

**The Influence of Attention on Dual-task
Performance and Cortical Excitability**

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I declare that this thesis is my own work and that, to the best of my knowledge and belief, it does not contain material from published sources without proper acknowledgement, nor does it contain material which has been accepted for the award of any other higher degree or graduate diploma in any university.

Signed: _____ Date: _____

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TABLE OF CONTENTS

Chapter 1: Literature Review

Abstract	1
Literature Review	3
1.1. Dual-task Methodology	4
1.2 Cognitive Explanations of Dual-Task Interference	5
1.3 Dual-Task Interference Effects	7
1.4 Cross-talk	13
1.5 Measuring Neural Cross-talk	14
1.6 Does Neural Cross-talk have Functional Implications?	18
1.7 Is Neural Cross-talk Modifiable?	20
References	26

Chapter 2: Empirical Report

Abstract	32
Empirical Report	34
2.1 Introduction	34
2.1.1 Explanations for Dual-task Interference	35
2.1.2 Neural Cross-talk	37
2.1.3 Neural Cross-talk and Performance	38
2.1.4 Modulation of Neural Cross-talk	40
2.1.5 Short Interval Intracortical Inhibition	41
2.1.6 Practical Implications of Investigating Cortical Excitability and sICI	44
2.1.7 The Current Study	44
2.2 Method	45
2.2.1 Participants	45
2.2.2 Design	46
2.2.3 Materials	46
2.2.4 Procedure	49
2.2.5 Data Analysis	52

2.3 Results	53
2.3.1 Reaction Time Task	53
2.3.2 Coordination Task	56
2.3.3 Excitability Data	59
2.4 Discussion	61
2.4.1 Neural Cross-talk and Alternative Explanations for Dual-Task Interference	63
2.4.2 Neural Cross-talk, Precision Movements and Future Directions	66
2.4.3 Conclusion	68
References	70
Appendices	75

LIST OF FIGURES

Literature Review

Figure 1: Average Premotor Times (ms) for RT and Dual-task Conditions	23
Figure 2: Average MEP Amplitude for Control, Single and Dual-task Conditions	24

Empirical Report

Figure 1: Mean Reaction Time (ms) for RT and Dual-task Conditions	54
Figure 2: Mean Premotor Times (ms) for RT and Dual-task Conditions	55
Figure 3: Mean Motor Times (ms) for RT and Dual-task Conditions	56
Figure 4: Mean Frequency Deviation Scores for Coordination and Dual-task Conditions Pre and Post-stimulus	58
Figure 5: Mean MEP Amplitude for Control, Single and Dual-task Conditions	60
Figure 6: Mean sICI for Control, Single and Dual-task Conditions	61

Literature Review:
The Influence of Attention on
Dual-task Performance and Cortical Excitability.

Abstract

In the literature researchers have endeavored to try and explain the phenomena of dual-task interference. Dual-task interference refers to the finding that when people perform two tasks simultaneously there is often a decrease in performance compared to when they perform one task alone (Pashler, 1994). Despite vast amounts of research exploring this, there has been no unified consensus about why dual-task interference actually occurs.

This literature review first explains the methodology termed the dual-task paradigm that is common used in research to study these interference effects. Following this the cognitive explanations for dual-task interference effects, namely the resource model and bottleneck model are explored. A number of studies are then presented that employed both cognitive and motor tasks to examine these effects.

Another less common explanation presented in the literature termed the cross-talk model is then reviewed. Cross-talk according to Navon and Miller (1987) is defined as when two tasks use separate mechanisms that interfere with each other, rather than share or compete for resources. This notion of cross-talk can be interpreted from a neural perspective, thus neural cross-talk can be seen as referring to when an area of the cortex activated during the performance of one task affects a different area of the cortex activated during the performance of a second task resulting in interference.

This review then explores a number of studies that used electrophysiological techniques, such as transcranial magnetic stimulation and position emission tomography that present findings consistent with the notion of neural cross-talk. Building on this notion of neural cross-talk research is then presented that suggests that neural cross-talk may play an important role in behaviour. The final part of this review explores evidence to suggest that neural cross-talk is modifiable.

Overall, the literature presented in this review highlights the fact that further research into the cause of dual-task interference is warranted. The evidence also suggests that neural-cross talk may play an important role in this interference; thus neural cross-talk should be explored in greater depth in future research examining interference.

Chapter 1: Literature Review

In everyday life people often perform two tasks simultaneously with ease, for example driving a car and listening to a radio. However there are other tasks which people can find extremely difficult to perform simultaneously, for example, writing notes in a lecture and listening to your friend talk to you. A common finding in research is that when people perform two tasks simultaneously (dual-task) their performance deteriorates compared to when they perform one task alone (single-task) (Pashler, 1994). This decrease in performance in dual-task situations relative to single-task performance is referred to as dual-task interference (Pashler, 1994). Despite the large amount of research identifying dual-task interference effects the underlying cause is still not fully understood, and this will be the focus of this literature review.

The first section of the literature review will examine the methodology used to study dual-task interference effects. The second section will explore two cognitive explanations presented to account for dual-task interference. The third section will discuss six studies that have employed both cognitive and motor tasks to identify dual-task interference. Sections four through to seven will consider the notion of neural cross-talk as a contributor to interference effects, explore its functional implications and look at whether it can be modified.

Section 1: Dual-Task Methodology

As stated above, it is not yet clear why a person's performance deteriorates when they are completing two tasks simultaneously compared to when they perform the one task alone. This phenomena of dual-task interference has been commonly investigated in research studies using a methodology referred to as the dual-task paradigm. The dual task paradigm requires participants to complete two tasks both concurrently and individually (Abernethy, Summers, & Ford, 1998). Interference is identified by examining changes in performance when participants complete two tasks simultaneously compared to individually (Tsang, Velazquez, & Vidulich, 1996). The two tasks that are completed are termed the primary and secondary tasks (Wickens, 1992). The primary task is viewed as the one to which participants allocate the most attentional resources, while the secondary task represents the one which participants allocate the remaining resources (Tsang, Shaner & Vidulich, 1995). Using dual-task methodology, research has found that if a participant allocates more attention to the primary task, then performance on the secondary task will decrease relative to if the secondary task is performed alone; this decrease in performance when two tasks are completed simultaneously compared to individually is indicative of dual-task interference effects (Abernethy et al., 1998).

As can be seen from the previous paragraph dual-task interference effects have been linked in the literature with the process of attention (e.g., Hiraga, 2005). Research to date has not been able to come up with a unified definition of attention, and there are a number of contexts in which it has been referred to, one of them being in terms of

‘limited capacity or resources’ (Abernethy et al., 1998). The term resources is defined as ‘mental energy or effort’ (Wickens, 1989, pg78) that is under voluntary control and limited in supply (Wickens, 1992). Therefore, attention in this context can be seen as referring to the mental energy or effort that a person allocates to a task/activity.

Section 2: Cognitive Explanations of Dual-task Interference

The resource model and the bottleneck model are the primary models that have been employed to account for dual-task interference effects. These cognitive models will be discussed with reference to applications to real world situations.

The resource model, or capacity model as it is also known, is based on the idea that people have a set amount of resources that they can allocate to different tasks (Kahneman, 1973). When a person is performing one task alone they are able to allocate all of their resources to performing the one task well. Yet when a person is performing two tasks simultaneously the resources that they have available for each task are reduced which can result in a decrease in performance on the two tasks. Consequently, dual-task interference occurs due to the limited resources available for the task (Pashler, 1994). An example of resources allocation in an everyday life situation would be if a person is listening to a teacher in class and at the same time trying to finish their assignment. The person’s ability to listen to their teacher is reduced because some of the resources required for them to do this are being used when they are completing their assignment.

Pashler (1994) has argued that people have some degree of control in terms of how they distribute their resources to different tasks; he illustrates this by giving the example of driving and talking to a person at the same time. A person is driving a car and having a conversation with a passenger simultaneously, when they encounter heavy traffic the person driving the car is able to focus more on their driving (allocating more attentional resources to it) rather than participating in a conversation with the passenger. This example also highlights what is termed a performance trade-off that is when more resources/attention are placed on a primary task than another secondary task and consequently performance on that secondary task decreases (Tsang et al., 1996). In this example, when the person driving encounters traffic more attentional resources are allocated to driving and consequently their ability to have a conversation with the passenger decreases.

The information presented in the literature concerning the resource model highlights two key points: 1) that when two tasks are performed simultaneously the resources available to perform each of these two tasks are reduced compared to if one task was performed alone which can result in dual-task interference 2) these dual-task interference effects can be modulated by the amount of resources of a person allocates to each of the specific tasks which consequently can result in a performance trade-off (Temprado, Zanone, Monno & Laurent, 2001).

An alternative explanation to account for dual-task interference is the bottleneck model. This model works on the premise that for some tasks it is not possible for people to

perform them at the same time, therefore these tasks have to be completed sequentially not concurrently. In this situation a bottleneck then occurs because the mechanisms needed to perform one task are being used by another task at the same time. This bottleneck means that one task has to be put on hold while the other task is performed which results in dual-task interference (Pashler, 1994).

Section 3: Dual-Task Interference Effects

The resource model and bottleneck models have been investigated in research using a range of different tasks including memory, reaction time, coordination, perceptual and speeded tasks. The first part of this section will discuss studies, cognitive and motor that highlight the range of tasks that have been employed to study dual-task interference effects. The second part of this section will review a number of studies that have further explored dual-task interference effects by manipulating the attentional priority that a person allocates to either the primary or secondary task.

Dual-task interference effects have primarily been studied using cognitive tasks. For example in a study conducted by Bunge, Klingberg, Jacobsen and Gabrieli (2000) (Experiment 1) participants performed two working memory tasks. The first task required them to read a sentence and then press a button indicating whether that statement was true or false, and in the second task they were presented five sentences and had to remember the last word of the sentences. Performance on both tasks was assessed as accuracy (e.g., for the reading task, the accuracy for whether the sentence was true)

and speed (e.g., on the memory task, how long it took to verify the words). Participants completed these tasks in single and dual-task conditions. In this study the neural correlates of dual-task performance were also examined using functional magnetic resonance imaging (fMRI). Dual-task interference effects were found on both tasks for speed but not for accuracy, with participants producing slower responses in the dual-task condition compared to the single, while the results from the fMRI indicated that there was an increase in activity in the prefrontal area of the cortex (a brain region thought to be involved in memory) when the dual-task condition was performed (Sruss, & Benson, 1984). The authors explained these findings in terms of the resource model stating that the increase in activity in the prefrontal cortex in the dual-task situation occurred due to the limited resources available relative to the single-task conditions.

Motor tasks have also been employed to study dual-task performance. These tasks can involve either discrete or continuous movements. A task that requires a discrete motor response is the reaction time (RT) task. Probe RT (or simple RT) tasks are visually simple discrete tasks that require the participant to make a response as quickly as possible to a stimulus, for example, the participant may have to press a button when a light comes on. In Probe RT tasks there is no choice involved and the participant is just responding to a stimulus (Wickens, 1992). A task that involves continuous motor response (e.g., a tracking task) requires the participant to perform the task for the entire duration of the experiment, rather than present discrete responses (Tsang et al., 1996), for example a participant may have to complete a bimanual coordination task that requires them to continuously produce a particular movement pattern.

To explore dual-task performance Tsang et al., (1996) conducted a study that employed both a motor task and a cognitive task. Participants had to complete a continuous tracking task (motor task) and a memory task (cognitive task) under single and dual-task conditions. For the tracking task participants used a joystick to position a moving cursor displayed on a line on a computer screen, while for the memory task participants were shown a small number of consonants on a computer screen that they had to remember, following this individual consonants were presented on the computer screen and participants had to identify whether it was from the memorized set. Performance on the tracking task was assessed as tracking error and tracking speed, while performance on the memory task was assessed by reaction time (RT). It was found that tracking error and RT were higher in the dual-task condition compared to the single, clearly demonstrating dual-task interference. Tsang et al., argued that this dual-task interference effect was due to resource limitations, with performance decreasing in the dual-task condition because of the lack of resources available relative to the single-task condition.

Dual motor tasks have also been employed to examine dual-task interference. There have been a number of studies (e.g., Hiraga, Summers & Temprado, 2004; Temprado, Zanone, Monno & Laurent, 1999; Temprado et al., 2001) that have examined performance, specifically RT, in dual-task situations compared to single. It has been found that RT is higher in dual-task situations compared to single, indicative of dual-task interference. Temprado et al., (1999, 2001) conducted two studies where participants had to perform two tasks, a bimanual coordination task that required them to perform movements with

the arms and a RT task, where they had to respond to an auditory tone by pressing a button on a joystick (Temprado et al., 1999) or respond by pressing buttons on a footswitch with their feet (Temprado et al., 2001). These tasks were completed in single and dual-task conditions. Performance was assessed as RT and for the coordination task as the standard deviation of relative phase - the amount of variability in the relative phase of the coordination task. For both studies it was found that RT was higher in the dual-task conditions compared to the single, indicative of dual-task interference; similar results were also found for standard deviation of relative phase. Temprado et al., (2001) argued that these dual-task interference effects occurred as a result of limited attentional resources. In the single-task conditions participants were able to allocate all their attentional resources to performing either the RT task or the coordination task, while in the dual-task conditions the resources they had available to perform each task was limited as their pool of resources had to be distributed between the two tasks. Consequently, performance was reduced in the dual-task conditions relative to single due to the lack of resources available (Temprado et al., 2001)

The studies presented above have examined the explanations that have been employed to account for dual-task interference effects in dual tasks compared to single. Dual-task interference effects can be further explored by manipulating the attentional priority that a person allocates to each of the concurrent tasks (Tsang et al., 1996). Attentional priority is often manipulated by instructing the participant to perform the prioritised task in the dual-task condition as well as they did as in the single-task condition, yet at the same time maintain an optimal level of performance on the secondary task. This method of

prioritisation is referred to in the literature as the optimum-maximum method and often results in a performance trade-off (Tsang et al., 1996). Two studies are now presented that have manipulated attentional priority that results in performance trade-offs.

