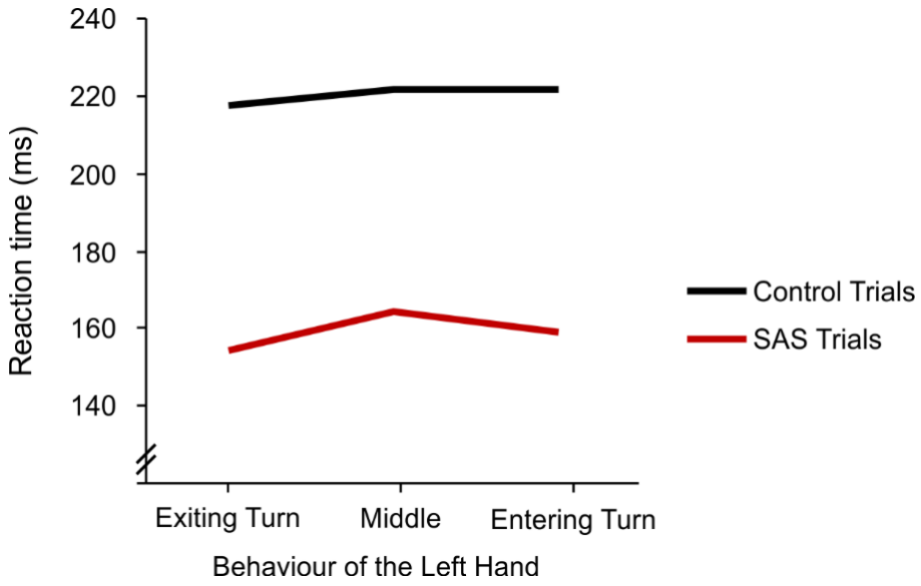

Figure 9. Mean probe RT as a function of Turning Point. Mean RT for the control trials was 217.4 (SD = 26.5) ms (Exiting Turn), 222.0 (SD = 25.1) ms (Middle), and 221.6 (SD = 24.2) ms (Entering Turn). For the SAS trials, mean RT was 154.2 (SD = 21.6) ms (Exiting Turn), 164.2 (SD = 25.7) ms, and 158.8 (SD = 24.3) ms (Entering Turn).

4.2. Transcranial Magnetic Stimulation

The mean TMS intensity of application was 34% (SD = 0.07). Mean MEP amplitudes and CSP durations for each participant were calculated for each location. Two separate 10

Location (all locations) RM-ANOVAs were conducted for each of the measures, and there were no significant main effects found for either the MEP amplitudes (*F (9,171)* = 2.146, *P* = 0.071) or CSP durations (*F (9,171)* = 0.778, *P* = 0.637).

Additionally, participants' mean MEP amplitudes and CSP durations per location were grouped into different movement phases and three separate RM-ANOVAs were conducted on the data. The results are described below.

4.2.1. MEP Amplitude

Although a 2 Direction (Flexion, Extension) RM-ANOVA did not reveal a significant main effect of Direction (*F (1,19)* = 0.420, *P* = 0.525), the 3 Location (Right, Middle, Left) RM-ANOVA revealed a significant main effect of Location (*F (2,38)* = 6.632, *P* = 0.003), suggesting that MEP amplitudes were .038 mV (SD = 0.05) smaller as the left hand passed through the right-side locations (i.e., closest to a participant's midline) compared to the middle (i.e., neutral) positions, and .028 mV (SD = 0.05) smaller at the right-side locations when compared to the left-side locations (i.e., furthest from the midline) (Figure 10).

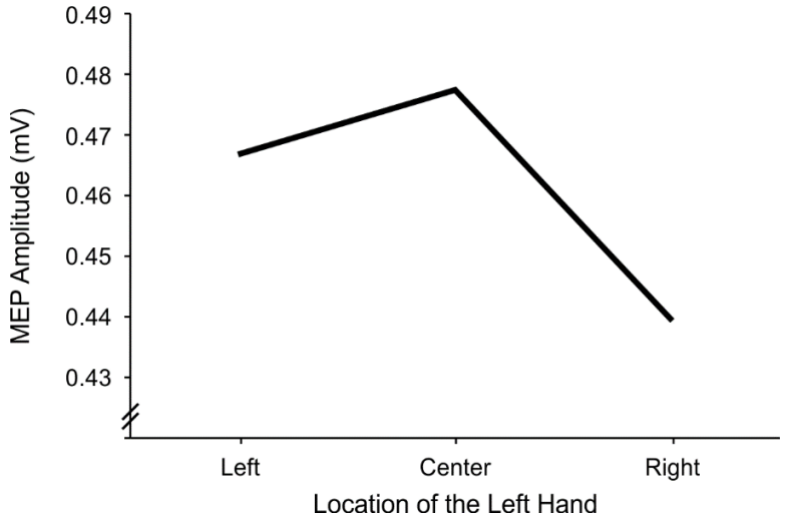

Figure 10. Mean MEP amplitude (mV) as a function of Location. MEP amplitudes were significantly smaller at the right locations (mean MEP = 0.439 (SD = 0.18) mV) when compared to the center (mean MEP = 0.478 (SD = 0.21) mV) and left (mean MEP = 0.467 (SD = 0.19) mV) locations.

Furthermore, a 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA also revealed a significant main effect (*F (2,38)* = 4.331, *P* = 0.020) of Location, indicating that MEP amplitudes were 0.023 mV (SD = 0.05) smaller at the locations that corresponded with the left hand exiting a turning point (i.e., starting to move in a new direction) when compared to the middle locations, and 0.028 mV (SD = 0.05) smaller when the hand was entering a turning point (i.e., ending a movement in a direction) when compared to the middle locations (Figure 11).

