THE TIMING AND RECIPROCITY OF MOTOR-COGNITIVE DUAL-TASK INTERFERENCE

INSIGHTS FROM ELECTROPHYSIOLOGY AND PURSUIT TRACKING

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Copyright Statement

Abstract

Our cognitive system is encased in a physical machine. The ability to process incoming information, and to make decisions in order to guide behaviour, must run in parallel to the operating of the body in which it is bound. Though often considered independent, coordinating the body has been found to interact with the mechanics of cognitive operations, and the loading of the cognitive system has been found to influence the way in which we coordinate the body. This bi-directional 'motor-cognitive' interference can pose significant risk to body safety. Continuous sensorimotor coordination, such as the delicate task of applying appropriate force to the breaks of a motor vehicle, is such a behaviour that could prove fatal if influenced by a demanding cognitive operation (e.g. reciting a shopping list). It is therefore paramount that a detailed understanding of how these interferences unfold is obtained. This thesis utilizes electrophysiological measures and a sensitive pursuit-tracking motor coordination task in order to unravel the intricate pattern of behavioural and psychological interferences that exist during fine motor coordination, and the processing of task-relevant information. Results demonstrate that during relatively basic task conditions, motor performance remained largely intact, while resourcing of attentional components of the cognitive task suffered dilution, resulting in poorer performance on the cognitive task. Only when one was required to update information in working memory (e.g. adding to a tally), did performance deficits in motor control occur. When the attentional components of the cognitive task were stressed (task-relevance was more ambiguous), motor performance deficits occurred. In sum, the load associated with referring to information held in working memory, and the updating of information held in working memory, introduces deficits in fine motor coordination, and maintaining accuracy during motor coordination results in modulations to the resourcing of attentional components during a basic cognitive task. These findings demonstrate a bi-directional interference pattern that is asymmetric, and sensitive to the working memory load of the cognitive task being performed.

Declaration

This thesis comprises the candidate’s own work and has not been submitted to this or any other University for a degree. All aspects of the thesis were completed by the candidate.

Publications

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Chapter 1: Introduction

Dual-Task Interference

Dual tasking is the concurrent performance of two tasks that can be performed independently, measured separately and have distinct goals (McIsaac et al, 2015). Although the successful simultaneous performance of two tasks can demonstrate the remarkable abilities of the human central nervous system (CNS), it is the performance deficits that often manifest during dual-tasking that reveal the specific intricate workings, and limitations of our cognitive system. Dual-task paradigms have a long history in the study of human cognition, and overloading a system (forcing the performance of two simultaneous tasks) is a powerful way of exploring what the parts of a system are, and how they function together (Pasher, 1994). When one attempts to execute two tasks simultaneously, the tasks often interfere with each other (Luck, 1998), and performance in one or both tasks are modulated relative to when each of the tasks are performed in isolation. This change in performance is defined as dual-task interference (DTI).

The cause of DTI in some task-pairs can often be easily explained. Take for example a task in which an individual is required to read through a paragraph of text, whilst simultaneously talking about something else. Here, there exists a conflict between what is being comprehended, and what is being produced. One could predict that the individual would not be able to recall the details of the paragraph, or generate coherent sentences. Both of these tasks would require many shared processes, with the performance of one of the tasks compromising the performance of the other (Heim et al, 2003). In many other dual-task scenarios, the reason for interference is not so clear (e.g. walking and talking). In the absence of any obvious shared cognitive functions or physical incompatibilities, there exists a framework by which interference is explained by the limitations of attention (Kahneman, 1973), the serial processing of information (Ruthruff et al., 2001), and the degree of similarity between tasks (Navon and Gopher, 1979). These are described below.

Theories of dual-task interference

Although a number of theories have emerged in order to describe the root cause of performance deficits observed during dual-task paradigms, they can be considered to fall into 3 main categories (Pashler, 1994), namely, capacity sharing models, bottleneck models, and cross-talk models.

Capacity sharing models: Of the most recognised theories of DTI is that of capacity sharing. This theory postulates that performance in multiple attention-demanding tasks deteriorates due to limitations in available processing resources (Tombu & Jolicoeur, 2003). Kahneman's model of attention (1973) describes attention as a flexible, limited resource that is allocated to simultaneously performed tasks via a central processor. As the demands of a task increase, more attention is allocated to said task. This would necessarily reduce the amount of attentional resources available for concurrent tasks, and behavioural deficits would be observed in one or both tasks. Navon & Gopher (1979) and Pashler (1994) suggested a multiple resources model, which states that different pools of attention are available to be allocated to concurrent tasks, with each task tapping into separate resources that are specific to functions used in the tasks. This, however, would postulate that individuals should be able to perform many tasks simultaneously without interference, given that they rely on separate resource pools. Empirically, however, it is demonstrated that even in the context of tasks such as walking and talking, a dual-task scenario that suggests little cognitive overlap, interference can be observed (Al-Yahya, 2011). In addition to the above, a phenomena known as attentional blink (Shapiro et al., 1997) might also explain dual-task performance deficits. Attentional blink describes the inability to process a stimulus if it is immediately preceded by another. That is, there exists an inability to process a stimulus if attention is still deployed to the processing of a preceding stimulus. As such, attentional blink can also be largely explained by assuming that the activation of multiple processes depends on a common capacity-limited attentional process for selecting behaviorally relevant events presented among temporally distributed distractors (Dux & Marois, 2009).

Bottleneck models: As an alternative to attentional-capacity sharing models, DTI can be explained by information-processing bottlenecks caused by multiple operations requiring access to a common processor or neural network (Ruthruff et al., 2001). This suggests that the performance of a dual-task would be hindered, given the presence of a central, single channel that directs attention to relevant processes necessary to perform a task. Interference occurs when two tasks require access to this single channel at the same time. This model need not suggest a single bottleneck, the presence of multiple bottlenecks that are associated with different types of cognitive functions could also explain interference patterns (De Jong, 1993). Support for this theory is demonstrated by the Psychological Refractory Period (PRP) effect, whereby a delay in reaction time is caused by a bottleneck that prevents preparation of a second action until the processing of a previous action is completed (Klapp, 2018). That is, when two tasks require the same mechanism at the same time, one or both tasks will be delayed (Pashler, 1994).