Mathews, Garry, Martin, and Summers (2006) conducted a study where participants had to perform a visual oddball task and a bimanual coordination task. In the visual task participants were shown a target circle displayed on a computer screen that they had to remember. Following this three shapes (including the target circle) were presented randomly on the screen and participants were required to click a footswitch as fast as possible in response to the target circle. In the coordination task participants were required to perform forearm pronation-supination movements. Participants completed these tasks in four conditions: 'single visual' – participants completed only the visual task, 'single motor' – participants completed only the coordination task, 'dual-task visual priority' – participants completed both tasks simultaneously but prioritised the visual task, and 'dual-task motor priority' – the same as dual-task visual priority except the coordination task was prioritised. Performance on the visual task was assessed through RT. It was found that RT was fastest for the single visual condition, followed by the dual-task visual priority condition then the dual-task motor priority condition, indicating that attentional priority can impact on performance. Performance was assessed on the motor task by the standard deviation (SD) of relative phase. SD of relative phase was lower (greater coordination stability) for the single motor condition and the dual-task motor priority condition compared to the dual-task visual priority condition. This result indicates that in the dual-task motor priority condition the increased attention allocated to

the coordination task reduced the variability in participants arm movements to the level of the single-motor condition. From both the RT and coordination task results it can be concluded that the manipulation of attentional priority effects performance (Matthews et al., 2006).

In another study, Hiraga (2005) (Experiment 4), the effects of attentional prioritisation on performance was examined using an RT task and a coordination task. In the RT task participants had to click a footswitch as fast as possible in response to a visual stimulus, while in the coordination task participants had to complete forearm anti-phase pronation-supination movements. Participants completed these tasks in three conditions: 'probe RT' – participants completed the RT task only, 'dual coordination' – participants had to complete the coordination task and RT task simultaneously while prioritising the coordination task, and 'dual RT' – the same as 'dual coordination' except the RT task was prioritised. It was found that RT was fastest for the probe RT condition, followed by the dual RT condition and the dual coordination condition. Performance was also assessed in the coordination task and was measured as the standard deviation of relative phase. It was found that variability was lower in the dual coordination condition than the dual RT condition. This finding demonstrates that dual-task performance is affected by attentional prioritisation.

Section 4: Cross-talk

The resource model and bottleneck models have been presented in the literature to account for dual-task interference effects. There is another explanation that has received less attention in the literature, but is arguably important: cross-talk. Cross-talk refers to when the activity/processes involved in one task affect the activity/processes involved in another task (Heuer, 1996). A number of different versions of 'cross-talk' have been described in dual-task research. One version is essentially a sharing version and states that dual-task interference occurs when two tasks are similar in content (e.g., completing two memory tasks simultaneously). In line with this version of cross-talk, it has been found that it is harder to perform two tasks simultaneously when they are similar (e.g., two tasks that require memory) compared to two tasks that are different (e.g., one task that involves memory and the other involves performing a motor response) (Pashler, 1994). If this is correct then it is implied that a greater degree of cross-talk is present when an individual is completing two tasks that are similar compared to if they were completing two tasks that were different. This sharing version of cross-talk is distinct from the resource explanation in that the individual has enough resources to carry out the two tasks yet despite this, the processing of one task still interferes with the processing of another task which results in a change in performance (Pashler & Johnson, 1994). Therefore in the example presented above, interference effects resulted not because the two memory tasks overloaded the person's resources but rather because processing one task interfered with the processing of the other task.

Another version of cross-talk termed ‘outcome conflict,’ has been presented in the literature by Navon and Miller (1987). They state that dual-task interference occurs because both tasks use separate mechanisms/components that interfere with each other, rather than share or compete for resources. An analogy to describe this type of cross-talk is when an individual is listening to the radio in the car and their mobile phone goes off, and consequently the music coming from the radio is disrupted. The music is disrupted not because the mobile phone and radio are competing for the same resources rather because the signals that are generated by the mobile phone interfere with the radio signals. This notion of cross-talk can be interpreted from a neural perspective. Neural cross-talk is when an area of the cortex activated during the performance of one task affects a different area of the cortex activated during the performance of a second task resulting in interference. Examples of neural cross-talk are evident in a number of studies (e.g., Carson et al., 2004; Sohn, Kang & Hallett, 2005) and will be discussed later in this review.

Section 5: Measuring Neural Cross-talk

Neurophysiological changes consistent with neural cross-talk can be identified using a number of different measures including functional magnetic resonance imaging (fMRI), position emission tomography (PET), electroencephalography (EEG) and transcranial magnetic stimulation (TMS). Johansen-Berg and Matthews (2002) employed fMRI to investigate how variations in attention to movement in single and dual tasks impact the primary motor cortex. In that study participants performed two tasks, a button press

sequencing task and a distracter task. The button press sequence task required the participant to respond to a visual stimulus by pressing four buttons in a specific sequence, while the distracter task was to count backwards in threes. These tasks were performed in single and dual-task conditions. The results from the fMRI revealed that there was a decrease in activity in the SMA, cingulate motor areas and insula when the dual-task was being performed relative to when a single-task was performed. However this result was not found for the primary motor cortex. The authors argued that the reason no significant differences were found could be because of variation for participants in the specific positions of the primary motor cortex activated by the finger press movements in the button press sequence task. For a result to be significant an effect for the majority of participants would have to be present and the location of this effect would have to be the same. The authors argued that this could be overly restrictive and consequently conducted further analysis. For the majority of participants it was found in the dual-task condition there was a decrease in activity in the primary motor cortex relative to the single-task condition (Johansen-Berg & Matthews, 2002). The reduction in activity in the SMA, cingulate motor areas, insula and primary motor cortex when the dual-task was being performed is indicative of neural cross-task as the performance of the two tasks simultaneously decreased the activity in the brain compared to when one task was performed alone.

Goldberg et al., (1997) employed PET scans to examine the neurophysiological effects of cognitive workload in single and dual-task situations. Participants were required to perform the Wisconsin Card Sorting Test (WCST) and a verbal shadowing task. In the

WCST a card was presented on a computer screen and participants then had to match it with one of four alternatives presented according to an abstract rule. In that task participants responded by pressing one of four buttons that corresponded to their choice of card. In the verbal shadowing task a word was presented from a tape recorder and the participant had to repeat that word back. Both these task were completed in single and dual-task conditions. The results from the PET scans indicated that there was a decrease in activity in the prefrontal area of the cortex in the dual-task condition relative to the single. This result could be interpreted as evidence of neural cross-talk with the performance of the second task reducing the activity in the prefrontal cortex. The authors argued that the resource explanation cannot fully account for their findings because if resources were involved then it would be expected that there would be an increase in physiological activity in the dual-task conditions due to more resources being required than in the single-task conditions and this was not found.

Findings consistent with neural cross-talk have been identified using TMS which measures cortical excitability. Excitability has been assessed in a number of different ways including: net excitability, short interval intracortical inhibition (sICI), silent period, and intracortical facilitation (ICF). Research measuring net excitability has employed single-pulse TMS. When single-pulse TMS is applied over the motor cortex it causes a response in the muscle contralateral to the stimulation known as an motor evoked potential (MEP). This MEP reflects the net excitability of the corticospinal pathway of the CNS (Floeter & Rothwell, 1999). If the net excitability is high, MEPs will be large with many neurons activated, while low excitability is associated with small MEPs. A study by Sohn and

Hallett (2004) found changes in net excitability consistent with neural cross-talk. In that study participants were required to move their right leg (tibialis anterior – TA) when an auditory signal was presented, while MEPs were recorded from an intrinsic hand muscle controlling the little finger of the right hand. It was found that the excitability of the little finger was suppressed during the movement of the TA. This finding clearly demonstrates neural cross-talk with the movement of the TA affecting the hand area of the M1.

TMS can also be used to examine inhibition in the motor cortex. There are two different measures of inhibition, sICI and silent periods. sICI is the excitability of the inhibitory circuits in the motor cortex (Kujirai et al., 1993) and can be assessed using paired-pulse TMS. While SP is the period of time where there is a brief silence in the EMG activity following TMS to the motor cortex when a person is attempting to perform a voluntary movement (Sohn et al., 2005). When assessing inhibition, sICI is employed when the muscle is inactive while silent periods are used when the muscle is active. A study by Meullbacher, Facchini, Boroojerdi, and Hallett (2000) was conducted to explore whether changes in sICI in the right M1 occurred during a voluntary contraction of the right hand muscle. In that study participants were required to perform a voluntary contraction of their right hand muscles, while MEPs were measured in muscles in their left hand. It was found when the right hand was active sICI in the left hand was reduced compared to when the right hand was inactive. This release of inhibition can be identified as neural cross-talk, with movement of the right hand affecting sICI in the right M1. Changes in SP consistent with neural cross-talk have also been identified. A study by Sohn, Kang and Hallett (2005) required participants to perform a voluntary movement of their right leg in

response to an auditory signal while MEPs were measured in a muscle of the right hand which was engaged in a voluntary contraction. It was found that SP in the hand muscle was shorter during the movement of the leg compared to when the leg was not moving, consistent with neural cross-talk between the leg and the hand.

Section 6: Does Neural Cross-talk Have Functional Implications?

Neural cross-talk has been identified using a number of different physiological measures and it is likely that it could play an important role in behaviour. A number of studies support this argument. As stated previously, Sohn, Kang and Hallett (2005) conducted a study that investigated SP during a dual-motor task. Participants had to contract the muscle of their right hand while performing a voluntary movement with their right leg. TMS was administered over the hand area of the left motor cortex. It was found that SP was reduced during the movement of the right leg. The authors argued that this change in inhibition (evidence of neural cross-talk) was present in order to help reduce the interference that occurs from completing two tasks simultaneously, thus emphasising the importance of neural cross-talk in behaviour.

Carson et al., (2004) also argued that neural cross-talk was important in motor performance. In that study participants were required to perform left wrist flexion and extension movements, while MEPs were recorded from the wrist muscle of the right arm. It was found that when the left wrist was performing flexion and extension movements MEPs from the right arm phasically increased. This finding is consistent with the concept

of neural cross-talk with the movement performed by the left wrist affecting the excitability of the hand area of the left motor cortex. The authors argued that this increase in excitability which occurred due to neural cross-talk may impact on behaviour. Stating that the excitability changes observed in the right arm are likely to facilitate in-phase movements and inhibit anti-phase movement. This argument presented by Carson et al., highlights the fact that neural cross-talk may not just be involved in dual-task interference and could actually facilitate performance in some situations.

Debaere et al., (2001) conducted a study that employed fMRI to examine brain activity during simultaneous movements of the wrist and foot. In that study participants completed five conditions: right wrist flexion and extension movements, right foot flexion and extension movements, isodirectional movements of the wrist and the foot, non-isodirectional wrist and foot movements and rest. It was found that when wrist and foot movements were performed simultaneously (the isodirectional and non-isodirectional conditions) there was an increase in activity in a number of different brain regions including the primary sensorimotor cortex and supplementary motor area relative to when individual movements of the limbs were performed. The authors argued that this increase in activity was needed so that the participant had the coordination required to move the two limbs simultaneously. This result highlights the importance of neural cross-talk between the wrist and foot areas of the motor cortex in interlimb coordination.

A more recent study conducted by Begeman, Kumru, Leenders and Valls-Sole (2007) investigated the physiological mechanisms of dual-task interference. In this study

participants performed a unimanual reaction time task in a single-task condition and in a dual-task condition. In the single-task (control) condition participants sat opposite a computer screen with their hands resting on a board in front of them, when a visual stimuli was presented on the computer screen they had to respond by pressing a button directly in front of their hand. In the dual-task (test) condition the participants had to perform that same reaction time task with one hand while as the same time perform rhythmic wrist movements with their contralateral hand. Performance was assessed as reaction time to the visual stimulus. It was found that reaction time increased when the participant was performing contralateral movements with their hand compared to when they performed the reaction time task alone, indicative of dual-task interference. The authors argued that one explanation for these interference effects could be a change in the excitability in the motor cortex. If this is the case then it can be hypothesised the neural cross-talk is involved. It is possible that when the rhythmic wrist movements were being performed excitability may have changed in the hand area of the motor cortex involved in performing the reaction time response; this change in excitability may have impacted on performance.

Section 7: Is Neural Cross-talk Modifiable?

In the previous section it was suggested that neural cross-talk can impact on behaviour. It is possible that other influences (e.g., visual input or attention) can be employed to modify this neural cross-talk. The modification of neural cross-talk would allow us to have some control over the degree to which it affects behaviour. A study by Garry,

Loftus and Summers (2005) demonstrates that neural cross-talk can be modified by visual input. That study investigated the effects of mirror viewing on changes in M1 excitability during unilateral hand movements. Participants performed a simple motor task with one hand (rhythmical index finger-thumb opposition movements). During movement, TMS was used to assess excitability of M1 controlling the opposite hand. In one condition participants looked towards their moving hand, while in another condition they looked towards their inactive hand, into a mirror placed between the hands. The mirror reflected the moving hand giving the illusion that the inactive hand was moving. Compared to a control (rest) condition MEPs were elevated in the inactive hand when the other hand was moved, consistent with cross-talk between the active and inactive M1. Interestingly, MEPs were larger when participants looked into the mirror compared with when they looked at the active hand. This finding suggests that cross-talk between motor areas is not fixed, but is subject to modulation by other factors that may be operating at the same time, in this case visual input.

Consistent with this notion that neural cross-talk can be modified are the findings of a recent fMRI study (Rowe, Friston, Frackowiak & Passingham, 2002). Participants performed two tasks, a motor task and a visual search task, concurrently and in single-task conditions. For the motor task participants performed a sequential key-pressing task. The visual search task required participants to detect letters presented on a computer screen. Participants completed tasks in four conditions: 'move condition' – participants just had to complete the motor task, 'search condition' – participants just had to complete the visual search task, 'dual condition' – participants completed both tasks

simultaneously, 'attend condition' – a single task condition where participants performed the motor task but were instructed to think about their movements in the task; participants also completed a 'rest condition' where they did not perform any of the tasks. The difference between the move condition and the attend condition is that participants in the attend condition were putting more attention into the motor task. The results from the fMRI demonstrated that there was no significant differences between the attend condition and the move condition for activation of the primary motor cortex, however increased connectivity between the prefrontal areas and the premotor areas for these two conditions was identified (Rowe et al., 2002). The concept of connectivity can refer to the activity occurring between two areas of the brain, thus connectivity can be viewed as being similar to the notion of neural cross-talk. The differences in attention in these two conditions (more attention being allocated in the attend condition than the motor) resulted in the differences in connectivity between the prefrontal and premotor areas of the brain.