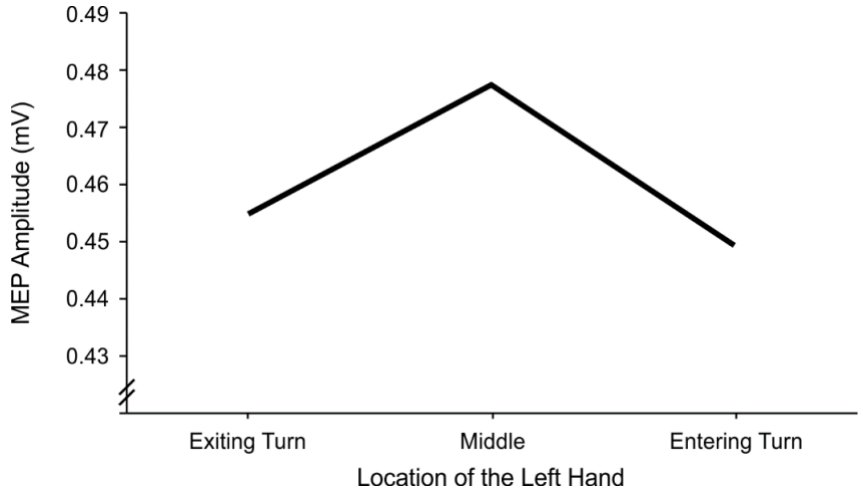

Figure 11. Mean MEP amplitude (mV) as a function of Turning Point. MEP amplitudes were significantly larger at the middle locations (mean MEP = 0.478 (SD = 0.21) mV) when compared to the locations associated with exiting a turning point (mean MEP = 0.455 (SD = 0.19) mV) and entering a turning point (mean MEP = 0.449 (SD = 0.19) mV).

4.2.2. Cortical Silent Period Duration

A 2 Direction (Flexion, Extension) RM-ANOVA revealed a significant main effect (*F (1,19)* = 5.330, *P* = 0.032) of Direction, indicating that CSP durations were 1.6 ms longer when the left hand was moving through extension than when it was moving through flexion (Figure 12). A 3 location (Right, Middle, Left) RM-ANOVA did not reveal a significant main effect of Location (*F (2,38)* = 1.061, *P* = 0.356), nor did a 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA (*F (2,38)* = 1.295, *P* = 0.286).

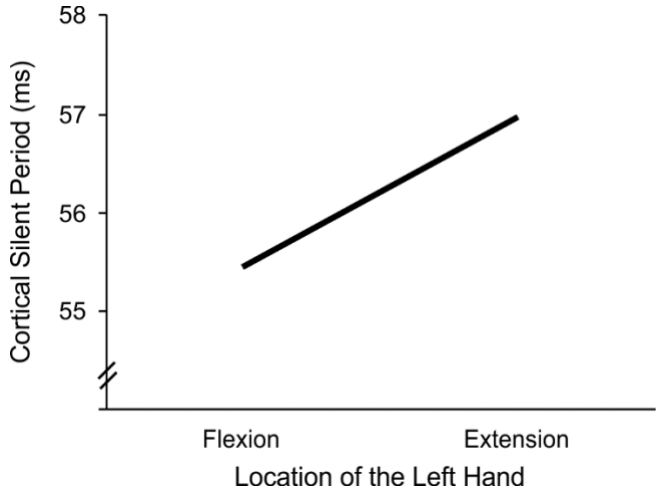

Figure 12. Cortical silent period (CSP) duration (ms) as a function of Direction. Mean CSP duration in flexion was 55.4 (SD = 25.4) ms and mean CSP duration in extension was 57.0 (SD = 24.5) ms.

4.3. SCM EMG Activity

Each participant completed 50 SAS trials. The percentage of SCM+ responses per participant is depicted in Figure 13. The mean percentage of SCM+ responses was 16%, with the highest individual response at 90%, and the lowest at 0%. Only 20% (4/20) of participants had an SCM+ response over 40% in the SAS trials.

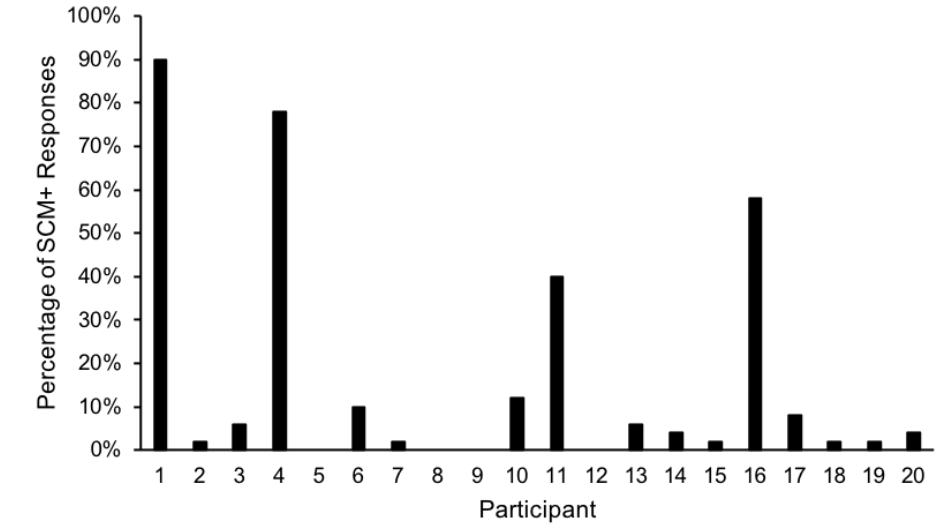

Figure 13. Percentage of SCM+ responses per participant in the SAS trials. The average percentage of SCM+ responses was 16% across participants. Only 20% of participants had a SCM+ response of over 40% of their trials.

A 10 Position (all locations) RM-ANOVA was conducted to analyze for differences in SCM activation at the different locations; however, there was no significant main effect of Position ($F\ (9,171)$ = 0.578, P = 0.814). Furthermore, participants' mean SCM activation (%) per location were grouped into different movement phases and three separate RM-ANOVAs were conducted on the data. Results indicated there were no significant differences found in a 2 Direction (Flexion, Extension) RM-ANOVA ($F\ (1,19)$ = 0.077, P = 0.784), a 3 Location (Right, Middle, Left) RM-ANOVA ($F\ (2,38)$ = 0.412, P = 0.665), or a 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA ($F\ (2,38)$ = 0.036, P = 0.965).

4.4. Continuous Motor Task: Root Mean Square Error (RMSE)

A secondary analysis was conducted on the performance of the continuous task before and after IS presentation for the probe RT task. The goal for the continuous task was to track the "ball" on the computer screen as accurately as possible. In order to understand participants' performance, the difference in their wrist position (°) in relation to the ball's position (°) was calculated as the mean RMSE in the time before (1 s) and after (1 s) the IS for the probe RT task.

Mean RMSE was calculated for each participant at each of the 10 locations and a 2 Time (Pre, Post) x 2 Stimulus (Control, SAS) x 10 Location (all locations) RM-ANOVA was conducted. Results revealed a significant main effect of Time ($F\ (1,19)$ = 66.299, P < 0.001), suggesting that, on average, continuous task performance was 3.15° worse following the presentation of the IS than before the IS. There was also a significant main effect of Stimulus ($F\ (1,19)$ = 37.225, P = 0.012), revealing that participants' performance was 0.43° worse in SAS trials compared to control trials. Additionally, there was a significant main effect of Position ($F\ (9,171)$ = 6.062, P < 0.001), indicating that RMSE was different depending on location.