Cross-talk models: Cross-talk models describe DTI arising from the degree of similarity between pairs of tasks. That is, interference may not depend on the operation per say, but could depend on the content of the information that is being processed (Navon and Gopher, 1979). Navon and Miller (1987) proposed that DTI could be the result of 'outcome conflict', whereby one task produces outputs, throughputs, or side effects that are harmful to the processing of another task (Pashler, 1994). Cross-talk models could also account for facilitation effects sometimes observed in dual-task paradigms (e.g. Cicogna et al, 2005), whereby two tasks sharing the same neural population is advantageous for performance in both tasks (Leone et al., 2017)

Cognitive-motor interference

Cognitive-motor interference (CMi) is a specific case of DTI, whereby the dual-task involves a motor task (e.g. pursuit tracking) and a cognitive task (e.g. counting backwards). Everyday tasks require a finely tuned integration of bottom-up and top-down cognitive operations alongside the need to control the body. Whether simply standing or sitting, or controlling a vehicle or operating machinery, cognitive processes must function in parallel to continuous sensorimotor coordination (CSC). CSC tasks are characterized by sustained, task-constrained patterns of body or limb movements generated by a combination of feedforward and perception-based feedback control processes (Seidler et al., 2004). Accurate performance on CSC tasks is often paramount to the safety of the human body, such as the maintenance of a stable posture so as not to fall victim to gravitational forces, or the delicate combination of breaking and accelerating while navigating road traffic. Such daily (dual) tasks that require said combination of operations include standing at a bus stop and reading the number of an oncoming bus, or maintaining lane position on the road while listening to directions. One might observe that we perform most cognitive-motor dual-tasks as an effortless untaxing feat, and that neither task should impede performance on the other given their reliance on (seemingly) separate processes. However, literature concerning CMi have demonstrated that CSC is prone to performance deficits during the simultaneous performance of non-motor related cognitive tasks (Fraizer & Mitra, 2008; Recarte & Nunes, 2003).

Patterns of cognitive-motor interference

As previously mentioned, performance deficits are often observed when performing two tasks simultaneously. The impact of dual-tasking on performance measures in a task are often quantified as a cost function. Dual-task cost (DTC) typically represents a percentage change in performance during dual-tasking relative to when a task is performed independently (Friedman et al., 1982). Though such performance deficits are common, the simultaneous execution of both a cognitive and a motor task can yield several possible interference patterns. Plummer et al. (2013) proposed a classification system to describe 9 possible interference patterns that can manifest in cognitive-motor dual-tasks. These include; (1) no interference (neither cognitive or motor task performance change as a function of dual-tasking, relative to when they are performed in isolation), (2) cognitive-related motor interference (performance in the cognitive task remains stable, however motor-task performance is degraded), (3) motor-related cognitive interference (performance in the motor task remains stable, however cognitive-task performance is degraded), (4) motor facilitation (cognitive performance remains stable, whereas performance in the motor task is improved relative to single task conditions), (5) cognitive facilitation (motor performance remains stable, whereas performance in the cognitive task is improved relative to single task conditions), (6) cognitive-priority trade off (improved performance in the cognitive task but impeded performance in the motor task is observed, relative to single task conditions), (7) motor-priority trade off (improved performance in the motor task but impeded performance in the cognitive task is observed, relative to single task conditions), (8) mutual interference (both tasks suffer as a function of dual tasking), and (9) mutual facilitation (performance in both the motor and cognitive tasks are improved relative to single task conditions.

Though Plummer et al. (2013) described 9 potential interference patterns that could manifest during dual-tasking, they did not acknowledge the influence of the types of tasks, or the possible impact of performer traits on the proposed outcomes. McIsaac et al. (2015) have expanded on the framework provided by Plummer et al. (2013) by defining a dual-task taxonomy. This emphasises the impact of task complexity, task pairings, novelty, environmental influences, and individual differences (e.g. skill) on the specific types of interference patterns classified by Plummer et al. (2013).

Cognitive-motor interference in fine motor tasks

Fine motor tasks are tasks that require the use of small muscle sets in order to achieve a goal such as grasping, object manipulation, or drawing (Gonzalez et al., 2019). This is in contrast to gross motor tasks that require large muscle control and movements, such as walking and balancing, which will be discussed below. A number of fine motor tasks have previously been used in the study of attention and motor-skill acquisition, such as the Bilibili Dentist game (Yoshikawa et al., 2020), finger tapping task (Penner-Wilger et al., 2007), and piano note-sequence tasks (Pascual-Leone et al., 1995). Though such tasks can provide a means of testing motor performance, they offer rudimentary measures of behaviour, and lack the resolution for finer-grained analyses of the mechanisms involved in precise motor control. An alternative means of studying fine motor control is the utilization of pursuit tracking methods.

Pursuit tracking: In the laboratory, pursuit-tracking involves continuously minimizing the positional error between a manually controlled cursor and an independently moving, computer-controlled visual target on a screen (Brown, 1998; Gazes et al., 2010). The continuous nature of pursuit tracking, and the instantaneous recording of the relative distances between a moving and a controlled object allows for the examination of the temporal mechanics of a motor task. That is, any deviation from a set trajectory provided by a computer-controlled target can be considered as performance error. Deviation measures are typically expressed in cartesian space (i.e. the physical distance between the moving target and the controlled curser, usually given in the number of pixels in both X and Y dimensions). A limitation of analysing tracking deviations using Cartesian coordinates in circular tasks is that separable estimates for the angular deviation (i.e., whether a controlled object is ahead or behind a computer-controlled object in terms of the angle subtended on a reference axis) or the radial deviation (whether the controlled object deviates into or out of a circle defined by a computer-controlled object) cannot be obtained. A given set of horizontal and vertical deviations could result from different angular and radial deviations depending on the quadrant of a circle. As such, an alternative means of analysing tracking deviations in a circular task is to convert Cartesian coordinates into polar coordinates (Choi et al., 2021).

Analysing tracking deviation timeseries in polar space for circular tracking tasks allows for the analysis of angular deviations (theta) and radial deviations (rho). Both theta and rho values can be positive or negative at a given time, and reflects the position of a controlled object relative to a computer-controlled object. A negative theta value would indicate that a controlled object is positioned behind a computer-controlled object, whereby the larger the (negative) value, the larger the angular difference. As such, a negative trend in a continuous measure of theta would indicate a slowing down of a controlled object relative to a computer-controlled object (Kim et al., 2017). In contrast, an increase in theta would indicate that a controlled object is positioned in advance of a computer-controlled object, and a positive trend in a continuous measure of theta would indicate a speeding up of a controlled object (Kim et al., 2017). The measure of rho reveals the radial difference between two objects at a given time point, and reflects whether a controlled object is positioned inside or outside of a circular trajectory defined by a computer-controlled object (Kim et al., 2017). A negative rho value indicates that a controlled object is positioned inside of a circular trajectory (closer to the centre of the circle), whereas a positive rho value would indicate that a controlled object is positioned beyond (outside) the trajectory set by a computer-controlled object (Kim et al., 2017).

The successful performance of a circular pursuit tracking task necessarily requires two separate motor behaviours and can be considered to reflect the dynamics of a mass-spring model. First, a tangential energy input is necessary to maintain the speed of a controlled object. In order to match the speed of a leading object, this applied tangential force must be predicted based on observation of the leading object. Given a failure to observe the speed set by the leading object (such as the redirection of attention), then the force applied to the controlled object might be too little or too large, resulting in a decrease or increase in theta, respectively. Secondly, given that the controlled object must follow the trajectory of the leading object, a centripetal action must be applied in order to curtail the movement of the controlled object so as to be continuously positioned at the boundary of a circle. That is, the tangential energy input must be accompanied by a continuous adjustment of the direction of the applied energy in order to maintain a circular action. If the centripetal action is too little, then the controlled object will stray out of the boundary of the circle, as indicated by an increase in rho. On the other hand, if too much centripetal action is applied, then the controlled object will stray inside the boundary of the circle, as indicated by a decrease in rho.