The study presented above suggests that neural cross-talk may be modulated by attention. Hiraga (2005) (Experiment 4) employed single-pulse TMS to examine whether different levels of attentional priority modified neural cross-talk at the level of the motor cortex (as reflected through changes in MEPs in a dual motor task). In that study participants had to complete an RT task and a coordination task in single and dual-task conditions. MEPs were measured from the right TA in the three conditions: probe RT, dual coordination and dual RT. If the change in behaviour between priority conditions was due to attentional modulation of neural cross-talk then this should be revealed through changes in

excitability. The results for RT task demonstrated that reaction time was fastest for the probe RT condition, followed by the dual RT then the dual coordination conditions (Refer to Figure 1).

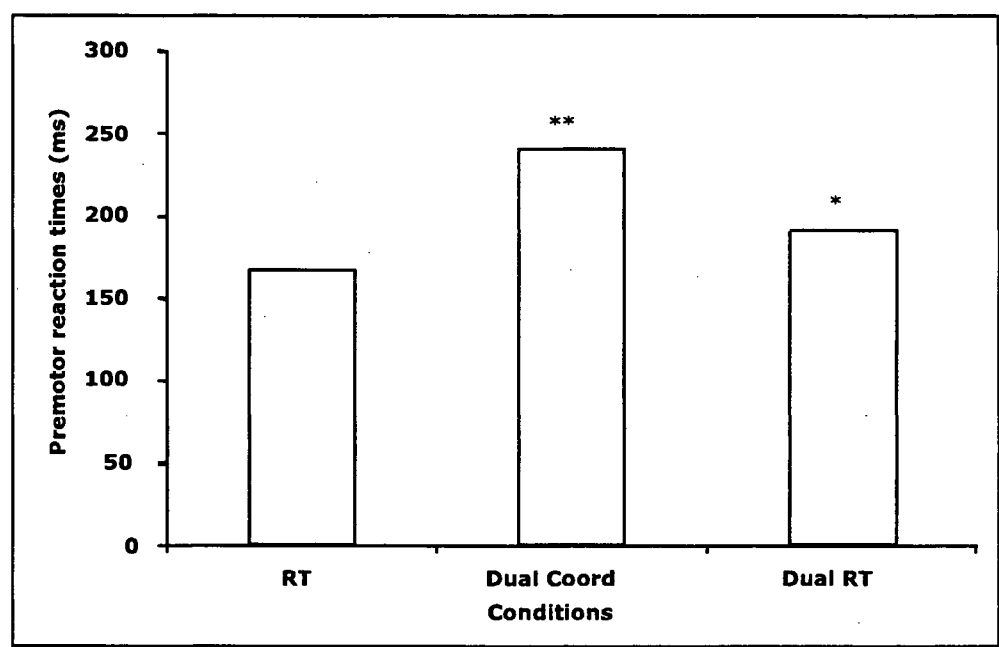


Figure 1. Average premotor times (ms) for RT and dual-task conditions. **Different from RT and Dual RT conditions. *Different from RT and Dual Coord conditions. (Hiraga, 2005, Unpublished doctoral dissertation, University of Tasmania).

The results for TMS revealed that MEPs were significantly higher in the dual-task conditions than in the single-task probe RT condition; however with regard to the two dual-task prioritisation conditions there was no significant difference in MEPs (Refer to Figure 2).

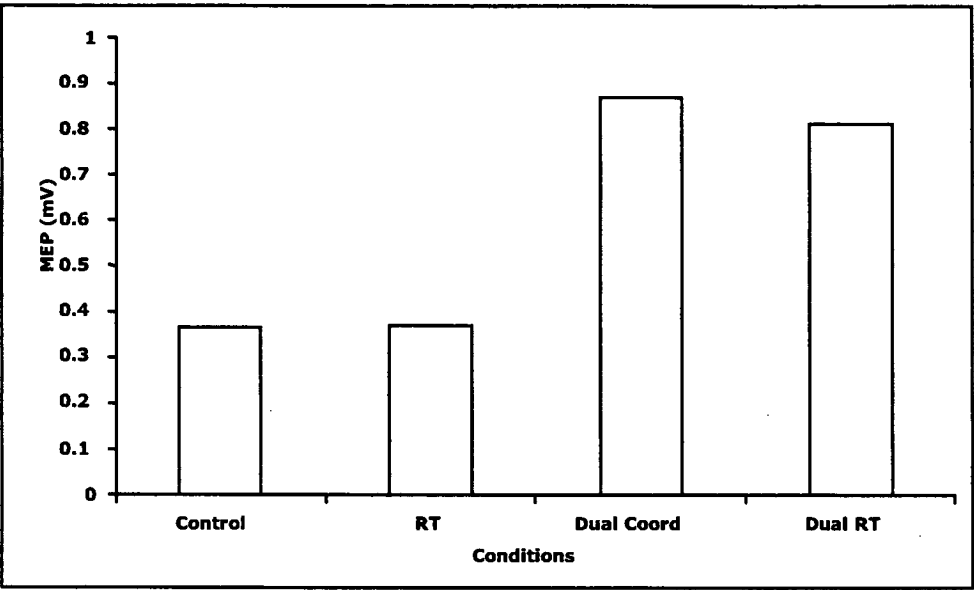


Figure 2. Average MEP amplitude for control, single and dual-task conditions (Hiraga, 2005, Unpublished doctoral dissertation, University of Tasmania).

The difference in MEPs in the single compared to the dual-task condition can be attributed to cross-talk, with the movement of the arms affecting the MEP measured from the leg. However MEPs were not sensitive to the prioritisation of attention, as demonstrated by the fact that there was no difference in MEPs in the two dual-task conditions. This evidence suggests that the changes in behaviour (RT) were not modulated by changes to neural cross-talk. Although the Hiraga et al. study did not find that neural cross-talk could be modified by attention it is still possible that neural cross-talk could be identified through some other neurophysiological measures, as described previously in this review.

In conclusion, while a great deal of research has been conducted to explore the phenomena of dual-task interference, as yet the underlying cause remains unknown. There have been a number of studies presented in this review that highlight the fact that neural cross-talk may contribute to dual-task interference and it is clear that further research into this area is needed. The current study aims to explore the role of neural cross-talk by extending Hiraga's study (Experiment 4) and examining whether neural cross-talk affects sICI and whether attentionally mediated effects on sICI could contribute to priority effects on performance.

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Empirical Report:
The Influence of Attention on Dual-task
Performance and Cortical Excitability

Abstract

The degradation in performance when an individual completes two tasks simultaneously (dual-task) compared to one task alone (single-task) is referred to as dual-task interference (Pashler, 1994). The attentional resource model and the bottleneck model have often been employed as explanations of interference.

Another explanation is neural cross-talk. Research (e.g., Sohn, Kang, & Hallet, 2005) has found that during the performance of two motor tasks the area of the motor cortex (M1) activated for one task affects the area of the M1 activated during the performance of a second task - this is neural cross-talk. It has been argued that neural cross-talk is important in the performance of motor tasks (Carson et al., 2004), consequently neural cross-talk may also contribute to dual-task interference.

The current study employed transcranial magnetic stimulation (TMS) to investigate whether neural cross-talk contributed to dual-task interference. Neural cross-talk was assessed during the performance of a reaction time (RT) task and a bimanual coordination task. Participants ($n = 12$) completed five conditions: 'coordination' – participants performed the coordination task only; 'RT' – participants performed the RT task only; 'dual coordination' – participants completed the RT task and the coordination task simultaneously while prioritising the coordination task; 'dual RT' – the same as 'dual coordination' except the RT task was prioritised; 'control' – participants did not perform either of the motor tasks and simply remained at rest. Cortical excitability and short

interval intracortical inhibition (sICI) (as measures of neural cross-talk) were assessed using single and paired-pulse TMS in all five conditions.

Dual-task interference was found for performance on both the RT task and the bimanual coordination task. This interference was also found to be modulated by the attention allocated to each specific task. Changes in excitability and sICI consistent with neural cross-talk were also found. Both excitability and sICI were higher when the coordination task was being performed. Unlike changes in performance, however, neural cross-talk did not vary with attentional priority suggesting that this mechanism was not the primary factor contributing to interference.

However, neural cross-talk should not be ruled out entirely. It is possible that participants adopted a behavioural strategy to overcome the effects of cross-talk. This possibility should be addressed in future studies.

Chapter 2: Empirical Report

For years research has tried to identify why individuals find it difficult to perform two tasks at the same time (Pashler, 1994). Despite the vast amount of research in this area it is still not clear why an individual's performance deteriorates when they complete two tasks simultaneously (dual-task) compared to when they complete one task alone (single-task). This decrease in performance is referred to as dual-task interference (Pashler, 1994). In the literature dual-task interference has been investigated using a methodology termed the dual-task paradigm, which is where interference effects can be identified by examining changes in an individual's performance when completing two tasks concurrently compared to individually (Tsang, Velazquez & Vidulich, 1996). A number of studies have used dual-motor tasks (e.g., Hiraga, 2005; Temprado, Zanone, Monno & Laurent, 1999; Temprado, Zanone, Monno & Laurent, 2001) to study dual-task interference effects.

In Temprado et al., (1999) participants had to complete a bimanual coordination task and a discrete RT task in single and dual-task conditions. In the coordination task participants had to perform forearm pronation-supination movements and in the RT task they had to respond to an auditory tone by pressing buttons on a joystick. Performance was assessed as RT and for the coordination task as the standard deviation of relative phase, with relative phase providing a measure of the position of one arm relative to the other during the movement. It was found that there was an increase in RT for the dual-task condition compared to the single, indicative of dual-task interference; similar results were also

found for the standard deviation of relative phase. Dual-task interference effects were also found in a study by Temprado et al., (2001) that employed a bimanual coordination task and a discrete RT task where participants had to press footswitch in response to an auditory signal. As with the first study dual-task interference was evident as greater RT in the dual-task condition relative to single. Temprado et al., (2001) explained the dual-task interference found in his studies using an attentional resource model (this will be discussed below).

Explanations for dual-task interference

Different explanations have been presented in the literature to account for dual-task interference, however a consensus has not been reached. One cognitive explanation, used by Temprado et al., (2001) to explain the effects in his studies, is termed the attentional resource or capacity model. The resource model states that individuals have a set amount of resources that they can allocate to different tasks (Kahneman, 1973). When an individual is completing a number of tasks simultaneously, performance may be reduced because the individual has fewer resources available to allocate to each task.

Consequently dual-task interference results because of the limited resources available for each task (Pashler, 1994). Temprado et al., explained his results in terms of resources, stating that performance on the coordination and RT tasks was reduced because participants allocated less attentional resources to the tasks (so in the dual-task conditions relative to the single).

An alternative cognitive explanation for dual-task interference is the bottleneck model. The bottleneck model operates on the premise that some tasks have to be completed sequentially not simultaneously. Consequently, a bottleneck occurs when the mechanisms needed to perform one task are occupied by another task at the same time. This results in dual-task interference because one task has to be put on hold whilst the other is being performed (Pashler, 1994). An example of a bottleneck would be if a person was asked to perform a finger tapping sequence with their right hand while simultaneously having to exert a specific amount of force on a surface also with their right hand. A bottleneck would result because the person would not be able to complete one task without stopping the other.

The research investigating dual-task interference has primarily focused on cognitive explanations. Alternatives to these are the cross-talk models. Cross-talk refers to when the activity/processes involved during of one task affect the activity/processes involved in another task (Heuer, 1996). A number of cross-talk models have been presented in the literature as an explanation for dual-task interference. One version can be described as a 'sharing version' which states that dual-task interference occurs when two tasks have similar content (e.g., performing two memory tasks simultaneously) (Pashler, 1994).

Another version of cross-talk, termed 'outcome conflict,' has been presented by Navon and Miller (1987). They hypothesised that dual-task interference occurs because both tasks use separate mechanisms that nonetheless interfere with each other, rather than share or compete for resources. Navon and Miller use the analogy of interference on

telephone lines to describe this type of cross-talk – when there are a number of telephone calls made simultaneously on parallel lines, interference will occur even if there are more available lines than the number of calls because the electrical current produced by one line will interfere with the current produced by the second parallel line.

Neural cross-talk

In the current study, Navon and Miller's (1987) notion of cross-talk was examined from a neural perspective. Neural cross-talk occurs when an area of the cortex activated during the performance of one task affects a different area of the cortex activated during the performance of a second task. It is predicted that this interaction between cortical areas could result in dual-task interference. Evidence in support of this concept of neural cross-talk arises from studies using transcranial magnetic stimulation (TMS) (e.g., Sohn & Hallett, 2004; Sohn, Jung, Kaelin-Lang and Hallett, 2003) that have identified neurophysiological changes consistent with neural cross-talk

TMS is a means by which to examine cortical excitability (Rothwell, 1997). Single-pulse TMS applied over the motor cortex causes a response in the muscle contralateral to the stimulated hemisphere known as a motor evoked potential (MEP). This MEP reflects the net excitability of the corticospinal pathway of the CNS (Floeter & Rothwell, 1999). In Sohn and Hallett's (2004) study participants were required to move their right leg (tibialis anterior – TA) after an auditory signal was presented, while MEPs were recorded from an intrinsic hand muscle controlling the little finger of the right hand. It was found that

the excitability of the little finger was suppressed during the movement of the TA. This finding clearly demonstrates neural cross-talk as voluntary movement of the leg affected the excitability of the hand area of M1.

Neural cross-talk and performance

Begeman, Kumru, Leenders and Valls-Sole (2007) discussed the possibility of excitability changes in M1 contributing to dual-task interference. In their study, participants performed a unimanual reaction time task under single and dual-task conditions. For the reaction time task participants sat opposite a computer screen with their hands resting on a board placed in front of them. During each trial visual stimuli were presented on the computer screen and participants had to respond by pressing a button directly in front of their hand. In the dual-task condition participants performed the same reaction time task while simultaneously performing a rhythmic wrist movement with their contralateral hand. It was found that reaction time was higher in the dual-task condition compared to the single-task condition. The authors discussed the possibility that the rhythmic wrist movement changed excitability of M1 controlling the reaction time task; this is consistent with the notion of cross-talk interfering with motor performance.