Furthermore, there was a significant Stimulus x Time interaction ($F\ (1,19)$ = 29.256, P = 0.003). Post-hoc tests indicated that while there were no differences in performance between

the control or SAS conditions at the two time points, RMSE was 2.77° greater PostProbe than PreProbe in the control trials, and 3.53° greater in the SAS trials (Figure 14). Furthermore, there was a significant Time x Position interaction ($F\ (9,171)$ = 10.363, P < 0.001). All other interactions were not significant (P > 0.05).

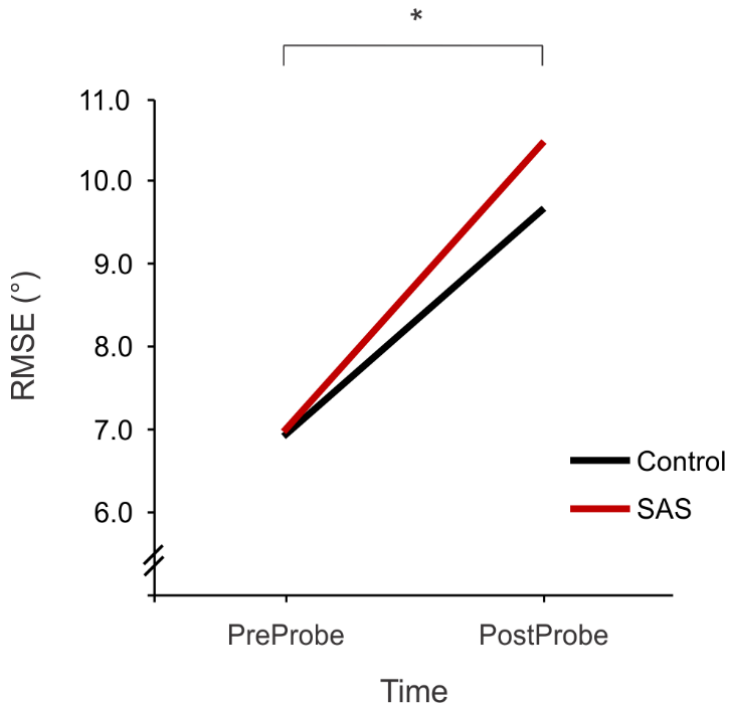

Figure 14. Mean RMSE (°) per condition as a function of Time. A 2 Time (Pre, Post) x 2 Stimulus (Control, SAS) x 10 Location (all locations) RM-ANOVA revealed a significant Time x Stimulus interaction. Post hoc tests indicated that although there were no differences between IS conditions at either of the time points, RMSE was 2.77° greater after the IS in the control trials than before the IS, and 3.53° greater in the SAS trials.

To further understand the Time x Position interaction within the RMSE data, mean RMSE from each of the locations was grouped into the different movement phases and three separate RM-ANOVAs were conducted. A 2 Time (Pre, Post) x 2 Stimulus (Control, SAS) x 2 Direction (Flexion, Extension) RM-ANOVA revealed a significant main effect of Time ($F\ (1,19)$ = 69.107, P < 0.001), indicating that continuous task performance was 3.33° worse following the presentation of the IS. There was also a significant main effect of Stimulus ($F\ (1,19)$ = 5.031, P = 0.037), revealing that continuous task performance was 0.33° worse in the SAS trials

compared to the control trials. The main effect of Direction was not significant ($F\ (1,19)$ = 0.432, P = 0.519). Furthermore, there was a significant Time x Stimulus interaction ($F\ (1,19)$ = 7.735, P = 0.012). Post-hoc testing indicated that while there were no differences in performance between stimuli at the two time points, RMSE was 3.00° greater PostProbe than PreProbe in the control trials and 3.65° greater in the SAS trials. Furthermore, while there was also a significant Stimulus x Direction interaction ($F\ (1,19)$ = 8.465, P = 0.009), post hoc testing indicated that there were no significant differences between any of the groups. All other interactions were not significant ($P > 0.05$).

Next, a 2 Time x 2 Stimulus x 3 Location (Right, Middle, Left) RM-ANOVA also revealed significant main effects of Time ($F\ (1,19)$ = 68.921, $P < 0.001$), indicating that continuous task performance was 3.30° worse following the presentation of the IS. There was also a significant main effect of Stimulus ($F\ (1,19)$ = 5.976, P = 0.024), revealing that participants' performance was 0.38° worse in the SAS trials compared to the control trials. The main effect of Location was not significant ($F\ (2,38)$ = 2.022, P = 0.146). There was a significant Time x Stimulus interaction ($F\ (1,19)$ = 8.011, P = 0.011), with post-hoc testing again indicating that while there were no differences in performance between the IS groups, RMSE was 2.95° greater after the presentation of the stimulus than before in the control trials, and 3.65° greater after a SAS in the SAS trials. All other interactions were not significant ($P > 0.05$).

Lastly, a 2 Time x 2 Stimulus x 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA revealed a significant main effect of Time ($F\ (1,19)$ = 66.561, $P < 0.001$), indicating that continuous task performance was 3.23° worse following the presentation of the IS. There was also a significant main effect of Stimulus ($F\ (1,19)$ = 6.497, P = 0.020), revealing that continuous task performance was 0.36° worse in the SAS trials compared to the control trials. Furthermore, there was a significant main effect of TurningPoint ($F\ (2,38)$ = 19.205, $P < 0.001$), indicating that participants were more accurate when the left hand was exiting a turning point (i.e., starting to

move in a new direction). Specifically, performance was 0.84° worse when the hand was passing through the middle locations than compared to when the hand was exiting a turn, and performance was 1.08° worse when the hand was entering a turning point compared to when it was exiting a turning point (Figure 15). Additionally, there was a significant Time x Stimulus interaction ($F\ (1,19)$ = 9.129, P = 0.007). Post-hoc testing indicated that while there were no differences in performance within the IS groups at the two time points, RMSE was 2.87° greater PostProbe than PreProbe in the control trials and 3.60° greater in the SAS trials. There was also a significant Time x TurningPoint interaction ($F\ (2,38)$ = 38.090, P < 0.001). Post-hoc testing indicated that while there were no differences between the locations during PreProbe performance, there were significant differences in RMSE in the PostProbe performances *and* significant differences between PreProbe and PostProbe performance (Figure 15). Specifically, participants were 1.60° less accurate in the middle locations than when exiting a turning point, and 2.35° less accurate when entering a turning point compared to exiting a turning point. Furthermore, when exiting a turning point, participants were only 1.87° worse in their PostProbe performance compared to PreProbe, whereas they were 3.39° worse at the middle locations, and 4.41° worse at the End locations. All other interactions were not significant (P > 0.05).