In sum, if the controlled object is falling behind (decrease in theta), then a correction for a reduced energy input is not being applied. If the controlled object is positioned ahead of the leading object (increase in theta), then too much tangential energy is being applied. If the controlled object is positioned outside of the circle (increase in rho), then not enough centripetal action is being applied (not turning enough), whereas too much centripetal acceleration (decrease in rho) would position the controlled object towards the centre of the circle.

Behavioural studies

Pursuit-tracking has a long history of use in studies of dual-task interference. Brown (1998) demonstrated the impact of pursuit tracking on timing performance during a temporal production task. The timing of produced tapping was impeded during dual-task conditions, though this was reduced following a practice period for the tracking task. This demonstrated that practice can reduce the attentional demands of a task, and lessen it’s effect on concurrent tasks. Strayer and Johnston

(2001) utilized a tracking task in which participants were required to track a moving target with a joystick. Of interest was the effects of active listening and conversation on tracking performance and the ability to quickly respond to a salient target with a button press. Interestingly, simply listening to a radio broadcast had no impact on tracking performance or reaction times to targets. Unconstrained conversations however, significantly increased reaction times to targets while participants were engaged in the tracking task. The authors postulate that the active engagement in conversation and the attentional demands of word generation are the contributing factors to performance deficits in tracking. These findings argue against a multiple-resource model of attention, as such models propose that an auditory-verbal task should not impede a visual-spatial task. Similar findings were observed by Kemper et al. (2009), in which language production significantly interfered with tracking performance. Interestingly, young and old adults were included in the study, and CMi was greater for young adults relative to older adults. Older adults were able to maintain stable tracking performance by speaking more slowly. These findings demonstrate that younger and older adults use different strategies to accommodate dual-task demands.

Maslovat et al. (2015) found evidence for a facilitative effect on preparatory activation during a dual-task paradigm when both tasks were motoric in nature. This was opposed to an attenuation effect when the primary task was a cognitive task. As such, motor performance in a secondary task was enhanced when the primary task involved pursuit tracking. This finding supports the idea that the performance on a task can be enhanced if a secondary task recruits similar neural pathways (Leone et al., 2017). In contrast however, McLeod (1977) and Lee & Digby (1986) found that pursuit tracking was hindered due to the requirement of a motor response in a secondary task. Such contrasting findings highlight the need for the consideration of the characteristics of the single tasks in order to fully understand the mechanisms involved.

Neuroimaging studies

Though behavioural measures can offer clear insights into the susceptibilities of certain cognitive operations to simultaneous motor demands, neuroimaging studies can reveal the direct engagement of cortical areas and networks in the processing of information during cognitive-motor dual-tasks. Neuroimaging is a non-invasive method of exploring the mechanisms of cognition via an indirect measure of cortical activation. Of the most popular neuroimaging methods, functional magnetic resonance imaging (fMRI) measures changes in local oxygenated blood flow, and convolves the haemodynamic response function with stimulus and task events during cognitive and motor tasks. Changes in the relative distribution of oxygenated and deoxygenated haemoglobin observed in the blood can be used to infer local cortical involvement. In addition, a more recent method is that of functional near-infrared spectroscopy (fNIRS). This optical method is also sensitive to cerebral blood flow, and is less technically and financially demanding relative to fMRI.

In a comprehensive review, Leone et al (2017) describes 4 potential patterns of CMi in neuroimaging studies that describe activation differences between single and dual-task conditions: over-additive, additive, under-additive, and miscellaneous.

Over-additive: Over-additive effects describe an increase in activation in cortical areas during dual-task conditions, or the involvement of additional areas that are not activated in single task conditions. That is, performance of a dual-task consists of more than a sum of the single tasks. For example, activations of the prefrontal cortex during dual-tasking that are not present under single task conditions for either task (Schubert & Szameitat, 2003; Wu et al., 2013). These studies demonstrate the important role of the prefrontal cortex, parietal cortex, and even the cerebellum in the coordination of multiple task demands, and could represent a control system that manages dual-task situations (Collette et al., 2005). Wu et al., (2013) suggested that the networks involved in individual tasks could be integrated into a single network by a linkage from distinct cortical areas. Over-additive activations could therefore suggest the existence of a locus for CMi in cortical areas associated with executive functions and top-down attentional control (leone et al., 2017)

Additive activation: additive activation describes dual-task cortical activations as a sum of the activations of the single tasks (Adcock et al., 2000), and implies that there is no specific brain regions engaged due to dual-tasking. Interference is the result of an overlap between processes involved in each separate single task, and the resource requirements of the dual-task are the combined requirements of the single tasks (Leone et al., 2017).

Under activation: under activation describes the observation of a dampening of a cortical response under dual-task conditions relative to single task conditions. Explanations for a reduction in activation are the dividing of activation across more cortical areas during dual-tasking (Just & Varma, 2007), and attentional resource dilution (Anderson et al., 2011). Just et al. (2008) observed a reduction of cortical activation in regions associated with the performance of a driving task when participants were engaged in sentence listening. This included a reduction in bilateral parietal, and extrastriate cortex during dual-tasking, relative to single task conditions.

*Miscellaneous***:** miscellaneous activations describe combinations of activation pattern. That is, the presence of both under and additive activations. Nijboer et al. (2014) used a combination of 3 single task and their dual-task combinations and found no evidence of a dedicated multitasking brain region, but identified both under and over additive activations in different cortical areas. The authors suggest that CMi is due to an overlap in attentional resourcing due to single task similarities.

In sum, the wealth of neuroimaging studies concerning CMi suggest that a specific locus of interference does not exist (Leone et al., 2017). Though some studies demonstrate an additional involvement of prefrontal areas in dual-task situations, these only occur in some task combinations, can could depend on the nature of the single tasks themselves. Given that such studies utilize many different task types, it is not possible to draw final conclusions based on the current available evidence.

Electrophysiological studies

Though neuroimaging techniques allow for the observation of the spatial distribution of activation during dual-tasks, it offers little for the observations of the temporal dynamics of information processing. Though modern neuroimaging techniques (e.g. event-related fMRI) offer a more precise investigation into the time course of task processing, it is electrophysiological methods such as electroencephalography (EEG) that provide the temporal resolution necessary to study the time course of task components in sufficient detail. EEG is the measurement of voltage fluctuations on the scalp during rest or task performance. Post-synaptic dendritic currents from cortical pyramidal cells propagate through the different mediums of the head via volume condition. These currents then exchange ions with the surface of electrode tips placed above the scalp via a conductive gel. The resulting signal is given in microvolts (μV) and can be positive or negative depending on the reference signal. EEG signals therefore present an oscillating time-series of voltage that reflects neural processing and other electrical sources.