Further evidence suggesting that neural cross-talk may impact on behaviour arises from a study by Carson et al., (2004) who argued that neural cross-talk is functionally important in motor performance. In that study the authors examined whether excitability of one hemisphere was affected by rhythmic hand movements controlled by the opposite

hemisphere. Participants were required to perform left wrist flexion and extension movements, while MEPs were recorded from the flexor carpi radialis (FCR) and extensor carpi radialis (ECR) muscles of the right arm. It was found that MEPs from the FCR muscle phasically increased when the left wrist was engaged in rhythmic flexion and extension movements. This finding is consistent with the concept of neural cross-talk with the movement performed by the left wrist affecting the excitability of the hand area of the ipsilateral left M1. The authors argued that this phasic increase in excitability caused by cross-talk could impact on behaviour, facilitating the performance of in-phase movements and disrupting the performance of anti-phase movements.

As previously stated, Temprado et al., (2001) argued that the dual-task interference effects found in his studies were due to limited resources. However it is possible that neural cross-talk may have contributed to these dual-task interference effects. Temprado et al., (2001) reasoned that if the interference was due to cross-talk then the degree of interference should have been greater in the study where the RT task involved the hands (1999) rather than the feet (2001). Temprado et al., (2001) did not find this in his studies and consequently concluded that cross-talk could not account for his findings, thus resources were a more plausible explanation. However, the logic used by Temprado et al., (2001) - that for neuroanatomically distant limbs (e.g., the foot and the hand) neural cross-talk should be limited - is not necessarily accurate (Hiraga, Garry, Summers & Carson, 2005). As discussed previously, Sohn and Hallett (2004) have demonstrated neural cross-talk between the hand and leg areas of M1. Thus the neural cross-talk explanation should still be considered when investigating dual-task interference effects.

Modulation of neural cross-talk

Neural cross-talk is thought to impact on behaviour, therefore it is important to explore factors (e.g., attention) that could modulate it and subsequently influence this behaviour. Garry, Loftus and Summers (2005) investigated the effects of mirror viewing on M1 excitability during unilateral hand movements. In that study participants performed a simple motor task with one hand (rhythmical index finger-thumb opposition movements) while TMS was used to assess excitability of M1 controlling the opposite hand. In one condition participants looked towards their moving hand, while in another condition they looked towards their inactive hand, into a mirror placed between the hands. The mirror reflected the moving hand giving the illusion that the inactive hand was moving. It was found that compared to a control (rest) condition MEPs were elevated in the inactive hand when the other hand was moved, consistent with neural cross-talk between the active and inactive M1. In addition MEPs were found to be larger when participants looked into the mirror compared with when they looked at the active hand. From these results it can be concluded that neural cross-talk can be modulated by visual input.

If neural cross-talk can be modulated by visual input it is possible that it can also be modified by other processes. An investigation of this was conducted by Hiraga (2005) (Experiment 4) who looked at whether neural cross-talk was influenced by attentional prioritisation/resources. The study was based on the work of Temprado et al., (1999, 2001) and employed two motor tasks - an RT task where participants had to dorsiflex the foot as fast as possible in response to a visual stimulus, and a bimanual coordination task

where participants had to perform forearm anti-phase pronation-supination movements. Participants completed these tasks in three movement conditions and a rest condition: 'rest' – participants did not perform either task, 'probe RT' – participants completed the RT task only, 'dual coordination' – participants had to complete the coordination task and RT task simultaneously while prioritising the coordination task, and 'dual RT' – the same as 'dual coordination' except the RT task was prioritised. Single-pulse TMS was administered throughout the experiment to determine whether different levels of attentional priority modified neural cross-talk (as reflected in MEP amplitude). It was found that performance on the RT task was better when it was prioritised and similar results were also found for performance on the coordination task. These results indicate that dual-task interference was modulated by attentional priority. For MEP amplitude it was revealed that corticospinal excitability was higher in the dual-task conditions relative to the probe RT condition and rest condition, indicative of neural cross-talk between the arms and the foot. However, no significant difference in corticospinal excitability was found between the two dual-task prioritisation conditions suggesting that neural cross-talk is not sensitive to the prioritisation of attention.

Short interval intracortical inhibition

The findings of Hiraga (2005) (Experiment 4) suggest that neural cross-talk is not modulated by attention, however it is possible that neural cross-talk is reflected in other neurophysiological mechanisms, not just the net excitability of the corticospinal pathway. The changes in neural cross-talk may be identified in the measure of short interval

intracortical inhibition (sICI) which reflects the excitability of the inhibitory circuits of the motor cortex (Kujirai et al., 1993). sICI may be important to dual-task interference as there is evidence to suggest that it plays an important role in movement initiation and temporal control of movements (e.g., Byblow & Stinear, 2006; Coxon, Stinear, & Byblow, 2006; Reynolds & Ashby, 1999)

Reynolds and Ashby (1999) assessed the role of sICI in movement initiation. sICI was assessed using paired-pulse TMS and was administered when participants were at rest and at different times prior to a wrist movement. It was found that prior to participants performing the voluntary movement there was a decrease in sICI. This reduction in sICI occurred before any other changes in excitability, which suggests that sICI plays an important role in movement initiation (Reynolds & Ashby, 1999).

Coxon, Stinear, and Byblow (2006) examined sICI in the temporal control of movement, specifically looking at whether it is involved in stopping a prepared movement (volitional inhibition). In that study, participants were shown a clock face (with 10 digits) displayed on a computer screen. On this clock face was a hand that revolved clockwise round the numbers (from 1-10). There were two types of trials, go trials and stop trials. During go trials the participant rested their hands on a keyboard and had to release a key so that when the hand revolved round the clock it would stop at the digit 8. On stop trials the hand on the clock face stopped moving before reaching the digit 8 and the participant had to make sure they did not release the key (Coxon, Stinear and Byblow, 2006). Paired-pulse TMS was administered before the participants released the key in the go and stop

trials. It was found that there was increased sICI in the stop trials compared to the go trials which suggests that sICI plays a role in controlling movement initiation/inhibition (Coxon, Stinear & Byblow, 2006).

Another study by Byblow and Stinear (2006) explored the role of sICI in the temporal control of movement. Changes in sICI were explored in the performance of two different movement patterns: synchronisation finger abduction movements and syncopation finger abduction movements. For the synchronisation movements participants had to abduct their index finger to press a button in time to an auditory metronome, while the syncopation movements required participants to abduct their finger between the metronome beats. Synchronisation movements are more stable than syncopation movements and when people attempt to perform syncopation a spontaneous transition to the synchronisation pattern often occurs (Byblow & Stinear, 2006). Paired-pulse TMS was employed to measure sICI and was administered to the first dorsal interosseous (FDI) muscle between button presses when the muscle was inactive. It was found that sICI was greater during syncopation movements relative to synchronisation movements. The authors explained that the increased sICI in the syncopation movements could have occurred to stop the person from making the transition to synchronisation movements. This finding highlights the importance of sICI in temporal control and in the performance of different movement patterns (Byblow & Stinear, 2006). The studies presented above indicate that sICI plays an important role in movement initiation and in the temporal control of movement. As such it is plausible that sICI may be affected by neural cross-talk contributing to dual-task interference. This will be the focus of the current study.

Practical implications of investigating cortical excitability and sICI

The current study explores the role of cortical excitability and sICI in dual-task situations. Investigating these neurophysiological components of dual-task performance can help to increase our knowledge of physiology and the motor system in general. It is important to do this, particularly with sICI, as the literature has identified it as playing an important role in a number of psychological disorders. For example, in a review article by Maeda and Pascual-Leone (2003) it was found that individuals with obsessive-compulsive disorder, and those with Tourette's disorder had low levels of sICI. It has also been identified in a study by Gilbert, Sallee, Zhang, Lipps, and Wasserman (2005) that sICI was correlated with hyperactivity in children with attention deficit hyperactivity disorder. In order to fully understand the role of sICI in these psychological disorders we have to first have to identify the role that it plays in a non-clinical sample, as was the goal of the current study.

The current study

The current study will examine whether neural cross-talk contributes to dual-task interference and whether this process can be modulated by attention. Specifically, it aims to extend the findings of Hiraga (2005) (Experiment 4) by investigating the contribution of sICI (using paired-pulse TMS) to dual-task interference. As with Hiraga participants will complete two motor tasks, a coordination task which required them to perform forearm anti-phase pronation-supination movements and an RT task which required them

to dorsiflex their foot as fast as possible on the presentation of a visual stimulus. The first hypothesis of this study is that dual-task performance will produce an increase in M1 excitability that will be unaffected by the prioritisation of attention. This hypothesis is based on Hiraga's finding that there was no difference in corticospinal excitability between the two dual-task conditions, despite their different attentional priorities. The second hypothesis assessed whether another form of excitability, sICI, can be modulated by attention and whether variations in sICI are accompanied by variations in dual-task interference. This hypothesis was derived from research (e.g., Byblow & Stinear, 2006) which suggests that sICI is involved in the temporal control of movement. It is predicted that there will be a release of inhibition when participants prioritise the RT task compared to the coordination task, while sICI is expected to be higher in dual-task conditions relative to single.

Method

Participants

Participants were recruited through personal networks. Twelve right-handed participants completed the study; 4 male and 8 female ($M = 29.6$ years, $SD = 6.8$ years). Participants had normal or corrected to normal vision. All participants provided written informed consent and completed a questionnaire that screened for contraindications to TMS (refer

to Appendix 1). This experiment was approved by the University of Tasmania Ethics Committee (Refer to Appendix 2).

Design

This experiment was a within-subjects repeated measures design. The independent variable (IV) was the task condition and had five levels: 'RT' – participants performed the RT task only; 'coordination' – participants performed the coordination task only; 'dual RT' – participants completed the RT task and the coordination task simultaneously while prioritising the RT task; 'dual coordination' – the same as 'dual RT' except the coordination task was prioritised; 'control' – participants did not perform either of the motor tasks and simply remained at rest. The dependent variables (DV) were RT, absolute deviation from target relative phase, standard deviation of relative phase, movement frequency, MEP amplitude and sICI ratio.

Materials

Coordination task. In the coordination task participants had to perform forearm, anti-phase pronation-supination movements using custom-built manipulanda (two levers). The levers were attached to a table and were 18cm in length and 2cm in diameter. Participants performed these movements while seated at in a height adjustable chair. To perform the anti-phase pronation-supination movements the participant held onto the two levers with both hands and rotated one toward the midline of the body (pronation) while the other

rotated away from the body (supination) and continued this in a cyclical manner (Hiraga, 2005).

Performance on the coordination task was assessed through the measures absolute deviation from target relative phase, standard deviation of relative phase and movement frequency. Absolute deviation from target relative phase measured participants overall deviation (in degrees) from the movement pattern (anti-phase). This measure was used to determine if participants performed the coordination task correctly (Matthews, Garry, Martin & Summers, 2006). The standard deviation of relative phase is the variability in the coupling between the limbs as measured by relative phase (Hiraga, 2005) when participants are performing the coordination task. Movement frequency was defined as the speed, in Hz, that participants performed the coordination task.

Reaction time task. A footswitch was used for the RT task and was positioned so that the participant's right foot was resting comfortably on it. Participants had to dorsiflex their foot as fast as possible when a visual stimulus was presented (Hiraga, 2005). The visual stimulus was a pair of flashing light-emitting diodes situated in an 8X4cm box directly in front of the participant and was presented at random 4-7 second intervals to minimize anticipation.

RT was assessed by measuring premotor time (PMT), motor time (MT) and overall reaction time (PMT + MT). Overall reaction time was analysed to provide an inclusive measure of task completion, as was the goal outlined to participants. PMT was defined as

the time from the presentation of the visual stimulus to EMG activity in the right TA and reflects processes that occur from the presentation of the stimulus to the start of the right TA movement, while MT is the time from the onset of the EMG activity to the participant's response which is releasing their right foot from a footswitch and reflects the time taken for the participant to actually complete the dorsiflexion movement (Davranche, Burle, Audiffren & Hasbroucq, 2005).

TMS. TMS pulses were applied to the scalp region overlying the leg area of the M1 using two Magstim Model 200 stimulators attached to a single 160mm angled figure-of-eight-coil (Magstim, UK) via a BiStim module. The BiStim module allows the output of two stimulators to be directed through a single coil. MEPs were measured by two Ag/AgCl surface electrodes that were attached to the skin overlying the tibialis anterior (TA) muscle of the right leg. A reference electrode was placed on the right lateral malleolus. The coil was orientated so that it delivered the current in a posterior-anterior direction. The 'hotspot' - the position on the scalp where consistent MEP responses are elicited in the TA - was identified by moving the coil to different positions on the scalp and looking for the location where there were consistently large responses. A mark was placed on the participants scalp on the hotspot to ensure the correct repositioning of the coil during the experiment. Resting Motor Threshold (RMT), test and conditioned intensities for the experimental conditions were then determined.

The coil was positioned over the 'hotspot' and RMT was determined as the lowest intensity to elicit an MEP $> 50\mu V$ in the relaxed TA muscle for three out of five pulses.

To identify the test intensity single-pulse TMS was adjusted to elicit MEPs $> 200\mu\text{V}$ for three out of five pulses for the relaxed TA (Hiraga, 2005). The intensity of paired-pulse TMS was then determined and involved delivering a weak TMS pulse that is unable to elicit an MEP alone 3ms before the suprathreshold test pulse. This 'weak' pulse is termed the conditioning pulse and it activates inhibitory circuits that act on the neural circuits targeted by the succeeding 'test' TMS pulse. This results in a smaller MEP relative to single-pulse TMS. The conditioning pulse was adjusted to elicit an MEP with an amplitude of approximately 50% ($100\mu\text{V}$) of the original test pulse. Inline with a number of other research studies (e.g., Coxon, Stinear, & Byblow, 2006; Thomson, Garry, & Summers, 2007) the test intensity was held constant during the experiment.

MEP amplitude was measured as the peak-to-peak amplitude of the TA MEP to the single-pulse TMS, and sICI was the ratio of the mean paired-pulse MEP to the mean single-pulse MEP.