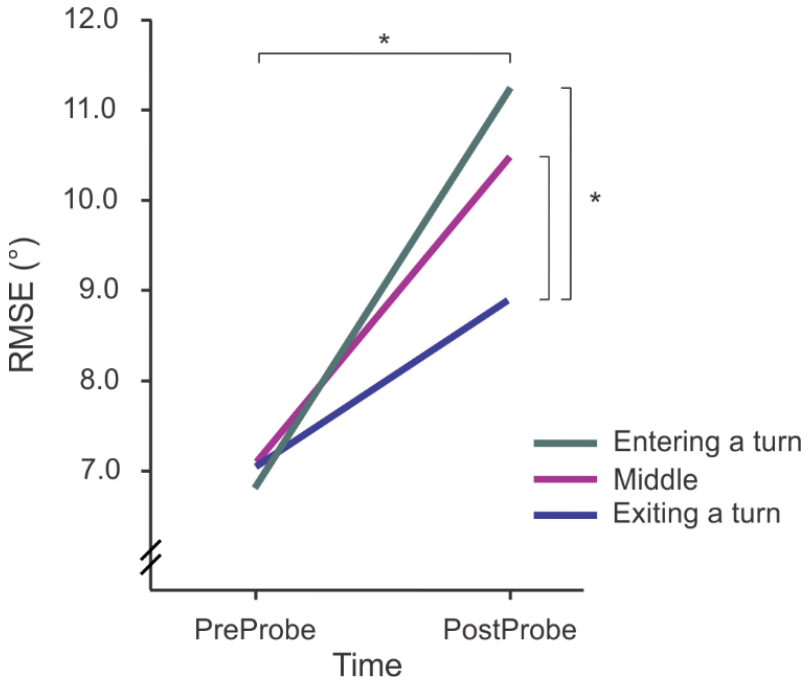

Figure 15. Mean RMSE (°) per condition as a function of Time (Turning Point locations). A RM-ANOVA revealed a significant Time x Turning Point interaction, indicating that participants were less accurate in the continuous task after the stimulus was presented for the probe RT task. Furthermore, participants were less accurate when their left hand was entering a turning point or at the middle locations, compared to when they were exiting a turning point.

4.5. Probe RT Task: Force Production

Secondary analysis was also conducted on the performance of the probe RT task. The goal of the probe RT task was for participants to increase the isometric force produced by their right wrist extensors from 10% to 40% of individual MVF upon IS presentation. Mean MVF was recorded at 5.14 (SD = 1.44) N. The mean peak force production data for each participant is depicted in Figure 16.

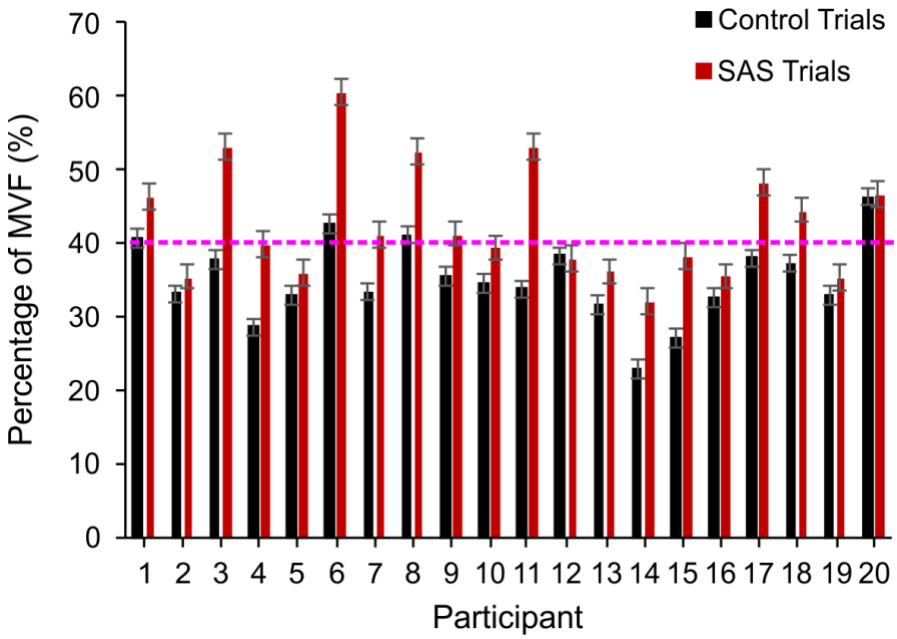

Figure 16. Mean peak force production (% of individual MVF) for each participant. Overall, the mean % of MVF for the control trials was 35.0% (SD = 6.47) and 42.7% (SD = 7.65) for the SAS trials. The pink line represents the target force goal of 40% individual MVF.

Generally, the mean peak force across all experimental trials was 38.8% (SD = 8.42). In control trials, mean peak force was measured at 35.0% (SD = 6.47), whereas mean peak force for the SAS trials was measured at 42.5% (SD = 8.57). A 2 Stimulus (Control, SAS) x 10 Location (all locations) RM-ANOVA revealed a significant main effect of Stimulus ($F\ (1,19)$ = 36.182, $P < 0.001$), suggesting that participants produced 7.5% more force in response to a SAS than to the control stimulus. The main effect of Location was not significant ($F\ (9,171)$ = 1.889, $P = 0.105$) and there were no significant interactions ($P > 0.05$).

The force production data for the probe RT task was also grouped into different movement phases. A 2 Stimulus (Control, SAS) x 2 Direction (Flexion, Extension) RM-ANOVA revealed a significant main effect of Stimulus ($F\ (1,19)$ = 34.980, $P < 0.001$), indicating that participants produced 7.5% more force in SAS trials compared to control trials. The main effect of Direction was not significant ($F\ (1,19)$ = .537, $P = 0.473$) and there were no significant interactions ($P > 0.05$). A 2 Stimulus x 3 Location (Right, Middle, Left) RM-ANOVA also

revealed a significant main effect of Stimulus ($F\ (1,19)$ = 35.187, P < 0.001), indicating that participants produced 7.5% more force in the SAS trials compared to the control trials. The main effect of Location was not significant ($F\ (2,38)$ = .758, P = 0.476) and there were no significant interactions (P > 0.05). Finally, a 2 Stimulus (Control, SAS) x 3 TurningPoint (Exit, Middle, Enter) RM-ANOVA revealed a significant main effect of Stimulus ($F\ (1,19)$ = 34.716, P < 0.001), indicating that participants produced 7.4% more force in the SAS trials compared to the control trials; however, the main effect of TurningPoint was not significant ($F\ (2,38)$ = 2.063, P = 0.141) and there were no significant interactions (P > 0.05).