Given that EEG is not a direct measure of the electrical activity of neurons, the resulting patterns of activity can reflect not only neuronal activity, but also sources of noise such as muscle activity and eye movements. Therefore, though the process of volume condition makes the measurement of EEG possible, it also renders the signal susceptible to signals that are not of interest. Regardless, modern EEG systems allow for the observation of voltage changes in the order of milliseconds, and can reveal instantaneous changes in cortical dynamics in response to stimulation and task demands. A number of measures can be derived from a continuous EEG measurement, and are typically considered to be categorised into time domain analyses and frequency domain analyses. Time domain analyses (such as Event-related potentials, described below) analyse the change in amplitude of a given signal in time, whereas frequency domain analyses involves the measurement of frequency modulations in the EEG, such as the change in power of a given band of frequencies.

Event-related Potentials: Event-related potentials (ERPs) are time and phase-locked responses contained in an ongoing EEG signal that can be recorded non-invasively from the scalp. ERPs can be considered manifestations of the processes involved in cognitive operations and the processing of physical stimulation, and present the response of large assemblies of cells that are involved in said operations. Following the averaging of many trials, reliable peaks/troughs can be observed at different times surrounding the onset of a physical or cognitive event. ERP nomenclature is typically characterised by the polarity of the component (P or N), followed by a time in milliseconds, or the temporal position of a local maximum/minimum. Specific ERP components are proposed to be associated with specific cognitive processes and are used as a tool to investigate the behaviour of the Central Nervous System (CNS) under different task conditions. ERPs can be categorised into two distinct groups; exogenous and endogenous. Exogenous ERP components are observed relatively early, and are sensitive to the physical properties of a stimulus, whereas endogenous components are observed relatively later, and are thought to reflect the processes involved in the evaluation of a stimulus and the preparing for a relevant response (Sur & Singa, 2009).

Two distinct properties of an ERP component are often reported; amplitude (or magnitude) and latency (either peak onset time or time of local maximum). ERP amplitude is sensitive to a number of parameters, though physiologically dependent on the number of contributing sources (the number of cells actively involved in an operation), their orientations, and the temporal synchronicity of their activity. Averaged ERP amplitudes are sensitive to trial-to-trial latency variability, whereby variation in single trial peak latencies broaden and lower measured average responses. Peak amplitudes of early exogenous components have been found to be modulated by stimulus intensity, such as brightness and contrast (Johannes et al., 1995), in that brighter stimuli induce larger amplitudes (i.e. the stimulation provides more ‘signal’, and the higher amplitudes are indicative of this), whereas the peak amplitude of later endogenous components have been found to be modulated by working memory load (Raney, 1993), arousal (Delplanque et al., 2006), and attention (Polich, 2007).

A number of ERP components have been considered in the literature on CMi. Though a large number of experimental paradigms have been developed in order to elicit specific ERP components for the study of cognitive phenomena, the visual oddball task has been demonstrated to be a robust and simple paradigm that reliably elicits a number of ERP components of interest. The visual oddball task requires participants to respond (overtly, e.g. with a button press, or covertly, e.g. silently counting) to relatively rare targets amongst a continuous train of standard (non-target) and target stimuli. A target stimulus can differ from standard stimuli in a number of ways (such as physical differences e.g. colour, or semantic differences). A number of variants have previously been used, such as 2 stimulus tasks (as described above), or 3 stimulus tasks, whereby the target and standard stimuli are accompanied by ‘target-like’ distractor stimuli. This task can be considered to consist of a number of separate task elements (Luck, 2014), each with a corresponding neural signature. First, one must detect a stimulus on the screen, second, this detected stimulus must be deciphered and compared against a representation of a target stimulus held in working memory. Third, once a stimulus has been appropriately classified, a response is prepared and executed (respond or not). If the task is to silently count the number of target stimuli, then an additional requisite is to add to a continuous count. A number of ERP components associated with each of these task components are detailed herein.

P1: Around 100 milliseconds following the presentation of a visual stimulus, a positive peak (when referenced to mastoids or an average of all electrodes) is reliably observed from occipital electrodes. P1 is a component often examined in studies of visual processing and visual attention and is thought to reflect early stage processing of visual stimulation (Hillyard et al., 1998; Mangun, 1995). P1 is an exogenous component and has been shown to be sensitive to the physical properties of a stimulus, such as brightness and contrast (Cesarei et al., 2013; Johannes et al., 1995), where higher contrast and brighter stimuli produce larger P1 amplitudes. P1 parameters have been demonstrated to be sensitive to selective visual attention (Hillyard et al., 1998; Luck et al., 1993; Rugg et al., 1987), where higher P1 amplitudes are observed when attention is directed to the location of a stimulus (and attenuated when a stimulus appears outside of the focus of visual attention (Luck et al., 1994)). An enhancement of P1 is thought to reflect the facilitation of early sensory processing for stimuli presented at an attended location (Luck et al., 1994). Though this demonstrates that P1 can be modulated by focused, spatial attention, there still exists the question as to whether non-spatial attentional mechanisms can influence P1. There is little evidence to suggest that endogenous, top-down, global attentional mechanisms modulate P1 (Hopfinger & West, 2005). Though most studies that have examined the effects of dual-tasking on P1 amplitudes found no manifestation of interference (Capizzi et al., 2013; Gherri & Eimer, 2010), others have demonstrated the effects of increased working memory load and non-spatial attentional effects on early visual evoked potentials, including P1 (Pratt et al., 2011; Ross et al., 2017; Taylor, 2002; Yang et al., 2015). This would suggest that at least under certain conditions, the early stages of visual processing are indeed modulated by the attentional state of an individual, and that the dilution of a central finite attentional resource due to ongoing simultaneous task demands, could impact the way in which we process visual information.

P2: the P2 ERP component manifests as a positive going perturbation in the signal (when referenced to mastoids or average) around 200 ms following the presentation of target stimuli. This is observed at midline fronto-central electrodes and is thought to reflect the evaluation of a stimulus for task-relevant features (Kim et al., 2008; Luck & Hillyard, 1994; Potts, 2004). P2 has also been demonstrated to represent the partial retrieval of semantic information from long-term memory into working memory (Raney, 1993). The evaluation of a stimulus for target features would necessarily involve the retrieval of what constitutes ‘target features’ from working memory. That is, a current stimulus or one that has been previously presented must be compared to a representation of a ‘target’ held in working memory (Potts, 2004). P2 amplitude has been found to increase when participants actively attend to stimuli (Hillyard et al., 1973), and demonstrated to be particularly insensitive to increases in task difficulty within a task (Shaw et al., 2018). P2 can therefore serve as means of investigating selective attention and working memory in visual target detection tasks (Potts et al., 1996). The susceptibility of the P2 component under dual-task conditions is not well understood. Luck (1998) and Tumber et al. (2014) found no modulation of P2 amplitude during dual-task conditions, suggesting a limited effect of divided attentional resources on P2. The effects of motor-cognitive dual-tasking on P2 therefore remain elusive.