Procedure

The first part of the experiment involved identifying the participant's TMS intensities that were used during the five experimental conditions, this part of the experiment lasted approximately forty-five minutes. Following this movement frequency was determined. This was set as 70% of their critical frequency, the frequency at which participants made a phase transition to an in-phase coordination pattern or showed disruption of the anti-phase pattern. To determine critical frequency participants were instructed to hold on to

the two levers and perform forearm anti-phase pronation-supination movements in time with an auditory signal.

The auditory signal was generated by a metronome that started at the frequency of 1 Hz, and increased at 8 second intervals by .25 Hz until the maximum frequency of 3 Hz was reached (Hiraga, 2005). Participants were instructed to keep in time with the metronome and maintain the coordination pattern to the best of their ability. After the participants completed this part of the experiment twice the researcher calculated critical frequency. Critical frequency was determined by playing back the trial and visually inspecting the displacement traces on the computer screen for a phase transition or disruption in the coordination pattern.

The second part of the experiment involved participants completing all five conditions, this part of the experiment lasted approximately one hour. Six trials were performed in each condition (with the first being a practise trial), each lasting 56 seconds. Nine visual stimuli were presented in each trial, four to seven seconds apart. Four TMS pulses (two single and two paired) were delivered at random intervals within a trial, each coincident with delivery of one of the visual stimuli. This was done in order to ensure that the participant's muscle was relaxed when TMS was delivered.

The control condition was always completed first in order to provide a means by which to evaluate changes in MEPs that occur in the other conditions. The single-task conditions were performed before the two dual-task conditions to provide participants with a

standard to aim for when performing the tasks in the dual-task conditions. The order in which the two single and dual-task conditions were completed was randomised via coin toss.

At the start of each trial in the experimental conditions the auditory signal was generated by the metronome for 5 seconds to help participants to produce the coordination pattern at the required speed (70% critical frequency). The duration of the auditory signal differs from Hiraga (2005) study where it was generated for the entire trial. This shortened auditory signal was employed to reduce the increased attentional demands that could occur if participants were concerned about keeping synchronised with the pacing signal during the trial. Following the cessation of the pacing signal participants were instructed to continue the anti-phase coordination task at the required frequency for the duration of the trial.

In the two dual-task conditions participants completed the RT task and coordination task simultaneously. The two dual-task conditions differed according to the task that was prioritised. Participants were instructed to perform one task (e.g., the RT task) in the dual-task condition as well as they did in the single-task condition, yet at the same time maintain an optimal level of performance on the other task (Tsang, Velazquez, & Vidulich, 1996). An example of instructions given in the dual RT condition was to perform the RT task as well as you did in the single-task condition but at the same time still maintain the coordination pattern.

Data analysis.

MEPs were analysed using the software program Signal. MEPs were excluded from analysis if EMG activity was present 100ms before TMS delivery. Individual MEPs were measured by peak-to-peak amplitude. The MEP amplitude, were then averaged within each condition to obtain a mean MEP amplitude. sICI was calculated as the ratio of the mean paired-pulse MEP to the mean single-pulse MEP for each condition. Both absolute deviation from target relative phase and standard deviation of relative phase were calculated from relative phase data (Hiraga, 2005). Absolute deviation from target relative phase was calculated by subtracting the target relative phase from participants mean relative phase (Matthews et al., 2006). Scores could range from 0-180; low scores demonstrating small deviation from the required anti-phase movement pattern. Circular statistics were used to derive the values for standard deviation of relative phase (Mardia, 1972). Averages were calculated for each condition with high values indicating greater variability of the coordination pattern (Hiraga, 2005).

Movement frequency was analysed using a deviation of frequency score that was calculated from the discrepancy between each participant's target frequency (70% of critical frequency) and the actual frequency that they performed the experimental conditions. Deviation of frequency was calculated to provide a measure of participant's individual frequency variability. A positive score indicated that the participant was moving faster than their required frequency while a negative score indicated that they were moving slower. Deviation of frequency was analysed by examining scores before

and after the visual stimulus in each trial. The mean frequency of three cycles before the visual stimulus and the mean frequency three cycles after the stimulus were obtained; this provided two scores for deviation of frequency - pre-stimulus and post-stimulus.

Reaction times (milliseconds) were averaged across each condition. Data for MEPs, reaction time task and coordination task were analysed using repeated measures analysis of variance (ANOVA). Violations of sphericity were corrected using the Huynh-Feldt epsilon correction and post-hoc tests to examine significant differences between means were conducted using the False Discovery Rate procedure (Curran-Everett, 2000). Statistical significance was assumed if $p \leq .05$.

Results

Reaction time task

Reaction time. A significant effect was found for condition ($F(2,22) = 22.64, p < .01$) (refer to Figure 1). Post-hoc tests revealed that reaction time for the dual coordination condition ($M = 346.47\text{ms}$, $SD = 36.31\text{ms}$) was significantly slower than the RT condition ($M = 285.35\text{ms}$, $SD = 35.42\text{ms}$) and dual RT condition ($M = 298.99\text{ms}$, $SD = 36.16\text{ms}$), while no significant difference was found between the RT condition and the dual RT condition. This finding suggests that prioritisation of the RT task can reduce interference to the level of the single-task condition. However this conclusion may not be

accurate considering the PMT and MT findings (which are discussed below) that suggest that the attentional effects on reaction time are more complex.

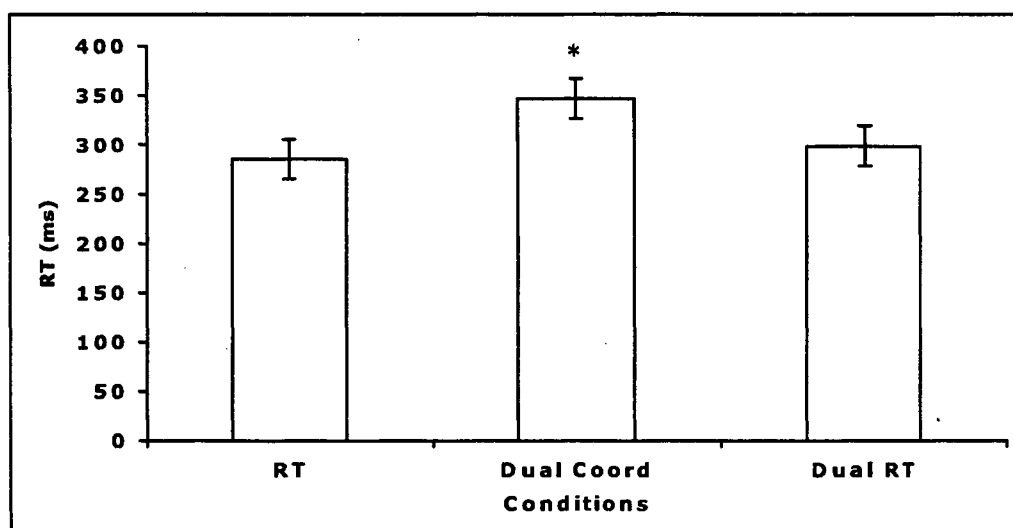


Figure 1. Mean reaction times (ms) for RT and dual-task conditions. *Significantly different from the RT and dual RT conditions. Error bars indicate 95% confidence intervals.

Premotor time. A one-way repeated measures ANOVA revealed a significant effect for condition, $F(2,22) = 34.40$, $p < .01$. Post-hoc tests found significant differences between all three conditions (refer to Figure 2). PMT was fastest for the RT condition ($M = 176.30\text{ms}$, $SD = 22.53\text{ms}$) followed by the dual RT condition ($M = 208.71\text{ms}$, $SD = 28.88\text{ms}$) and then the dual coordination condition ($M = 243.53\text{ms}$, $SD = 32.46\text{ms}$). This result demonstrates that attentional prioritisation reduced the degree of interference in the

dual task conditions, although prioritisation of the RT task did not eliminate interference completely.

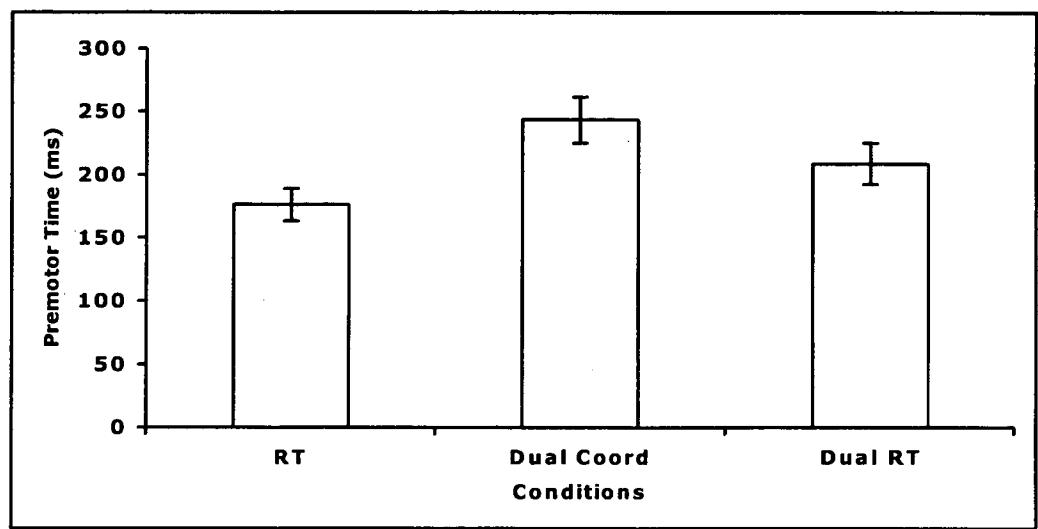


Figure 2. Mean premotor times (ms) for RT and dual-task conditions. Premotor time differed between all three conditions. Attentional prioritisation to the RT task reduced premotor time in the dual task conditions. Error bars indicate 95% confidence intervals.

Motor time. A one-way repeated measures ANOVA revealed a significant effect for condition ($F(2,22) = 5.16, p = .015$) (refer to Figure 3). Post-hoc tests found that motor time was significantly faster in the dual RT condition ($M = 90.28\text{ms}, SD = 18.48\text{ms}$) than the dual coordination ($M = 103.10\text{ms}, SD = 22.78\text{ms}$) and the RT condition ($M = 107.29\text{ms}, SD = 29.33\text{ms}$). The reduced motor time in the dual RT condition indicates that participants were performing the dorsiflexion movement faster in this condition than in the RT or dual coordination conditions.

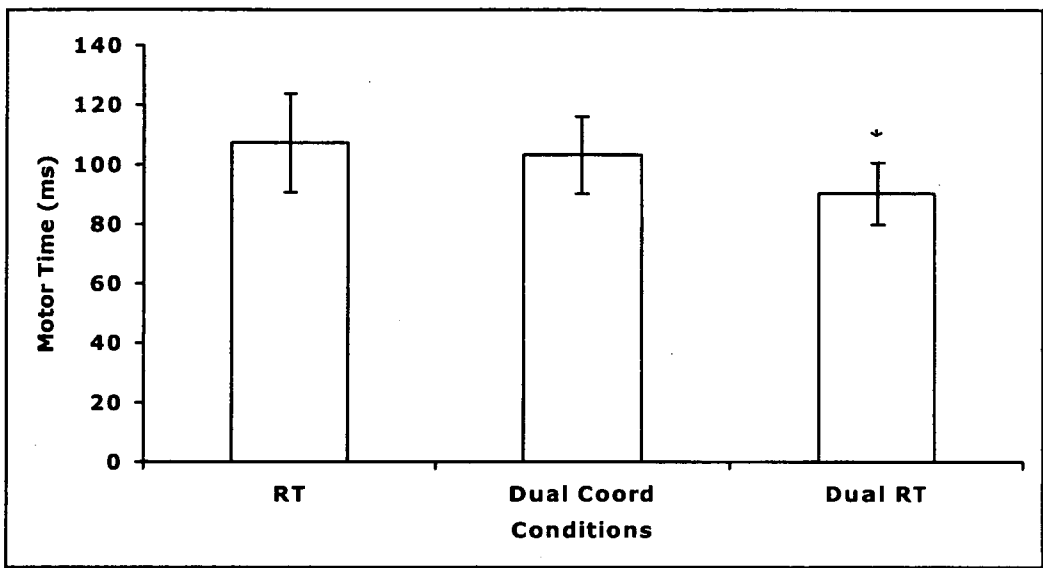


Figure 3. Mean motor times (ms) for RT and dual-task conditions. *Significantly different from the RT and dual coordination conditions. Error bars indicate 95% confidence intervals.

Coordination task

Absolute deviation from target relative phase. A one-way repeated measures ANOVA revealed that there was no significant difference among the coordination ($M = 4.10$ degrees, $SD = 3.24$ degrees), dual coordination ($M = 5.00$ degrees, $SD = 4.35$ degrees) and dual RT conditions ($M = 6.16$ degrees, $SD = 3.93$ degrees) ($F(2,22) = 1.72$, $p > .05$). The small deviation scores demonstrate that participants performed the task correctly in anti-phase mode.

Standard deviation of relative phase. A one-way repeated measures ANOVA revealed that there was no significant difference among the conditions: coordination

condition ($M = 15.02$, $SD = 4.93$), dual coordination ($M = 16.10$, $SD = 5.22$) and dual RT condition ($M = 16.01$, $SD = 3.58$), ($F(2,22) = 1.94$, $p > .05$). This indicates that coordination stability did not differ for single and dual-task conditions and was unaffected by attentional prioritisation.

Deviation of frequency (movement frequency). Deviation of frequency was analysed using a 2 (time: pre-stimulus & post-stimulus) X 3 (condition: coordination, dual coordination & dual RT) X 2 (hand: left & right) repeated measures ANOVA (refer to Figure 4). Significant main effects were found for time ($F(1,11) = 8.70$, $p < .05$) and condition ($F(2,22) = 16.52$, $p < .01$), but not for hand ($F(1,11) = .14$, $p > .05$). Significant interactions were found for time by condition by hand ($F(2,22) = 4.80$, $p < .05$) and for time by condition ($F(2,22) = 8.26$, $p < .01$).