5. Discussion

5.1. Attentional Demands of a Continuous Motor Task

The purpose of the present experiment was to determine if certain moments within a continuous motor task demand more central capacity (i.e., attention) by examining probe RT and measures of corticospinal excitability. RT differences were found between the trigger locations of the continuous task, with the longest RT latencies recorded at the middle locations (corresponding to 0° wrist flexion and extension), as well as at the locations that corresponded with the left hand entering a turning point within the movement cycle (Figure 9). In contrast, the shortest RT latencies were found at the locations that corresponded with the left hand exiting a turning point. In the TMS trials, larger MEP amplitudes were measured at the locations associated with longer RT latencies, and smaller MEP amplitudes were measured at the locations associated with shorter RT latencies (Figure 11).

To our knowledge, this is the first study to investigate how attentional demands within a continuous primary motor task differ by fixing the presentation of the probe RT stimulus to the location of the limb performing the primary task. To review, a similar study was conducted by Posner and Keele (1969) in which they investigated the attentional demands of a discrete primary motor task in a probe RT paradigm. In their study, the authors had participants perform

a wrist-twist (pronation/supination) action while an RT task was probed at different locations (°) within the wrist-twist movement and they found that the longest RT latencies were measured at the start or at the end of the primary movement, and the shortest RT latencies were measured at the middle locations (Posner & Keele, 1969; as reported in Schmidt & Lee, 2011, p 119). It was suggested that these results were due to the start and finish positions of the discrete wrist-twist movement demanding more central processing than the middle portion of that movement (Schmidt & Lee, 2011).

Although we initially expected to find similar results to Posner and Keele, the present experiment found the middle locations to have the longest RT latencies, and one reason for this could have to do with the different tasks used in each experiment. Posner & Keele (1969) employed a discrete targeting task that involved moving a pointer to a target within a time constraint (700 ms), whereas the primary task in the present experiment was a continuous tracking task involving 40° of wrist flexion and extension every second (80° in 1000 ms) to track a ball on a computer screen (Figure 2). During performance of this task, participants watched the ball as it moved back and forth in a straight horizontal line, and this line matched the movement plane of their left wrist as it flexed and extended to follow the ball right and left. As such, there were two “turning points” in each movement cycle, with one occurring as the hand completed 40° of flexion and switched to extension, and the other occurring as the hand completed 40° of extension and switched to flexion. It is likely that participants would have had to start preparing to change direction as their left hand passed through the middle locations and moved towards the turning point locations. In other words, when the RT task was probed at the middle locations, the continuous task was demanding more attention as preparation was underway to accurately reverse direction at the required turning point.

From a timing perspective, the wrist was required to change direction approximately every 500 ms. Previous studies using a psychological refractory period (PRP) paradigm have

shown that RT of two sequentially presented stimulus-response pairs is significantly slower if the stimuli are presented in quick succession (100 – 200 ms); however, two motor tasks can be prepared sufficiently in close succession if there is enough time (> 500 ms) for adequate response preparation for each task to occur (Lien & Proctor, 2002; Maslovat et al., 2013; Pashler, 1994). This decrease in performance has been attributed to a response preparation bottleneck occurring when the two movements are attempted to be prepared simultaneously (Maslovat et al., 2013).

In the present study, the simultaneous response preparation for the turning point and the probe RT task may have contributed to the longer RT latencies measured at the middle of the movement and at the locations before the turning point, for these locations corresponded with a time range of approximately 250 – 100 ms *before* the wrist would change direction. In other words, it is possible that if participants were asked to perform the secondary task within this time window, the attentional demands of the continuous task as the wrist prepared to change direction would conflict with response preparation for the probe RT task. In contrast, it is possible that at the locations that corresponded with the left hand *exiting* a turning point, there was adequate time separating the response preparation occurring for the continuous task and for the probe RT task, allowing the required central processing to occur and faster premotor RTs to be recorded.

A similar pattern was also evident in the TMS trials, as the larger MEP amplitudes were associated with the middle locations (Figure 10 & 11). Previous work has associated smaller MEP amplitudes with higher levels of response preparation due to a higher amount of activity in intracortical inhibitory processes that are holding the movement until stimulus identification (Davranche et al., 2007; Hannah et al., 2018; Kennefick et al., 2014; Smith, Maslovat, & Carlsen, 2019; Touge, Taylor, & Rothwell, 1998). For example, Touge et al. (1998) reported smaller MEP amplitudes in association with shorter RT latencies when assessed in a simple RT paradigm with a fixed (i.e., predictable) foreperiod – a testing paradigm that allows for a high

level of response preparation to be achieved. Furthermore, it has been reported that “optimal response preparation”—evident by low RT latencies and small MEP amplitudes—was found 300 – 400 ms following a warning signal in a simple RT task with a predictable foreperiod (Smith, Maslovat, Drummond, & Carlsen, 2019). Taken together with the RT measurements, the MEP results in the present experiment suggest that optimal response preparation for the probe RT task was not able to occur at the middle locations, likely due to an increase in central capacity requirements for the continuous task as the left hand prepared to approach a turning point.

5.1.1. StartReact effect and response preparation

A startling acoustic stimulus (SAS) was occasionally presented in place of the control probe RT stimulus for experimental trials, as a SAS has previously been used to assess preparation levels of motor responses within dual-task testing paradigms (Begeman et al., 2007; Maslovat et al., 2015). Typically, SAS trials are assessed for the presence of the “StartReact” effect, which is the rapid involuntary triggering of a prepared movement in association with short latency EMG activity in the SCM muscle. The absence of EMG activity in the SCM muscle is usually indicative of a low level of response preparation for the required motor task (Carlsen et al., 2012; Maslovat et al., 2015).