P300/P3b: Of the most frequently utilized ERP components in understanding attentional mechanisms involved in cognitive tasks is the P300, also known as the P3 complex. The P3 complex consists of a series of positive deflections (when referenced to mastoids or average) observed in the signal following the presentation of a novel (relative to preceding stimuli) and/or task relevant stimuli (i.e. those which require a response/further evaluation). The P3 complex contains several parts that reflect an information processing cascade when attentional and memory mechanisms are engaged (Polich, 2007). Around 300 ms following the presentation of a novel stimulus (i.e., a stimulus with physical/semantic differences to the ones preceding it), a peak can be observed at fronto-central electrodes. This is known as the P3a (or, Novelty P3), and is thought to represent the updating of the current ‘mental model’ of the stimulus context. If the current stimulus does not differ from the preceding stimulus, then sensory evoked potentials (such as P1 and P2) will be observed, but not a P3a. However, in the case of the identification of a new stimulus, attentional processes ‘update’ the stimulus representation, and a P3a is also observed (Kujala & Näätänen, 2003).

If the currently presented stimulus is task-relevant (i.e., requires a response or further evaluation), then a P3b can be observed. P3b is a large positive deviation in the signal observed at central-parietal electrodes. Therefore, the P3b is subsequent to the frontal P3a, when a novel, task-relevant stimulus is presented. P3b is therefore associated with endogenously driven effortful orienting, as opposed to orienting a response due to novelty (Luck, 2014; Polich, 2007). P3b magnitude has been demonstrated to be influenced by concurrent task demands (Isreal et al., 1990; Kida et al., 2004; Kok, 2001) and is often measured and considered as an index of attentional resource allocation (Polich, 2007). This is demonstrated in dual-task paradigms, where an increase in task difficulty and working memory load in a primary task, can attenuate the amplitude of P3b elicited from stimuli in a secondary task (Matthews et al., 2005; Pratt et al., 2011; Ross et al., 2018). P3b amplitude and latency modulation can therefore be a useful tool for investigating the taxing effects of specific cognitive loads and additional task demands on stimulus processing and response preparation. In the case of motor-cognitive interference, P3b amplitude in response to target stimuli has been shown to be attenuated during the simultaneous performance of a motor task (Al-Yahya et al., 2011; Isreal et al., 1980), potentially indicating a draw on attentional resources, and manifesting as an attenuation of P3b amplitude. Therefore, the degree to which P3b amplitude is attenuated during the performance of an additional (simultaneous) task, can reveal the attentional cost of said task.

Frequency based measures: EEG time series present summations of continuous oscillating voltages both at rest, and during the performance of a task. The frequencies of these oscillations have been associated with behavioural and cognitive states, and can present dynamic changes in their power (and thus proportion of their total power relative to the total power of the entire EEG bandwidth), in response to an event, and the processing of stimulation. Changes in the parameters of said frequencies (such as power and phase) in response to such events can be referred to as Event-Related Spectral

Perturbations (Delorme & Makeig, 2004). An increase in power of a certain frequency observed at some electrode following an event is referred to as event-related synchronization (ERS), whereas a decrease following an event is referred to as event-related desynchronization (ERD). These frequencies can also be observed simultaneously at two separate sites, so as to express a degree of similarity in the spectra across both sites. This is known as coherence, and is expressed as a coefficient for each frequency. Event-related changes in the degree of similarity of power and phase within a frequency across electrode sites are referred to as event-related magnitude coherence, and event-related phase coherence, respectively. The behaviours of these coefficients allow for the examination of network scale phenomena in the brain, and can be used to study the flow of information processing, and the functional connectivity of local and global structures (Locatelli et al., 1997).

A number of frequency measures have been considered in the CMi literature, and a selection of these will be described herein.

Alpha power: Frequencies between 7 and 14 Hz within the EEG typically define the range of the alpha band. Alpha has a long history in the field of cognitive neuroscience, and is typically considered to reflect active inhibition of cortical functioning (Klimesch et al., 2007; Sumich et al., 2018). Though often associated with the idling brain (Mulholland, 1995), research has demonstrated associations between alpha power and cognitive operations (Basar et al., 1989; Kolev & Schurmann, 1992). More specifically, attention and working memory processing has been found to be associated with an increase in frontal alpha power and phase from 500 to 1000 ms post stimulus onset (Kolev et al., 2001; Krause et al., 2000; Yordanova & Kolev, 1998). This literature demonstrates a functional relationship between an event-related increase in alpha at frontal electrode sites, and WM demands during a task. Though alpha power at fronto-central sites in tasks involving WM processes is thought to reflect inhibition of task-irrelevant information (Klimesch et al., 1998), recent work using post-cuing paradigms, that allow systematic manipulation of relevant and irrelevant WM load (Manza et al., 2014), suggest that fronto-central alpha power reflects maintenance of task-relevant WM load, and is related to task accuracy. An event-related decrease in alpha power at parietal electrode sites has been identified during oddball tasks at around 300 ms following the presentation of target stimuli, and is thought to reflect processes comparable to those involved with the generation of P3b (Bernat et al., 2007; Sutoh, 2000). P3b is considered to reflect context updating of a target stimulus (Donchin & Cole, 1988) and information acquisition processes (Rushkin et al., 1990), but has been found to be insensitive to memory retention (Rushkin et al., 1990). In contrast, reductions in alpha power may reflect processes related to memory operations. (Rushkin et al., 1990). Alpha ERD has also been shown to occur after the onset of P3b, suggesting a dissociation with P3b and is perhaps reflective of later cognitive processes (Sutoh et al., 2000). As such, the magnitude of ERD seems to reflect not only stimulus-related recognition processes (as also indicated by P3b), but also the amount of mental effort in task (Käthner et al., 2014; Krause et al., 2000). The extent of cortical alpha oscillations suggests that such processing involves more cortical fields to a greater degree than that expected for automatic sensory-perception processes (Sutoh et al., 2000). Therefore, parietal alpha ERD is considered to reflect increased cognitive processing during the processing of target stimuli in oddball tasks (Yordanova & Kolev, 1998), and has been shown to represent increased attentional resource allocation and memory updating (Peng et al., 2015). Alpha ERD is thought to indicate an increased excitability level of cells in active cortical areas, which may reflect an enhanced information transfer in thalamo-cortical circuits (Neuper & Pfurtscheller, 2001). If increased cognitive processing (as indicated by alpha ERD) is impaired by dual-tasking, parietal ERD ought to be attenuated. As such, parietal alpha power may inform the specific utilization of attentional resources allocated to working memory/action monitoring and to high-order multisensory processing, respectively (Shaw et al., 2018).

Beta power: Frequencies between 15 and 22 Hz within the EEG typically define the range of the beta band. Beta activation is often observed during active periods of concentration (Grønli et al., 2016), sensory gating in the somatosensory system (Neuper et al., 2006), selective attention (Engel & Fries, 2010), and large scale neuronal integration (Donner & Siegel, 2011). Frontal beta ERS has been found to be elicited during target stimulus processing in a visual working memory task (Pesonen, 2007), and during anticipation of WM demands (Altamura et al., 2010). This literature demonstrates a functional relationship between an event-related increase in beta at frontal electrode sites, and WM demands during a task. Beta band activity has also been associated with mathematical operations (Fernández et al., 1995; Lin et al., 2011), whereby an increase in beta power is observed for difficult arithmetic. A number of studies that report modulations in frontal beta activity during WM tasks report frequencies that would normally be considered to comprise alpha activity (e.g. Onton & Makeig, 2005; Deiber et al., 2007). As such, modulations in activation in both frontal alpha and low-beta power have been observed during WM tasks.