Post-hoc tests for the main effect of time revealed that movement frequency increased after the visual stimulus was presented (pre-stimulus, $M = .12\text{Hz}$, $SD = .09$; post-stimulus, $M = .15\text{Hz}$, $SD = .11$). For the main effect of condition a post-hoc test identified significant differences between all three conditions with deviation of frequency lowest for the coordination condition ($M = .02\text{Hz}$, $SD = .12$), followed by the dual coordination condition ($M = .14\text{Hz}$, $SD = .15$) and the dual RT condition ($M = .23\text{Hz}$, $SD = .16$). This result indicates a performance trade-off with movement frequency becoming more variable when the RT task was prioritised.

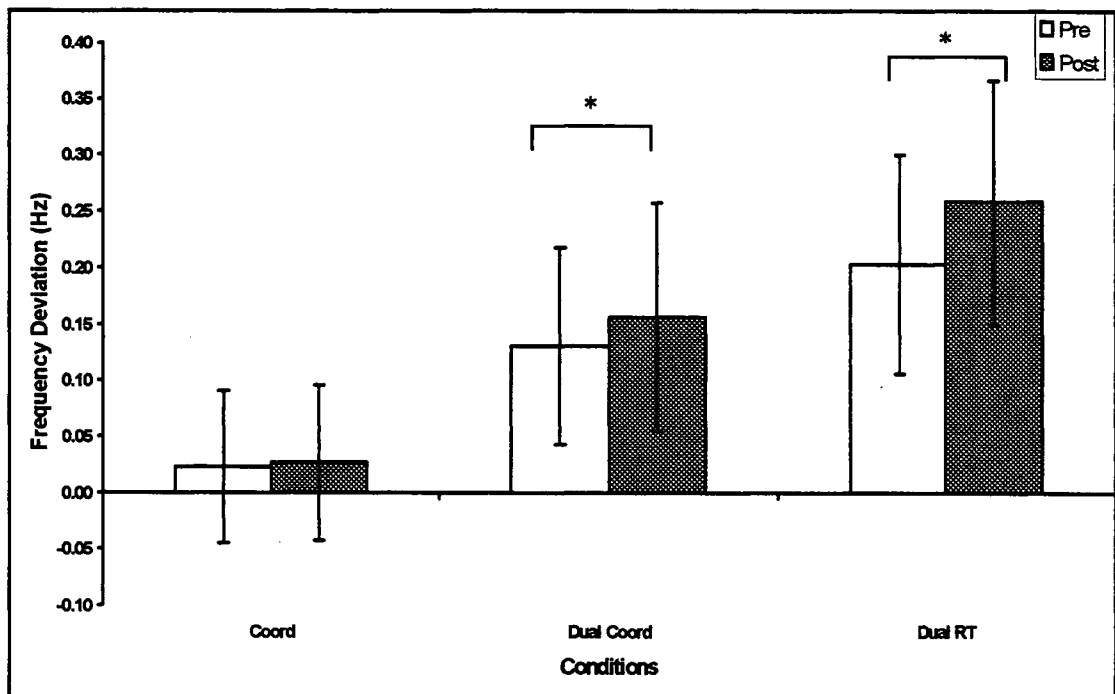


Figure 4. Mean frequency deviation scores for coordination and dual-task conditions pre and post-stimulus. Prioritisation of the coordination task was associated with lower frequency deviation. *Significantly different frequency deviation from pre-stimulus to post-stimulus. Error bars indicate 95% confidence intervals.

For the significant two-way interaction (time by condition) deviation of frequency increased from pre-stimulus to post-stimulus and this increase differed across conditions, with the greatest increase in deviation of frequency occurring for the dual RT condition (refer to Figure 4). This indicates that coordination stability differs according to attentional prioritization. The three-way interaction was significant, however it was not analysed as it seemed to have occurred due to an increased deviation of frequency for the right hand from pre-stimulus to post-stimulus in the dual coordination condition. As the interaction occurred due to a change across the variable hand it was not examined, as this variable was not theoretically important.

Excitability data

TMS intensities. Participants' averaged RMT was ($M = 44\%$, $SD = 8\%$). As a percentage of RMT, test and conditioned intensities were ($M = 122\%$, $SD = 11\%$) and ($M = 66\%$, $SD = 7\%$), respectively.

Single-pulse MEPs. A one-way repeated measures ANOVA revealed a significant effect for condition ($F(2,21) = 9.15$, $p < .01$). Post-hoc tests revealed that MEP amplitude was significantly higher in the coordination condition ($M = 0.82\text{mV}$, $SD = 0.60$), dual coordination condition ($M = 0.78\text{mV}$, $SD = .60$) and dual RT condition ($M = 0.88\text{mV}$, $SD = .77$) than the control ($M = 0.53\text{mV}$, $SD = .38$) and RT conditions ($M = 0.44\text{mV}$, $SD = .30$) (refer to Figure 5). No significant differences were found between the two dual-task conditions indicating that excitability was not modified by attentional priority. MEP amplitude for the control and RT conditions did not differ significantly either. This suggests that the increase in excitability in the coordination conditions is a consequence of the arm movement, consistent with neural cross-talk.

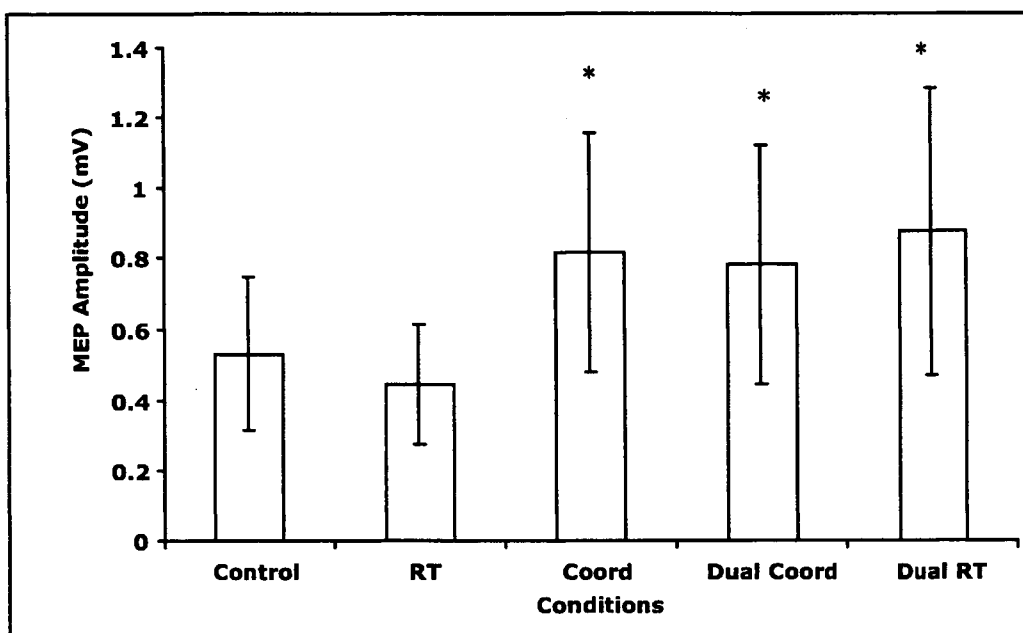


Figure 5. Mean MEP amplitude for control, single and dual-task conditions.

*Significantly different from the control and RT conditions. Error bars indicate 95% confidence intervals.

Paired-pulse MEPs. A significant effect for condition was found ($F(2,20) = 4.28$, $p = .03$). Post-hoc tests showed that sICI was significantly lower (reflected in a higher ratio in Figure 6) in the four experimental conditions relative to the control. The greatest release of inhibition occurred in the RT condition, although it was not significantly different from the coordination or dual-task conditions. Attentional prioritisation did not appear to affect sICI as no significant differences were found between the dual-task conditions.

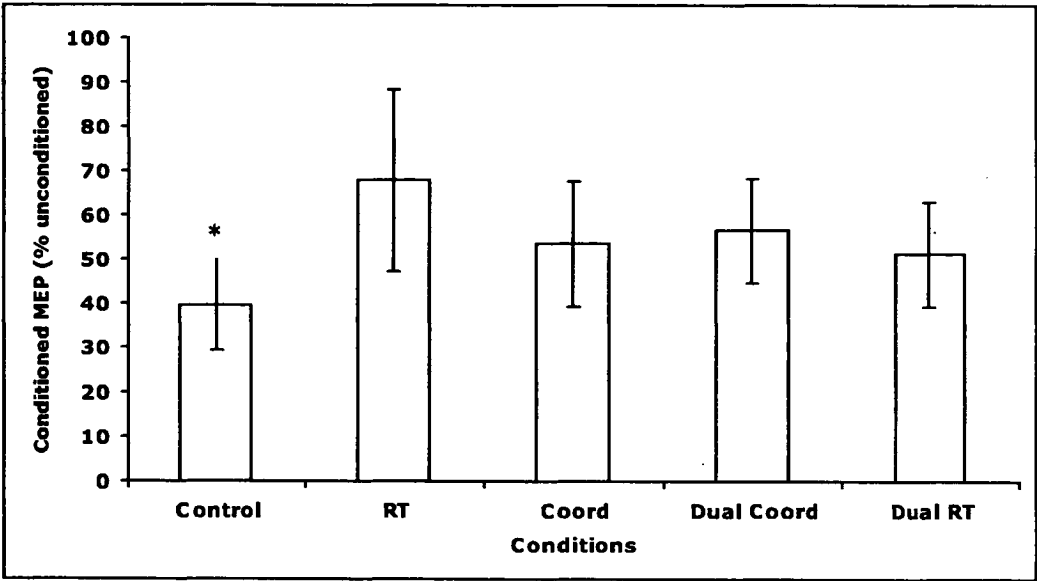


Figure 6. Mean sICI for control, single and dual-task conditions. *Significantly different from the experimental conditions. Error bars indicate 95% confidence intervals.

Discussion

The current study employed a dual task paradigm using two motor tasks to investigate the contribution of neural cross-talk to dual-task interference. Dual-task interference effects were found for premotor time and deviation of frequency scores. As predicted, this interference was modulated by attentional priority. For example, premotor time was fastest for the RT condition followed by the dual RT condition then the dual coordination condition. The behavioural effect of manipulating attention on the two motor tasks is consistent with previous findings (e.g., Hiraga, 2005; Temprado et al., 2001). As the attentional manipulation was successful (dual-task interference effects were found) any

neurophysiological changes, specifically neural cross-talk, that contributed to this interference were able to be explored.

The first hypothesis explored the role of cortical excitability in dual-task interference. Excitability were found to be higher in the two dual-task conditions compared to the control and RT conditions, which is consistent with Hiraga (2005) (Experiment 4). However, in contrast to what was predicted, excitability was found to be as high in the coordination condition as it was in the two dual-task conditions. The increase in cortical excitability when the coordination task was being performed (relative to the control and RT conditions) is indicative of neural cross-talk with the movement of the arms affecting the excitability in the leg. If neural cross-talk was playing a dominant role in the interference found in the RT task then excitability should vary with interference. However, as neural cross-talk (at least in terms of cortical excitability) was unaffected by the prioritisation of attention it seems unlikely that it was solely responsible for the dual-task interference found in this study.

The excitability findings of the current study differ from Hiraga (2005) study (Experiment 2), which explored neural cross-talk in a rest condition, coordination only condition and dual-task condition. In that study it was found that excitability was highest for a dual-task condition followed by the coordination only condition and then the rest condition. Hiraga's results differ from the results in the current study, as no difference was found in excitability between the coordination condition and the dual-task conditions. A possible explanation for this is the methodological differences between the two studies. In Hiraga

a metronome was presented throughout the coordination task so that participants could maintain the coordination pattern at the required frequency. This may have resulted in the task becoming more attention demanding, with participants having to concentrate not only on performing the coordination task but also keeping in time with the metronome. This increase in attentional demands may have made the dual-task conditions more challenging to perform, and consequently resulted in greater excitability in the two dual-task conditions. As the current study did not have this additional attentional demand it is thought that this may have limited the rise in excitability in the two dual-task condition.

The second hypothesis explored the role of sICI in dual-task interference. No significant differences were found for sICI between the experimental conditions. This finding is consistent with Thomson et al., (2008) where no significant changes were found between dual and single-task conditions for sICI despite the fact that performance decreased in a dual-task condition. However, the finding in our study that sICI was lower (although not significantly) in the RT condition than the coordination and dual-task conditions does suggest that neural cross-talk could be involved in interference.

Neural cross-talk and alternative explanations for dual-task interference.

The excitability changes found in this study clearly indicate that neural cross-talk is not the primary factor contributing to dual-task interference. If neural cross-talk were involved, changes in excitability would be associated with changes in interference. This was not the case.

Two cognitive models need to be considered when interpreting our findings – the bottleneck model and attentional resources. The bottleneck model is based on the premise that some tasks have to be completed sequentially not simultaneously. Consequently dual-task interference is a consequence of one task being put on hold while the other is completed (Pashler, 1994). In Temprado et al. (2001) the bottleneck model is ruled out as an explanation for dual-task interference. He argues that if a bottleneck was occurring then there should be a cessation of movement on the coordination task when the stimulus for the RT task is presented, this was not found in his study. The same argument can be put forward for our results. Participants' frequency deviation scores did increase after the visual stimulus was presented, however on the displacement traces that were used to determine frequency there was no cessation of movement during the actual foot response. Therefore it is highly unlikely that the bottleneck model can be responsible for the dual-task interference found in our study. However, it does need to be taken into consideration that even after the visual stimulus was presented inertia may have made it impossible for a physical stopping of the arm movement to occur, thus a bottleneck may have occurred and it just was not detected (Temprado et al. 2001).

The more plausible explanation for the dual-task interference effects found in our study is attentional resources. The resource explanation argues that individuals have a set amount of resources that they can allocate to different tasks (Kahneman, 1973). Consequently, when an individual is performing two tasks simultaneously performance is reduced due to the limited resources available to each task (Pashler, 1994). As stated previously results from our study did not provide support for the neural cross-talk model. Thus the resource

explanation needs to be considered. In our study the behavioural results can be explained through attentional resources, with the more resources allocated to the task (e.g. RT or coordination) the less interference. Further support for attentional resources arises from Temprado et al., (2001) who argued that the dual-task interference observed was due to limited attentional resources. In this report it was stated that the interference Temprado et al., (2001) found may have been due to neural cross-talk, however given the results of the current study that suggest that neural cross-talk was not modified by attention it is concluded that resources are probably the main factor contributing to interference.