In the present study, a 120 dB white noise SAS was presented in place of the IS in 25% of the experimental trials. This type of SAS has been used previously and is usually a reliable stimulus for eliciting a startle reflex (SCM+) response in at least 60% of SAS trials *if* participants are fully prepared (Carlsen, 2015). Previous work using a SAS in a dual-task paradigm has also reported high percentages of SCM+ trials (55 – 70%), which supports the idea that response preparation of a secondary motor task can be achieved at a high level while performing a concurrent motor task (Maslovat, Carter, & Carlsen, 2017; Maslovat et al., 2015). For example, Maslovat and colleagues (2015) reported 55% SCM+ responses in a dual-task condition containing an easy motor task, and 61% SCM+ responses in the dual-task condition containing

a difficult motor task (Maslovat et al., 2015). In addition, Maslovat et al. (2017) reported 70% SCM+ responses in a bimanual task involving in-phase or anti-phase elbow flexion and extension movements. Nevertheless, in the present study, there was a very low percentage of SCM+ responses within the SAS trials in that the average percentage of SCM+ responses was 16% (Figure 13). Furthermore, only 20% (4/20) of participants had SCM+ responses in over 40% of their SAS trials. Due to the extremely low percentage of SCM+ trials in most participants, no comparison was run between RTs measured in SCM+ and SCM- trials.

Another reason for the observed low level of SCM+ responses in the present study may be that the participants recruited for the experiment were simply unlikely to exhibit a startle reflex. We did not assess for a reliable startle reflex during the practice blocks of the testing session. The confirmation of an SCM+ result during the practice trials may have indicated whether a participant was capable of presenting an SCM+ response within a single RT task paradigm, and thus confirming that a high level of preparation for the RT task was achievable. In previous studies investigating response preparation with a SAS, a participant's data is usually excluded from analyses if they do not exhibit a "reliable SCM+ response", which is typically defined as SCM+ responses in at least 60% of the SAS trials (Maslovat et al., 2017). In the present study, this exclusion criterion was not enforced as only 2 out of 20 participants had SCM+ responses in over 60% of their SAS trials (Figure 12).

5.1.2. Task complexity and response preparation

Another reason for the low percentage of SCM+ responses within the SAS trials could be due to the level of complexity of the motor tasks. Motor tasks that require more than one movement are often described as "complex" or "difficult" and these tasks are thought to engage a larger amount of central processes than a single movement performed in a "simple" task (Carlsen et al., 2012). Normal RT latencies for simple tasks performed in response to normal (control) auditory stimuli are measured at approximately 140 ms, whereas startle-elicited RT latencies are typically measured at < 80 ms (Carlsen et al., 2012; Valls-Solé et al., 1999). In

contrast, in the present study, the mean probe RT for the control trials was 219.0 (SD = 31.6) ms and 158.4 (SD = 26.7) ms for the SAS trials (Figure 6B). Furthermore, dual-task testing paradigms are described as more complex than single task testing paradigms, and as such the RTs measured in dual-task paradigms are typically longer than in single task paradigms (Schmidt & Lee, 2011; Pashler, 1994). Thus, it may be the case that the motor tasks in the present study were “complex”, and—when assessed in a dual-task testing paradigm—the larger amount of central demand would make it *less* likely for advanced response preparation of a secondary task to occur, as evident by the slower RT results of this study.

As an alternative, it is possible that the middle of the primary task was the most complex location within the movement. Previous research has suggested that the location within a movement that corresponds with a transition point from acceleration to deceleration may correspond with an increase in RT (van Donkelaar & Franks, 1991). However, in the present study, the acceleration profile of the continuous task was not analyzed, so additional analyses of these data may be necessary in order to further understand the characteristics of the primary task.

In addition, previous TMS studies have also reported that measures of corticospinal excitability increase within dual-task testing paradigms when compared to single task testing paradigms (Corp, Rogers, Youssef, & Pearce, 2016). Furthermore, MEP amplitudes have been reported to increase with movement complexity, in that larger MEP amplitudes have been associated with longer RT latencies typical for complex motor tasks. For example, Kennefick and colleagues (2019) measured corticospinal excitability at various time points following IS presentation in a simple RT paradigm that involved a motor task that required either 1, 2, or 3 movements. The authors reported that MEP amplitudes were larger and RT latencies were longer in the 2 and 3 movement conditions compared to the single movement condition, and suggested that the size of MEP was influenced by central processing, in that actions demanding more central capacity (i.e., more “complex” movements) for response preparation also

increased corticospinal excitability (Kennefick et al., 2019). In the present study, this interpretation is reflected at the middle locations within the continuous motor task (Figure 10 & 11). At these locations, participants were probably engaged in a more complex level of central processing as they were preparing the switch in direction required at the turning points within the movement cycle. As this decision-making would require a larger amount of central processing, it is unsurprising that the MEP amplitudes were larger at these moments in the movement.

5.1.3. Unpredictable stimulus presentation and response preparation

The exact onset of response preparation for a motor task can be dependent on the predictability of IS presentation, and predicting the exact moment of IS presentation can be difficult in tasks that have a long or unpredictable foreperiod (Schmidt & Lee, 2011; Kennefick et al., 2014; Smith, Maslovat, Drummond, et al., 2019). Typically, a foreperiod is defined as the period of time between a warning signal and IS presentation (Schmidt & Lee, 2011; Niemi & Näätänen, 1981). It is thought that the presence of a warning signal prior to the presentation of an IS results in higher levels of response preparation (as measured by short RT latencies) as a warning signal acts as a “Get Ready” cue (Niemi & Näätänen, 1981; Touge et al., 1998). Therefore, another reason for the low level of response preparation for the RT task in the present results could be due to the absence of a consistent and discrete warning signal. In the present study, there was no formal “foreperiod” as the trials were run in a continuous manner. In other words, the timing of the IS was unpredictable, as only the completion of the previous probe RT trial would provide any information to participants about when to begin preparing to perform the RT task for the next trial. Furthermore, the random presentation of the IS, in addition to the three stimulus conditions (TMS, Control, SAS), would have made anticipating the IS reasonably difficult. Thus, based on the slow RTs recorded in all trials *and* the small number of SCM+ trials, participants appear to have been unsuccessful at achieving a particularly high level of preparation for the probe RT task.