Fronto-parietal magnitude and phase coherence: Increased attentional resources required by dual-task demands are thought to necessitate involvement of prefrontal cortex (Cudmore et al., 2000). Coordination in the fronto-parietal network (Corbetta & Shulman, 2002) underpinning attention and WM tasks (such as oddball detection) is electrophysiologically reflected in alpha-band coherence between frontal and parietal sites (Güntekin & Başar, 2010; Sadaghiani et al., 2012; Sauseng et al., 2006; Van Schouwenburg et al., 2017). Güntekin et al. (2008) have shown for example, that impaired cortical connectivity in Alzheimer's reduces fronto-parietal alpha-band coherence in a visual oddball task. Magnitude (amplitude) and phase coherence are measures of the instantaneous synchronicity (amplitude correlation and phase angle correlation, respectively) of brain regions within certain frequency bands, and are expressed as time series of coefficients. Any change in the demands of a network is expressed as modulations to said coefficients over time. Regarding dual-tasking, Kwon et al. (2015) demonstrated that attentional top-down processes as signified by fronto-parietal alpha coherence can be reduced during word recall and a simultaneous ocular-motor task, suggesting that the addition of a secondary task can tax the operations of a frontal-parietal network.

Spectral power over motor cortices: Manual task execution is accompanied by an event-related desynchronization (ERD) over contralateral primary motor cortex characterized by reduced power in the alpha (7-13 Hz) and beta (13-30 Hz) bands (Pfurtscheller & Lopes da Silva, 1999). This reduction in alpha and beta power is thought to represent an active involvement of the motor cortex in a task. Reductions in such frequencies have also been observed during the mere observation of movement (Muthukumaraswamy & Johnson, 2004). There exists very literature on dual-task effects on alpha and beta ERD observed over motor cortex, though Lin et al. (2011) did observe a reduction in beta power over motor cortex during dual-tasking relative to a single task condition.

Cognitive-motor interference in gross motor coordination

The literature presented above highlight CMi in the context of fine motor coordination. Though CMi has been observed in tasks that utilize elementary motor tasks (such as pursuit tracking), there also exists literature on CMi in the context of gross motor coordination, such as driving and maintaining a stable posture. Performance in CSC tasks, such as driving a motor vehicle, goal-directed walking or even upright standing, must be maintained while carrying out a conversation, a sequence of memory or problem-solving operations, or planning future actions. In the case of driving, such dual-task effects have been of particular research interest with respect to interference from mobile (cellular) telephone conversation (Recarte & Nunes, 2003; Strayer & Johnston, 2001). Dual-task gait and balance have also been extensively researched as concurrent cognitive load is a recognized risk factor in falling in old age (Amboni et al., 2013; Rubinstein, 2006), and declining dual-task performance is a salient feature not only of healthy aging (Fraizer & Mitra, 2008; Springer et al., 2006), but also the time course of neurological conditions such as Parkinson’s disease (Bloem et al., 2001; Yogev-Seligmann et al., 2007), multiple sclerosis (Leone et al., 2020; 2015) and dementia (Ijmker & Lamoth, 2012). Recent research has shown that a range of cognitive tasks interfere with everyday CSCs such as driving (Beede & Cass 2006; Nijboer et al., 2016; Recarte & Nunes, 2003), walking (Al-Yahya et al., 2011; Holtzer et al., 2012) and balancing (Fraizer & Mitra, 2008), and that the level of interference tends to be greater in old age relative to healthy young individuals (Li & Lindenberger, 2002). Thus, despite their apparent autonomy in the healthy young and middle-age adults, everyday CSC tasks make demands on higher level cognitive resources.

In the context of CSC-cognitive dual-tasking, the literature on driving (Beede & Kass, 2006; Nijboer et al., 2016; Recarte & Nunes, 2003) and gait (Al-Yahya et al., 2011; Amboni et al., 2013) suggests that executive function (EF) operations are the most prone to interference, but research on balancing has been framed in terms of competition for, and allocation of, attentional resources (Redfern et al., 2001; Woollacott & Shumway-Cook, 2002). EF broadly refers to higher cognitive processes involved in holding and manipulating task-relevant information in working memory (Baddeley, 1996; D'Esposito et al., 1999), and allocating processing resources as required (sometimes termed executive attention) (Baddeley, 2007; Norman & Shallice, 1986; Royall et al., 2002). In terms of specific information-processing operations, EF includes updating (monitoring and altering WM contents), shifting (switching between task sets) and inhibition of irrelevant information or processes (Miyake et al., 2000; Miyake & Friedman, 2012).

CMi can pose serious consequences for the human body. One must process incoming information and make judgements and decisions, all while operating the machinery of the body. If the ability to control the body becomes perturbed, then it could be argued that this would present greater risks to body safety than interruptions to cognitive performance. That is, the destabilisation of posture would present greater risks to body safety than the incorrect comprehension of a sentence while walking. In light of this, it might be expected that motor tasks (such as posture control) would be prioritised over any simultaneous non-motor cognitive operations. This is supported by the 'posture first' principle, whereby older populations demonstrate a prioritisation of motor performance, at the expense of cognitive task performance (Lacour et al., 2008; Lion et al., 2014). As for other populations, there are contradictory findings, whereby 'posture first' and 'cognitive first' prioritisation have been demonstrated for healthy young adults (Berger & Bernard-Demanze, 2011; Bloem et al., 2006; Jacob et al., 2011). The exact patterns of interferences are seemingly dependent on the complexity of the tasks, and the associated risks to body safety (Fraizer & Mitra, 2008).

Challenges in the measurement and interpretation of CMi

The physiological, biomechanical, and cognitive mechanisms that are susceptible to interference during motor-cognitive tasks are poorly understood. There exists a number of challenges that hinder the understanding, or even the detection, of subtle dual-task interferences, both in real-world scenarios and in experimental tasks. The first challenge is that it is generally possible to circumvent performance deficits by means of the reduction of CSC speed (Al-Yahya et al., 2011; Haigney et al.,

2000) to enable diversion of information-processing cycles or resources to a concurrent cognitive task. When the CSC exhibits slower speed in the presence of a concurrent cognitive task, it can be unclear whether the interference source was at the level of concurrent attentional resource demands or the EF of switching resources between task sets. A CSC task that does not permit such strategic speed variation could help isolate the effects of common information-processing resource demands.

The second challenge is that everyday CSCs have a degree of performance tolerance that can be exploited to fit in the demands of a concurrent cognitive task. For example, highway lane width and walking paths allow a level of trajectory deviation without compromising safety or overall task goals (Nijboer et al., 2016; Springer et al., 2006). It is usually possible to strategically allow for a level of error to accumulate in order to fit in the demands of a secondary task. It is the subtle build-up of accumulated errors that may prove consequential for dramatic performance deficits, however these subtleties are often masked, given the acceptable tolerances in the task set. That is, a compromise to performance accuracy may allow for successful overall performance, however the accumulation of non-detrimental sacrifices in accuracy could explain the eventual task failure. A CSC task that isolates the use of perceptual information to continuously stabilize the coordination (i.e., exposes all deviations as error) could help locate the precise loci of interference between processes of CSC maintenance and the operations of a concurrent cognitive task.