However, the neural cross-talk explanation cannot be ruled out completely, there is evidence in the results from the current study that indicate that it may be important. First and most importantly, neural cross-talk was always accompanied by dual-task interference. This is illustrated in the premotor time results; performance was degraded in the dual-task conditions (higher premotor times) relative to the single task RT condition. This change in performance was always accompanied by increased excitability in the dual-task conditions relative to the single.

Further evidence highlighting the importance of neural cross-talk arises from the excitability and motor time data. Excitability was found to be higher in the two dual-task conditions relative to the single-task RT condition indicative of neural cross-talk. It is possible that participants may have adopted a strategy to overcome the effects of cross-talk without directly modifying it. The motor time data supports this possibility. Motor time was fastest for the dual RT condition followed by the dual coordination and RT

conditions. Participants' may have allocated more attentional resources to the dual RT condition to try and limit the effect of neural cross-talk, which resulted in the reduced motor time relative to the dual coordination condition.

Neural cross-talk, precision movements and future directions

It is speculated that in this study participants were able to modify their behaviour, that is perform RT task in different ways (i.e. changing their foot movement) to compensate for the effects of neural cross-talk. If correct, then a task that is more sensitive to a change in behavioural strategy may be better able to reveal the effects of cross-talk, for example, tasks that require precise movements or precise force control. In these tasks, adopting a behavioural strategy to compensate for the effects of cross-talk could not be adopted without incurring a performance deficit. An additional advantage is that research (e.g., Schieppati, Trompetto & Abbruzzese, 1996; Tinazzi et al., 2003) has found that tasks that require fine precision or force control seem to require a higher level of excitability than more simple tasks. This could make these tasks more sensitive to cross-talk.

Further evidence to suggest neural cross-talk may be seen in tasks that require more precise movements arises from the coordination task where frequency deviation scores were found to increase from pre stimulus to post stimulus for the two dual-task conditions. This coordination task was a more complex task than the simple RT task, with participants having to coordinate both arms in a bimanual coordination pattern. It is thought that neural cross-talk from the leg to arm areas of M1 underlie this, with the left

motor cortex activated during the foot response affecting the left and right areas of the motor cortex involved in performing the arm movements. An alternative explanation is that the TMS which was administered simultaneously with the visual stimulus may have caused the participants to increase the speed of their arm movements. However, this is unlikely given that there was limited increase pre stimulus to post stimulus in the coordination condition where TMS was present but not the foot response. This will need to be addressed in future research.

Another avenue for future research to explore is whether brain areas other than the M1 could be responsible for dual-task interference. The current study focused purely on the M1 region of the brain using TMS. It is possible that the interference found in our study could be attributed to neural cross-talk occurring in areas of the brain upstream of M1. Evidence to support this possibility arises from studies that have employed other neurophysiological measures (e.g., PET scans & fMRI). For example, Goldberg et al. (1998) found that when two cognitive tasks were performed simultaneously there was a decrease in activity in the prefrontal cortex (as measured by a PET scan) compared to when one of the cognitive tasks was performed alone. This indicates neural cross-talk as performing each cognitive tasks would activate different areas of the brain, and thus cross-talk would be identified by a decrease in activity in the prefrontal cortex.

Conclusion

Dual-task interference was found for both the RT task and the coordination task.

Performance on both tasks was modified by attention, with improved performance when the specific tasks were prioritised. Neural cross-talk effects were identified for both cortical excitability and sICI, however this neural cross-talk was not modulated by attentional priority. On the basis of these two findings we have to conclude that neural cross-talk was not the sole factor contributing to the interference found in this study.

Rather, it is speculated that although neural cross-talk may have had some contribution to the interference it is more likely that attentional resources played a much larger role.

It is hypothesised that the neural cross-talk found in this study was not benign and that it still had some contribution to the interference found. Participants may have allocated attentional resources to the dual-task conditions to limit the effects of cross-talk. This conclusion opens a number of avenues for future research. First, conducting a study that examines neural cross-talk employing tasks that require precise movements or precise force control. This would ensure that the participants would not be able to employ a strategy to over-ride the effects of neural cross-talk and thus the effects neural cross-talk would be more easily detected. A second avenue for future research arises from the possibility that neural cross-talk effects may occur in an area up-stream of the motor cortex. A study could be conducted that employs a different neurophysiological measure to identify neural cross-talk. Even though neural cross-talk was not the primary factor

contributing to the interference found in this study it is clear that it is important in the performance of dual-tasks.

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APPENDIX

1. Consent Form and TMS Screening Questionnaire	76-77
2. Ethics Approval	78
3. Statistics	
3.1. Reaction Time: One-Way Repeated Measures ANOVA	80
3.2. Premotor Time: One-Way Repeated Measures ANOVA	81
3.3. Motor Time: One-Way Repeated Measures ANOVA	82
3.4. Absolute Deviation from Target Relative Phase: One-Way Repeated Measures ANOVA	83
3.5. Standard Deviation of Relative Phase: One-Way Repeated Measures ANOVA	84
3.6. Deviation of Frequency: 2 (time) X 3 (condition) X 2 (hand) Repeated Measures ANOVA	85
3.7. Single-Pulse MEPs: One-Way Repeated Measures ANOVA	89
3.8. Paired-Pulse MEPs: One-Way Repeated Measures ANOVA	90



DATE: _____

School of Psychology

Information Sheet for Participation in a Research Project**“Neural correlates of performance trade-offs and interference in dual tasks”**

Chief Investigator: Prof. J.J. Summers, School of Psychology, University of Tasmania (Rm. 124, Arts Building, (03) 6226 2884).

Research Associate: Dr. M.I. Garry, School of Psychology, University of Tasmania (Rm. 109, Arts Building, (03) 6226 2204).

Student Research: Felicity Brown, School of Psychology, University of Tasmania (Human Motor Control Laboratory, Arts Building, (03) 6226 2243)

Thank you for participating in an investigation looking at the neural basis of dual-task interference during voluntary movement. In the present study you will be asked to perform two tasks, a continuous coordination task performed using your hands and a discrete reaction time (RT) task using your foot. You will perform both tasks simultaneously while attempting to maximise the performance of one of the tasks (prioritising one task). The study will examine whether neural activity in the part of the brain that controls the foot response depends on which of the two tasks is prioritised. In order to measure this neural activity the neurophysiological technique called transcranial magnetic stimulation (TMS) will be used.

Although this research will not be applied to a special population or involve any type of therapeutic intervention, it will provide a foundation upon which we can better understand the mechanisms of movement disorders and attentional deficits (e.g., Parkinson's disease, stroke, ADHD, etc). This research is being undertaken as part of a Master's degree in Psychology.

Study Procedures

The experiments will take place in the Human Motor Control Laboratory, Room 228, Arts Building Level 2, University of Tasmania, (03) 6226 2243. The research will involve (a) neurophysiological measures of motor cortex excitability and (b) behavioural measures involving a continuous coordination task and a discrete RT task.

(a) Neurophysiological Measures – Transcranial Magnetic Stimulation (TMS)

In this study we employ a procedure called TMS. TMS is a non-invasive, safe and painless technique used for studying brain function. The technique consists of applying brief magnetic pulses through a coil positioned over the scalp. In this study we will be measuring the excitability of the part of the motor cortex that controls the muscles of your right leg. To ensure the coil is properly positioned, a small mark will be made with an erasable pen marker on the scalp over the appropriate location. To measure the activity in relevant muscles, small sticky recording electrodes will be placed on the skin over the tibialis anterior (TA) and soleus (So) muscles of your right leg. When the magnetic pulse is delivered you will hear a click and feel a slight tap on your scalp. This is not painful. You may also experience slight movements of your right leg. TMS is very safe and well established procedures for the use of TMS will be followed in the study.

(b) Behavioural Measures – Bimanual Coordination and Reaction Time Tasks

The bimanual coordination task will involve holding two handles, one with each hand, and performing continuous pronation-supination (back and forth) movements of the forearms. You will be asked to coordinate your movements so that one handle moves toward the body midline while the other handle moves away from the body midline. This action will be demonstrated by the investigator before you begin, and you will be given an opportunity to practice the movement.

There will also be a reaction time (RT) task in which you will be asked to lift your right foot off a switch as fast as possible whenever a small light positioned in front of you is illuminated. The light will turn on at random intervals so you will not be able to predict its occurrence.

Experimental procedure. The study will be conducted in a single session lasting approximately two hours. During the session you will be seated in an adjustable chair. Recording electrodes will be placed over the leg muscles and the scalp location and TMS intensities determined. This will involve moving the TMS coil to different scalp positions and applying TMS of varying intensities. This part of the experiment will take approximately 45 minutes. The speed at which you will perform the coordination task will then be determined by asking you to perform the coordination task while trying to keep pace with an auditory metronome that gradually speeds up. The coordination pattern you will be performing becomes difficult to maintain at fast speeds and there is a tendency to switch to a different pattern. The speed at which this occurs will be used to determine the movement speed for the main part of the experiment. This part of the experiment will take approximately 10 minutes.

In the main part of the experiment TMS will be delivered at random intervals during trials of one-minute duration. During a trial you will perform the coordination and RT tasks simultaneously. On some trials you will be asked to prioritise the coordination task while on other trials you will be asked to prioritise the RT task. You will also perform trials involving only the coordination task, only the RT task, and while remaining relaxed (do nothing). You will be allowed rest breaks between trials and are free to request a rest break at any time during the session. This part of the experiment will take approximately one hour.

Risks & Discomforts. There are very few possible risks or discomforts associated with these procedures. On very rare occasions magnetic stimulation may cause a headache. If this occurs and you wish stop the session, we will do so. Whether you experience any discomforts or not, you have the right at any stage of the experiment to withdraw without prejudice. If you are receiving course credit for participation you will receive credit for the total time you were involved with the experiment. The investigators will be available after the session to answer any questions you may have regarding the investigation.

Confidentiality. Every effort will be made to maintain confidentiality of research data. Your individual experimental data will be stored on computer disk, access to which will be available only to the investigators via a password system. Future reference to your data will be by participant number only.

Contact persons: If you wish to obtain more information, please contact one of the following researchers:

Prof. Jeff Summers (6226 2884 or Jeff.Summers@utas.edu.au)

Dr. Mike Garry (6226 2204 or michael.garry@utas.edu.au)

Ms. Felicity Brown (6226 2243 or fcbrown@postoffice.utas.edu.au)

The procedures described above have received ethical approval (H7298) from the Human Research Ethics Committee (Tas) Network. Any queries you have regarding the ethics of the investigation may be directed to the Executive Officer of the Network (Marilyn Pugsley, Phone 6226 7479). If you are a University of Tasmania student you may wish to discuss any concerns confidentially with a University Student Counsellor free-of-charge (03 6226 2697).

You will be provided with a copy of this information sheet and a statement of informed consent to keep. When finalised, results of the study will be posted on the University of Tasmania website, <http://www.scieng.utas.edu.au/psychol/index.asp>.



School of Psychology

Informed Consent Form

“Neural correlates of performance trade-offs and interference in dual task”

1. I have read and understood the Information Sheet for this study.
2. The nature and possible effects of Transcranial Magnetic Stimulation have been explained to me.
3. I understand that the technique involves the following procedure: surface EMG recording and magnetic stimulation of the motor cortex. One session lasting approximately two hours will be required to complete the experiment.
4. I understand that the magnetic stimulation may cause a little discomfort during stimulus delivery to the scalp.
5. I do not have a cardiac pacemaker, metal implants, or medical pumps in my body. I do not have any metal in my head such as shrapnel, surgical clips or fragments from welding. I do not suffer from seizures and there is no history of seizures in the members of my immediate family. I have not had neurosurgery and I have not had a head injury severe enough to require hospitalisation. I do not suffer from frequent or severe headaches. I do not have haemophilia.
6. I understand that all research data will be securely stored on the University of Tasmania premises for a period of 5 years. The data will be destroyed at the end of 5 years.
7. Any questions that I have asked have been answered to my satisfaction.
8. I agree that research data gathered for the study may be published provided that I cannot be identified as a subject.
9. I agree to participate in this investigation and understand that I may withdraw at any time without any effect.

Name of Participant: _____

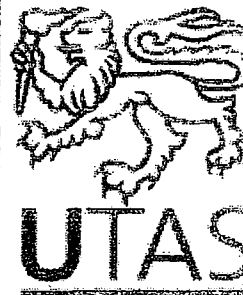
Signature of Participant: _____ Date: _____

I have explained this project and the implications of participation in it to this participant, and I believe that the consent is informed and that he/she understands the implications of participation.

Name of Investigator: _____

Signature of Investigator: _____ Date: _____

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Marilyn.Knott@utas.edu.au
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MEMORANDUM

HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

AMENDMENT TO EXISTING APPLICATION APPROVAL

24 January 2007

Professor Jeffery Summers
Psychology
Private Bag 30
Hobart

H7298: Neural correlates of performance trade-offs and interference in dual-task performance

Dear Professor Summers

The Tasmania Social Sciences Human Research Ethics Committee has approved the Amendment to the above project on 24/1/2007.

Amendment description:

Change to researchers list.
Deleted Cynthia Hiraga as student investigator, and added Felicity Brown as MPsy student investigator.

Yours sincerely

A handwritten signature in black ink, appearing to read "M. Knott", is written below the "Yours sincerely" text.