5.1.4. Bimanual movements and measures of corticospinal excitability

The present study also found significantly smaller MEP amplitudes when TMS was applied while the left hand was moving through the “right” locations (i.e., closer to the midline) compared to the “middle” (i.e., neutral) and “left” locations (i.e., furthest from the midline) (Figure 10). A reason for this may be due to the modulation of corticospinal excitability that has been measured during in-phase and anti-phase bimanual movement (Neva, Legon, & Staines, 2012). In bimanual movements, “in-phase” refers to the simultaneous activation of similar muscles in each limb, whereas “anti-phase” refers to the simultaneous activation of non-similar muscles within each limb (Maslovat et al., 2017; Neva et al., 2012). Previous work has reported that corticospinal excitability increases during in-phase movements, whereas it is typically unaltered during anti-phase movements (Neva et al., 2012). In the present study, the performance of the probe RT task at the left locations could correspond with an in-phase bimanual movement, as both wrists would be in some degree of extension at the same time. In other words, the simultaneous activation of bilateral wrist extensors could account for the high MEP amplitudes measured at these locations. Furthermore, it has been reported that corticospinal excitability is modulated by the type of contraction (concentric or eccentric contraction) of a tested muscle, with larger MEPs found during concentric contractions than eccentric contractions (Chye, Nosaka, Murray, Edwards, & Thickbroom, 2010), as well as larger MEPs found in more forceful contractions over less forceful contractions (Di Lazzaro et al., 1998). Taken together, these studies support the idea that larger MEP amplitudes may indicate facilitatory corticospinal excitability in homologous muscles of the opposite limb during ongoing movement, *and* smaller MEP amplitudes could indicate inhibitory activity from non-similar muscles of the opposite limb during ongoing movement.

A third result from the TMS trials was that when the locations within the continuous task were grouped by direction (i.e., flexion and extension), there were longer CSP durations measured during extension (Figure 12). The CSP is a TMS-induced interruption in EMG activity

recorded from the target muscle (Ziemann et al., 1997). As there was a concurrent upper-limb task being performed at the time of TMS application, it is possible that central processes controlling the contralateral limb impacted corticospinal excitability; however, concurrent muscle contractions are not thought to influence CSP durations (Terao & Ugawa, 2002). In the present study, the significant differences were quite small (1.6 ms), so it is possible that the "in-phase" homologous bimanual activity slightly influenced the corticospinal excitability of M1; however, more research is required to confirm this association.

5.2. Secondary Analyses

In a secondary analysis, the RMSE of the continuous task was calculated for 1 second before and 1 second after IS presentation. Results suggest that participants were less accurate on their performance of the continuous tracking task in the 1 second after IS presentation compared to the 1 second before IS presentation (Figure 14 & 15). In other words, the performance of the probe RT task disrupted participants' ability to accurately perform the continuous tracking task. This was expected as it is a reasonably robust finding that motor performance is typically worse in dual-task paradigms versus single task paradigms (Pashler, 1994). In the present study, participants made more errors within the continuous task when they were probed at the middle locations regardless of stimulus condition, adding further support to the hypothesis that the middle locations were more demanding of attention than the other locations (Figure 15). Interestingly, participants were *much* less accurate on the continuous task if the probe RT trial involved a SAS rather than the control IS (Figure 14). Maslovat and colleagues (2015) found similar effects on primary motor task performance in SAS trials, and suspected that the decrease in performance was likely due to the startle reflex response interfering with the performance of the task, as opposed to any differences in central capacity demands or attention allocations between control and SAS trials (Maslovat et al., 2015).

A transient isometric force production task was chosen for the secondary task, as it allowed us to measure a CSP following the application of TMS, and we also believed it would

provide participants with the best opportunity to achieve a high level of engagement in the task without inducing muscle fatigue (Carlsen, Almeida, et al., 2012; Drummond et al., 2017). Furthermore, an extension task was chosen over a flexion task to ensure that the observed motor response was representative of a prepared motor program and not just a startle reflex response (i.e., generalized flexion) (Brown et al., 1991). Although the participants performed the task more forcefully in the SAS trials than compared to the control trials, results demonstrated that there were no significant differences between the locations in force production, suggesting that participants performed the secondary task quite consistently across the locations (Figure 16).

Chapter III: General Discussion

The goal of the present study was to contribute to the knowledge regarding how the central processes involved in the control of bimanual tasks operate within a dual-task paradigm. The RT differences we found in this study were small, and thus caution must be taken when interpreting these results, and when expressing the impact or application of these results in real-life scenarios. The experimental tasks for the present study were developed specifically for testing the central processes within a laboratory setting, and the direct transferability of the results into real-world, multi-tasking situations is unknown. However, the results suggest that although the human brain is able to coordinate multiple movements at the same time, the performance of one task is affected by the performance of another. Furthermore, the attentional demands of the primary task seem to have a detrimental effect on preparatory levels for a secondary task, as noted by increases in premotor RT, differences within the measures of corticospinal excitability, and low to absent startle reflex responses. Thus, we feel confident in reporting that the present experiment has added to the growing literature regarding how the brain performs when multi-tasking; specifically, how shifting attentional demands within a complex continuous task can impact our ability to prepare a secondary action.

1. Limitations and Future Directions

1.1. Experimental Design

The main result of the present experiment was that RTs were slower when the RT task was probed as the left hand was passing through the middle locations (0° in flexion and extension) of the continuous task. The main reason attributed to this result was the presence of higher attentional requirements at these locations in order to accurately navigate the turning points within the continuous task. As such, an interesting addition to the current experimental design would be the use of a continuous motor task that does not have turning points, such as a

circular movement (e.g., spinning a wheel) in order to fully understand how movement requirements affect probe RT within dual-task testing paradigms.

Furthermore, no analysis was conducted to investigate whether the time between probe RT trials (i.e., the “foreperiod”) had an effect on premotor RT. In the present study, the stimulus for the probe RT task was presented approximately every 2 – 6 seconds, with the average length of time between trial stimuli being approximately 4 seconds. Generally, as a foreperiod increases so does the probability of the probe RT stimulus, so participants are more likely to be at a higher level of response preparation in tasks that have a longer, but somewhat predictable, foreperiod – resulting in shorter RT latencies (Donders, 1969; Smith, Maslovat, & Carlsen, 2019). Arguably, as there was such a low level of response preparation evident for the probe RT trials within the present results, it is unlikely that the length of time between trials had an effect on RT. Regardless, further analysis of the time between trials could be an interesting addition to the study.

Another interesting addition to the experimental design would to measure eye movement within this dual-task testing paradigm. In the present study, visual feedback was displayed on the computer screen continuously throughout the experimental trials in order to assist participants with their performance (Figure 2). Due to the nature of the continuous task, one would expect participants to view the continuous task’s feedback the majority of the time, with minimal time spent on the probe RT task’s feedback until IS presentation; however, as eye movement or gaze was not measured in the present study, there is no way to confirm this assumption. Measuring eye movement may provide additional information regarding the attentional demands within our dual-task testing paradigm. Furthermore, eye movement may also provide additional insight into corticospinal excitability during the tasks. Previous work has reported that measures of corticospinal excitability are influenced when passively observing videos of rhythmic movements, an effect explained by mirror neuron activity (Gangitano, Mottaghy, & Pascual-Leone, 2001). Thus, it would be interesting to investigate if this pattern of

corticospinal excitability modulation carries over into the observation of any movement, such as tracking visual feedback on a computer screen.