The third challenge in understanding CSC-cognitive dual-task interference is that most everyday cognitive tasks involve perceptual, attentional and executive function sub-processes. Interference between such tasks and CSCs may affect one or more of these sub-processes, and the effects may or may not be symmetrical. Behavioural measures such as accuracy or response time in cognitive tasks, and the variability of lane deviation, stride length or body sway, cannot by themselves resolve the chronometric details of these interactions as they reflect the cumulative effects of the tasks' central and response-related information-processing components. If the sequence of neurophysiological events associated with the sub-processes of a cognitive task are known and observable, investigating these events' interactions with a CSC stabilization task could provide a more detailed understanding of the structure and timing of CSC-cognitive interference.

The current set of studies

Below I detail the aims, objectives and hypotheses for the current set of studies.

Aims

This thesis aims to provide a detailed understanding of the information-processing mechanisms and chronometry of motor-cognitive inference by observing the temporal dynamics of the CNS during the processing of cognitive load-bearing events, in time-locked juxtaposition with temporal and spatial deviation patterns in a CSC task. This method allows for the identification of key cognitive components that are involved in the task and how these components interact with CSC. The design of the collective set of experiments allowed for the examination of the magnitude and directionality of interference patterns that may exists across both tasks, both when the task demands are basic, and when specific elements of the cognitive task are stressed.

Objectives

The body of work contained in this thesis addressed the above challenges by asking participants to perform a visuomanual pursuit-tracking task (Chernikoff et al., 1955), and used electrophysiological techniques to investigate the chronometric details of this CSC's interactions with the extensively studied cortical dynamics of the visual oddball task. The key interest in this task combination was that the timing and reciprocity of influence from either task to the other could be studied at the level of component processes. It is seldom clarified whether, for example, the attentional component of a cognitive task that is disrupted by a concurrent CSC is also the cognitive task component that disrupts CSC performance. Addressing the challenges outlined above and utilizing the high temporal resolution of electrophysiological events enabled the present study to detect possible asymmetries in interference at the level of task components.

The use of pursuit-tracking in the presented set of experiments addressed the first two challenges identified above by enforcing the maintenance of CSC speed, and allowing no strategic trajectory deviation or variability without accumulating detectable positional errors. The derived pursuit tracking deviation time series allowed for the examination of instantaneous angular (theta) and radial (rho) deviations throughout the processing of oddball task stimuli.

To address the issue of cognitive sub-processes, a visual oddball task was used as the concurrent cognitive task. The oddball task required an action only when the less frequent of two possible stimuli was detected (Hillyard et al., 1973). The template for the target stimulus had to be maintained in WM and matched to the current perceived stimulus. This involved top-down facilitation of matching features and inhibition of non-matching ones (D’Esposito & Postle, 2015). As a physical response (such as clicking a button or pressing a foot pedal) could introduce an additional motor interference, the participants instead produced a cognitive response–mentally tallying the number of targets detected over the current block of trials. This covert-response variant of the oddball task has an electrophysiological signature analogous to that of the overt, motor-response version in the stimulus processing phase (Potts, 2004; Salisbury et al., 2001; Verleger et al., 2016), but it also involves an additional WM component of maintaining the current target count, and an executive function of updating (Garavan et al., 2000) the tally every time a target is identified. The oddball task is well suited to studying dual-task interference at the level of information-processing components because extensive research has linked its electrophysiological correlates to the time course of its underlying cortical processes (Polich, 2007).

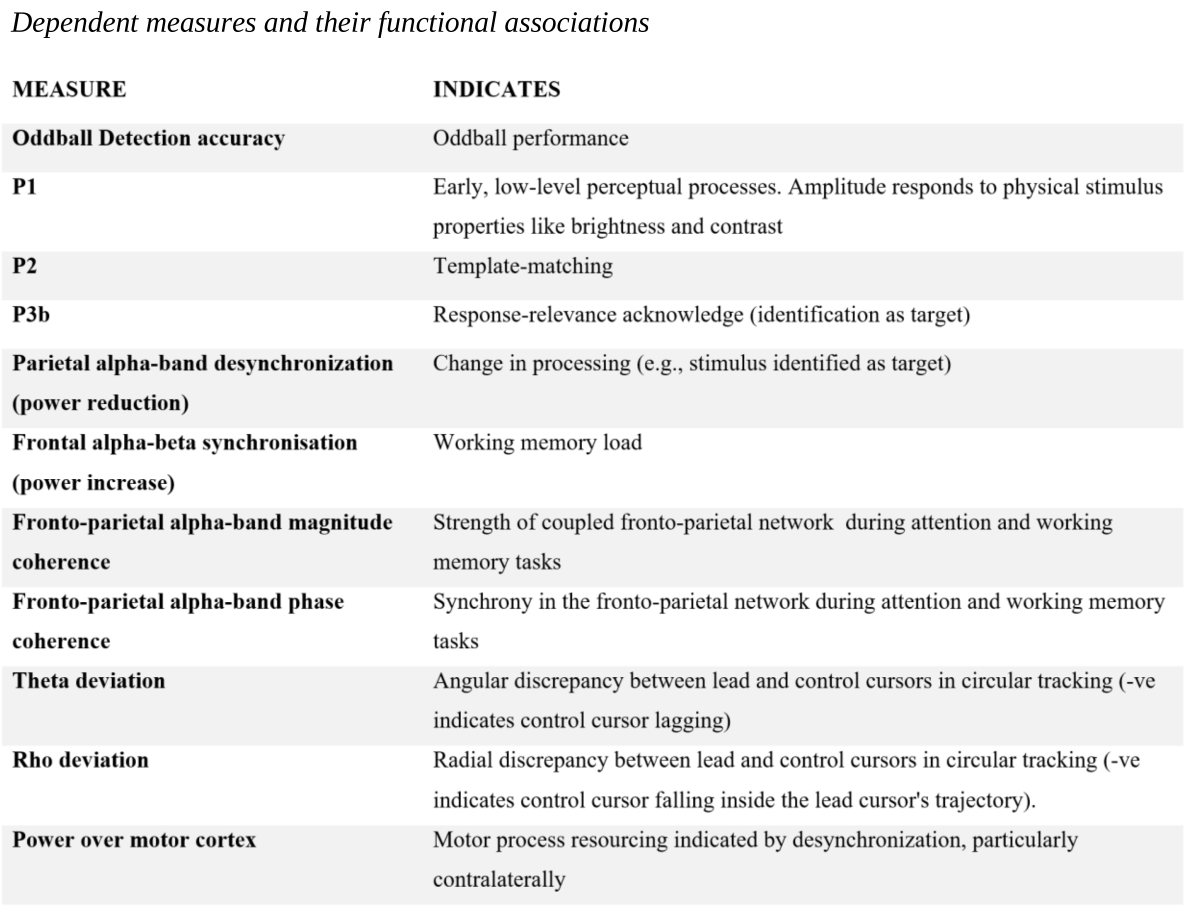
Hypotheses

In summary, it was hypothesized that performing the tracking task concurrently with the oddball task would not affect the oddball task at the P1 timescale, but would attenuate P2 and P3b amplitudes, indicating reduced attentional resourcing of oddball task performance. It was also expected that dual-tasking would attenuate parietal alpha-band ERD, indicating impaired target detection in the oddball task. Further, it was expected that an increase in frontal alpha/low-beta power (and lower accuracy) in the dual-task target condition would be observed, confirming an overall increase in WM load in that condition. Also, a reduction in fronto-parietal alpha-band coherence in the dual-task condition was expected, an indication of degraded resourcing in the dual-task condition.