Ethics Executive Officer

for

Appendix 3.1: Reaction Time: One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	24703.866	2	12351.933	22.641	.000
	Greenhouse-Geisser	24703.866	1.989	12420.098	22.641	.000
	Huynh-Feldt	24703.866	2.000	12351.933	22.641	.000
	Lower-bound	24703.866	1.000	24703.866	22.641	.001
Error(condition)	Sphericity Assumed	12002.034	22	545.547		
	Greenhouse-Geisser	12002.034	21.879	548.558		
	Huynh-Feldt	12002.034	22.000	545.547		
	Lower-bound	12002.034	11.000	1091.094		

Pairwise Comparisons

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (RT)	2 (DUCO)	-61.118(*)	9.391	.000	-81.788	-40.448
	3 (DURT)	-13.634	9.324	.172	-34.157	6.888
2 (DUCO)	1 (RT)	61.118(*)	9.391	.000	40.448	81.788
	3 (DURT)	47.483(*)	9.881	.001	25.735	69.232
3 (DURT)	1 (RT)	13.634	9.324	.172	-6.888	34.157
	2 (DUCO)	-47.483(*)	9.881	.001	-69.232	-25.735

Appendix 3.2: Premotor Time: One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	27131.230	2	13565.615	34.402	.000
	Greenhouse-Geisser	27131.230	1.978	13714.442	34.402	.000
	Huynh-Feldt	27131.230	2.000	13565.615	34.402	.000
	Lower-bound	27131.230	1.000	27131.230	34.402	.000
Error(condition)	Sphericity Assumed	8675.098	22	394.323		
	Greenhouse-Geisser	8675.098	21.761	398.649		
	Huynh-Feldt	8675.098	22.000	394.323		
	Lower-bound	8675.098	11.000	788.645		

Pairwise Comparisons

(I) condition (J) condition		Mean Difference (I-J) Std. Error Sig.(a)			95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (RT)	2 (DUCO)	-67.231(*)	8.046	.000	-84.941	-49.521
	3 (DURT)	-32.414(*)	8.492	.003	-51.104	-13.724
2 (DUCO)	1 (RT)	67.231(*)	8.046	.000	49.521	84.941
	3 (DURT)	34.817(*)	7.766	.001	17.724	51.909
3 (DURT)	1 (RT)	32.414(*)	8.492	.003	13.724	51.104
	2 (DUCO)	-34.817(*)	7.766	.001	-51.909	-17.724

Appendix 3.3: Motor Time: One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	1885.666	2	942.833	5.159	.015
	Greenhouse-Geisser	1885.666	1.483	1271.404	5.159	.026
	Huynh-Feldt	1885.666	1.660	1135.969	5.159	.021
	Lower-bound	1885.666	1.000	1885.666	5.159	.044
Error(condition)	Sphericity Assumed	4020.946	22	182.770		
	Greenhouse-Geisser	4020.946	16.315	246.465		
	Huynh-Feldt	4020.946	18.260	220.210		
	Lower-bound	4020.946	11.000	365.541		

Pairwise Comparisons

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (RT)	2 (DUCO)	4.185	6.937	.559	-11.083	19.454
	3 (DURT)	17.011(*)	4.324	.002	7.494	26.529
2 (DUCO)	1 (RT)	-4.185	6.937	.559	-19.454	11.083
	3 (DURT)	12.826(*)	4.956	.025	1.918	23.735
3 (DURT)	1 (RT)	-17.011(*)	4.324	.002	-26.529	-7.494
	2 (DUCO)	-12.826(*)	4.956	.025	-23.735	-1.918

Appendix 3.4: Absolute Deviation from Target Relative Phase:
One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	22.721	2	11.360	1.775	.193
	Greenhouse-Geisser	22.721	1.623	13.998	1.775	.201
	Huynh-Feldt	22.721	1.864	12.190	1.775	.196
	Lower-bound	22.721	1.000	22.721	1.775	.210
Error(condition)	Sphericity Assumed	140.766	22	6.398		
	Greenhouse-Geisser	140.766	17.854	7.884		
	Huynh-Feldt	140.766	20.503	6.866		
	Lower-bound	140.766	11.000	12.797		

Appendix 3.5: Standard Deviation of Relative Phase: One-Way
Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	8.584	2	4.292	1.940	.168
	Greenhouse-Geisser	8.584	1.910	4.493	1.940	.170
	Huynh-Feldt	8.584	2.000	4.292	1.940	.168
	Lower-bound	8.584	1.000	8.584	1.940	.191
Error(condition)	Sphericity Assumed	48.676	22	2.213		
	Greenhouse-Geisser	48.676	21.014	2.316		
	Huynh-Feldt	48.676	22.000	2.213		
	Lower-bound	48.676	11.000	4.425		

Appendix 3.6: Deviation of Frequency: 2 (time) X 3 (condition) X 2 (hand)

Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
TIME	Sphericity	.029	1	.029	8.701	.013
	Assumed					
	Greenhouse-Geisser	.029	1.000	.029	8.701	.013
	Huynh-Feldt	.029	1.000	.029	8.701	.013
	Lower-bound	.029	1.000	.029	8.701	.013
Error(TIME)	Sphericity	.036	11	.003		
	Assumed					
	Greenhouse-Geisser	.036	11.000	.003		
	Huynh-Feldt	.036	11.000	.003		
	Lower-bound	.036	11.000	.003		
COND	Sphericity	1.024	2	.512	16.526	.000
	Assumed					
	Greenhouse-Geisser	1.024	1.584	.646	16.526	.000
	Huynh-Feldt	1.024	1.807	.567	16.526	.000
	Lower-bound	1.024	1.000	1.024	16.526	.002
Error(COND)	Sphericity	.682	22	.031		
	Assumed					
	Greenhouse-Geisser	.682	17.426	.039		
	Huynh-Feldt	.682	19.873	.034		
	Lower-bound	.682	11.000	.062		
HAND	Sphericity	.000	1	.000	.147	.709
	Assumed					
	Greenhouse-Geisser	.000	1.000	.000	.147	.709
	Huynh-Feldt	.000	1.000	.000	.147	.709
	Lower-bound	.000	1.000	.000	.147	.709
Error(HAND)	Sphericity	.011	11	.001		
	Assumed					
	Greenhouse-Geisser	.011	11.000	.001		
	Huynh-Feldt	.011	11.000	.001		
	Lower-bound	.011	11.000	.001		
TIME * COND	Sphericity	.016	2	.008	8.267	.002
	Assumed					
	Greenhouse-Geisser	.016	1.404	.011	8.267	.007
	Huynh-Feldt	.016	1.547	.010	8.267	.005
	Lower-bound	.016	1.000	.016	8.267	.015
Error(TIME*COND)	Sphericity	.021	22	.001		
	Assumed					

TIME * HAND	Greenhouse-Geisser	.021	15.444	.001		
	Huynh-Feldt	.021	17.020	.001		
	Lower-bound	.021	11.000	.002		
	Sphericity Assumed	.001	1	.001	1.318	.275
	Greenhouse-Geisser	.001	1.000	.001	1.318	.275
Error(TIME*HAND)	Huynh-Feldt	.001	1.000	.001	1.318	.275
	Lower-bound	.001	1.000	.001	1.318	.275
	Sphericity Assumed	.005	11	.000		
	Greenhouse-Geisser	.005	11.000	.000		
	Huynh-Feldt	.005	11.000	.000		
COND * HAND	Lower-bound	.005	11.000	.000		
	Sphericity Assumed	7.06E-005	2	3.53E-005	.197	.822
	Greenhouse-Geisser	7.06E-005	1.499	4.71E-005	.197	.760
	Huynh-Feldt	7.06E-005	1.682	4.19E-005	.197	.786
	Lower-bound	7.06E-005	1.000	7.06E-005	.197	.665
Error(COND*HAND)	Sphericity Assumed	.004	22	.000		
	Greenhouse-Geisser	.004	16.487	.000		
	Huynh-Feldt	.004	18.507	.000		
	Lower-bound	.004	11.000	.000		
TIME * COND * HAND	Sphericity Assumed	.002	2	.001	4.795	.019
	Greenhouse-Geisser	.002	1.920	.001	4.795	.020
	Huynh-Feldt	.002	2.000	.001	4.795	.019
	Lower-bound	.002	1.000	.002	4.795	.051
	Sphericity Assumed	.004	22	.000		
Error(TIME*COND*HAND)	Greenhouse-Geisser	.004	21.125	.000		
	Huynh-Feldt	.004	22.000	.000		
	Lower-bound	.004	11.000	.000		

Pairwise Comparisons

Time

(I) TIME	(J) TIME	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (pre-stimulus)	2 (post-stimulus)	-.028(*)	.010	.013	-.049	-.007
2 (post-stimulus)	1 (pre-stimulus)	.028(*)	.010	.013	.007	.049

Condition

(I) COND	(J) COND	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (Coord)	2 (DuCo)	-.118(*)	.026	.001	-.175	-.061
	3 (DuRT)	-.206(*)	.042	.001	-.299	-.113
2 (DuCo)	1 (Coord)	.118(*)	.026	.001	.061	.175
	3 (DuRT0	-.087(*)	.038	.040	-.170	-.005
3 (DuRT)	1 (Coord)	.206(*)	.042	.001	.113	.299
	2 (DuCo)	.087(*)	.038	.040	.005	.170

Time * Condition

TIME	COND	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1 (pre-stimulus)	1 (Coord)	.023	.031	-.045	.090
	2 (DuCo)	.130	.040	.043	.218
	3 (DuRT)	.203	.044	.106	.300
2 (post-stimulus)	1 (Coord)	.027	.031	-.042	.096
	2 (DuCo)	.156	.046	.055	.257
	3 (DuRT)	.258	.049	.150	.366

Time * Condition * Hand

TIME	COND	HAND	Mean	Std. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
1 (pre-stimulus0	1 (Coord)	1 (Left)	.021	.031	-.047	.089
		2 (Right)	.024	.031	-.043	.091
	2 (DuCo)	1 (Left)	.136	.040	.048	.224
		2 (Right)	.125	.040	.037	.212
	3 (DuRT)	1(Left)	.202	.045	.103	.300
		2 (Right)	.204	.043	.108	.300
2 (post-stimulus)	1 (Coord)	1(Left)	.028	.032	-.043	.099
		2 (Right)	.026	.031	-.042	.093
	2 (DuCo)	1(Left)	.148	.042	.054	.241
		2 (Right)	.164	.050	.054	.273
	3 (DuRT)	1(Left)	.256	.047	.152	.360
		2 (Right)	.260	.051	.147	.374

Appendix 3.7: Single-Pulse MEPs: One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	1.743	4	.436	9.147	.000
	Greenhouse-Geisser	1.743	1.647	1.058	9.147	.003
	Huynh-Feldt	1.743	1.899	.918	9.147	.002
	Lower-bound	1.743	1.000	1.743	9.147	.012
Error(condition)	Sphericity Assumed	2.096	44	.048		
	Greenhouse-Geisser	2.096	18.118	.116		
	Huynh-Feldt	2.096	20.894	.100		
	Lower-bound	2.096	11.000	.191		

Pairwise Comparisons

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (Control)	2 (RT)	.086	.054	.139	-.032	.204
	3 (Coord)	-.286(*)	.082	.005	-.466	-.106
	4 (DuCo)	-.252(*)	.085	.013	-.440	-.065
	5 (DuRT)	-.347(*)	.119	.014	-.609	-.085
2 (RT)	1 (Control)	-.086	.054	.139	-.204	.032
	3 (Coord)	-.372(*)	.110	.006	-.614	-.130
	4 (DuCo)	-.338(*)	.095	.005	-.547	-.129
	5 (DuRT)	-.432(*)	.130	.007	-.719	-.145
3 (Coord)	1 (Control)	.286(*)	.082	.005	.106	.466
	2 (RT)	.372(*)	.110	.006	.130	.614
	4 (DuCo)	.034	.052	.524	-.080	.148
	5 (DuRT)	-.060	.075	.440	-.226	.105
4 (DuCo)	1 (Control)	.252(*)	.085	.013	.065	.440
	2 (RT)	.338(*)	.095	.005	.129	.547
	3 (Coord)	-.034	.052	.524	-.148	.080
	5 (DuRT)	-.094	.045	.059	-.193	.004
5 (DuRT)	1 (Control)	.347(*)	.119	.014	.085	.609
	2 (RT)	.432(*)	.130	.007	.145	.719
	3 (Coord)	.060	.075	.440	-.105	.226
	4 (DuCo)	.094	.045	.059	-.004	.193

Appendix 3.8: Paired-Pulse MEPs: One-Way Repeated Measures ANOVA

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
condition	Sphericity Assumed	4886.273	4	1221.568	4.282	.005
	Greenhouse-Geisser	4886.273	1.825	2677.111	4.282	.031
	Huynh-Feldt	4886.273	2.169	2252.515	4.282	.023
	Lower-bound	4886.273	1.000	4886.273	4.282	.063
Error(condition)	Sphericity Assumed	12551.934	44	285.271		
	Greenhouse-Geisser	12551.934	20.077	625.182		
	Huynh-Feldt	12551.934	23.862	526.027		
	Lower-bound	12551.934	11.000	1141.085		

Pairwise Comparisons

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.(a)	95% Confidence Interval for Difference(a)	
					Lower Bound	Upper Bound
1 (Control)	2 (RT)	-28.050(*)	7.448	.003	-44.443	-11.658
	3 (Coord)	-13.746(*)	5.346	.026	-25.512	-1.981
	4 (DuCo)	-16.740(*)	3.463	.001	-24.361	-9.119
	5 (DuRT)	-11.508(*)	4.116	.017	-20.568	-2.449
2 (RT)	1 (Control)	28.050(*)	7.448	.003	11.658	44.443
	3 (Coord)	14.304	10.834	.214	-9.542	38.150
	4 (DuCo)	11.310	8.111	.191	-6.542	29.162
	5 (DuRT)	16.542	9.965	.125	-5.391	38.475
3 (Coord)	1 (Control)	13.746(*)	5.346	.026	1.981	25.512
	2 (RT)	-14.304	10.834	.214	-38.150	9.542
	4 (DuCo)	-2.994	5.640	.606	-15.408	9.420
	5 (DuRT)	2.238	5.748	.704	-10.413	14.889
4 (DuCo)	1 (Control)	16.740(*)	3.463	.001	9.119	24.361
	2 (RT)	-11.310	8.111	.191	-29.162	6.542
	3 (Coord)	2.994	5.640	.606	-9.420	15.408
	5 (DuRT)	5.232	3.892	.206	-3.334	13.798
5 (DuRT)	1 (Control)	11.508(*)	4.116	.017	2.449	20.568
	2 (RT)	-16.542	9.965	.125	-38.475	5.391
	3 (Coord)	-2.238	5.748	.704	-14.889	10.413
	4 (DuCo)	-5.232	3.892	.206	-13.798	3.334