1.2. Dual-Task Interference

It is understood that humans have a limited capacity to perform two motor tasks at the same time, in that we are more likely to respond slower and produce more movement errors while attempting to perform two actions at once compared to when we perform each task separately (Begeman et al., 2007; Pashler, 1994). There are two main models in the motor behaviour literature that try to explain dual-task interference: the central capacity sharing model and the central bottleneck model. The results of the present study provide support for both of these models.

The central capacity sharing model operates on the idea that total information processing capacity is shared fluidly amongst motor tasks during dual-task performance (Pashler, 1994). In other words, when two motor tasks are performed simultaneously, the central processes involved for *response selection, preparation,* and *initiation* of each task are the same and likely shared during performance. Thus, if more central resources are required for the performance of one task over the other (in general), *or* if more resources are required for a specific aspect of one task over the other, one would expect to see a detrimental effect on the performance of the secondary task. In the present study, when the RT task was probed at the middle locations of the continuous motor task, longer RT latencies were measured which suggest that, at these moments, more central resources were allocated to the performance of the continuous motor task over the probe RT task.

Furthermore, larger MEP amplitudes were measured in the TMS trials at the same moments within the continuous motor task that were associated with the longer RT latencies. In a prepared state, larger MEP amplitudes have been associated with lower levels of inhibitory activity which is thought to reflect a lower level of response preparation for a task. In the present study, the middle locations had increased RT latencies and MEP amplitudes. Furthermore, the

timing of the continuous task had the middle locations aligned with preparation for a turning point in the movement cycle; thus, it is likely that participants were unable to prepare for the RT task to the same level at these locations compared to the other locations. Based on the above, the results of the present study also add support to the central bottleneck model of dual-task interference, which suggests that it is not possible to prepare multiple simultaneous movements to a high level, due to a response preparation bottleneck (Maslovat et al., 2013; Pashler, 1994).

1.3. Transcranial Magnetic Stimulation

TMS has been used extensively to assess corticospinal excitability during motor tasks, and – more recently – has been used to investigate cortical contributions to response preparation (Hannah et al., 2018; Kennefick et al., 2014; Rossini et al., 2015; Smith, Maslovat, & Carlsen, 2019). Indeed, TMS was specifically chosen for the present study to measure corticospinal excitability at the moment of stimulus presentation for the RT task – a moment that should reflect the level of response preparation achieved for the immediate performance of that task. Importantly, premotor RT from the TMS trials was not measured or compared to the premotor RTs of the control or SAS trials. The primary reason for this was because RT was used as a measure of preparatory level and the application of TMS can directly impact premotor RT (Day et al., 1989; Hannah et al., 2018; Smith, Maslovat, & Carlsen, 2019). Previous work that has directly assessed RT performed within TMS trials applied TMS on every experimental trial in order to ensure the changes induced by TMS were consistent across all testing conditions (Smith, Maslovat, & Carlsen, 2019). In the present study, TMS was applied as the IS for only 50% of the trials, therefore the premotor RTs from these trials were not compared to the control or SAS trials. An interesting addition to the present experimental protocol could be to apply TMS with the IS on every trial in order to confirm the differences in corticospinal excitability discovered within the present results.

An additional future direction inspired by the current results could be to use TMS to investigate corticospinal excitability within a psychological refractory period (PRP) paradigm,

such as the experiment conducted by Maslovat and colleagues (2013). In their study, the time interval between two stimuli was manipulated to assess how overlapping response preparation and response initiation affects RT for two ballistic movements. The authors found that the RTs of the second motor task were not influenced when the stimuli for the two tasks were presented more than 500 ms apart, but RT was significantly slower when the stimuli were presented in quick succession (100 – 200 ms). The authors attributed these results to a central response preparation bottleneck (Maslovat et al., 2013). The addition of TMS to this experimental design could provide additional insight into corticospinal excitability during a response preparation bottleneck.

1.4. Startling Acoustic Stimulus

In the present study, an unexpectedly low percentage of SAS trials elicited a startle reflex response (SCM+) in addition to the planned motor action (i.e., StartReact effect). This could be viewed as a large limitation to the results of this study, as a high proportion of SCM+ trials within SAS trials typically indicates that participants have successfully engaged in advance motor preparation. Indeed, the information collected from SCM+ trials could have provided additional information regarding the degree of response preparation for the RT task as it was performed at the different locations of the continuous motor task. That is, if participants had exhibited a startle reflex more consistently, differences in SCM+ percentages between probe locations may have been evident. One reason for the low level of SCM+ responses could have been that certain participants did not exhibit a reliable startle under any circumstances; thus, analyzing the startle reflex response during the practice trials and excluding individuals who demonstrate low to absent SCM+ responses could have slightly ameliorated this issue. Therefore, it is suggested that this pretest be included when employing a SAS within a dual-task testing paradigm to measure advance response preparation in order to ensure the highest probability of SCM+ responses.

Finally, a low level of startle reflex responses in the present results could have been due to the complexity of the two tasks selected for this experiment. In other words, it is possible that the required movements for each task were too “difficult” to prepare at a high level in advance of stimulus presentation. If such, it could be useful to repeat the experiment and employ a simple (i.e., “easy”) condition of each motor task in order to investigate if/how the factor of complexity influenced the present results.

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Appendix A: Safety Screening Questionnaire for Transcranial Magnetic Stimulation

Please answer the following questions by putting a check mark (√) in the appropriate box.

1.	Have you ever had an adverse reaction to transcranial magnetic stimulation?	YES □	NO □
2.	Had a seizure?	YES □	NO □
3.	Had an EEG (electroencephalogram)?	YES □	NO □
4.	Had a stroke?	YES □	NO □
5.	Had a head injury (include neurosurgery)?	YES □	NO □
6.	Do you have any metal in your head (outside the mouth) such as shrapnel, surgical clips, or fragments from welding or metalwork?	YES □	NO □
7.	Do you have any implanted devices such as cardiac pacemakers, medical pumps, or intracardiac lines?	YES □	NO □
8.	Do you suffer from frequent or severe headaches?	YES □	NO □
9.	Have you ever had any other brain-related condition?	YES □	NO □
10.	Have you ever had illness that caused brain injury?	YES □	NO □
11.	Are you taking any medications?	YES □	NO □
12.	Does anyone in your family have epilepsy?	YES □	NO □
13.	Are you pregnant?	YES □	NO □

PARTICIPANT NAME: _____

PARTICIPANT SIGNATURE: _____ DATE: _____