In terms of tracking performance, any disruption resulting from the concurrent oddball task would be detectable as angular (theta) and radial (rho) deviations from the set trajectory. More importantly, the timing of such deviations would be highly informative in time-locked juxtaposition with the electrophysiological indicators of the oddball task's cortical processes. Positional error accruing in the P2 timescale would be indicative of a top-down attentional process in a concurrent cognitive task that disrupts tracking. Deviation in the P3b timescale would implicate the processes of task-relevance judgement. If error build-up occurs later still, then the executive function of updating (incrementing the target count) would be the most likely interference source.

The above hypotheses were derived from the expectation that the concurrent tracking task would impede resourcing of the oddball task. In the reverse direction, if the cognitive task load interfered with tracking, it was expected that positional errors would develop at the time periods of this interference. Also, if the concurrent oddball task negatively impacted resourcing of the tracking task, weaker ERD over contralateral motor cortex in the dual-task condition was expected.

The key interest in this work lies in the symmetry and synchrony of the expected interference. If the component of the oddball task that had a negative impact on tracking was also the task component that was impaired by tracking, then it would be expected that these reciprocal effects would be synchronous. On the other hand, if, say, tracking affected the attentional components of the oddball task, but it was the later executive function component of the oddball task that impaired tracking, then it was expected to present temporally separated directional effects on electrophysiological components and task performance.



Dependent measures and their functional associations

MEASURE	INDICATES
Oddball Detection accuracy	Oddball performance
P1	Early, low-level perceptual processes. Amplitude responds to physical stimulus properties like brightness and contrast
P2	Template-matching
P3b	Response-relevance acknowledge (identification as target)
Parietal alpha-band desynchronization (power reduction)	Change in processing (e.g., stimulus identified as target)
Frontal alpha-beta synchronisation (power increase)	Working memory load
Fronto-parietal alpha-band magnitude coherence	Strength of coupled fronto-parietal network during attention and working memory tasks
Fronto-parietal alpha-band phase coherence	Synchrony in the fronto-parietal network during attention and working memory tasks
Theta deviation	Angular discrepancy between lead and control cursors in circular tracking (-ve indicates control cursor lagging)
Rho deviation	Radial discrepancy between lead and control cursors in circular tracking (-ve indicates control cursor falling inside the lead cursor's trajectory).
Power over motor cortex	Motor process resourcing indicated by desynchronization, particularly contralaterally

Table 1.1. Experimental measures and their functional associations. A brief description of each measure considered throughout the series of experiments presented in the thesis.

Synopsis of experiments

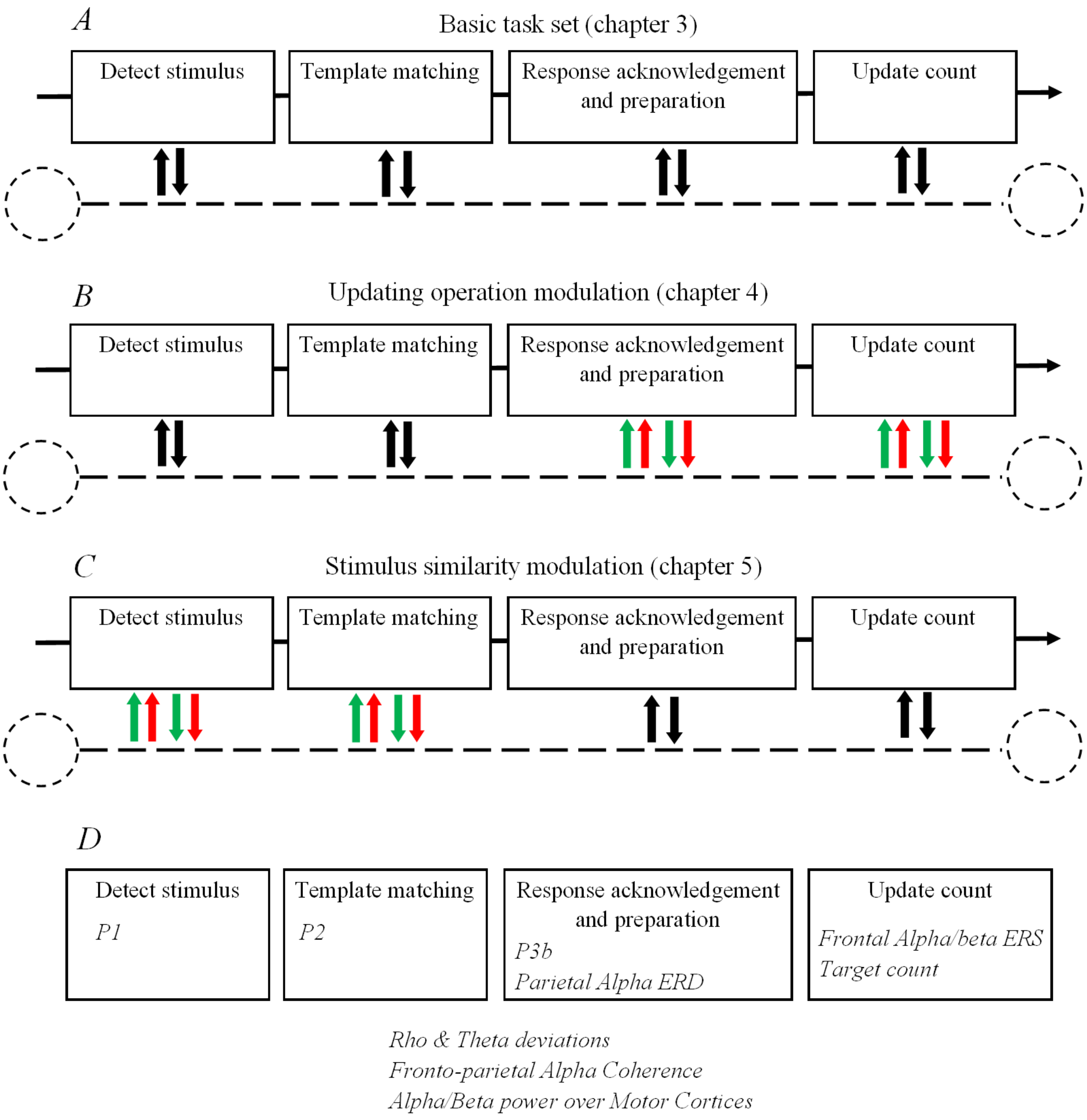


Figure 1.1. The experiments and potential patterns of interference. (A) potential interference patterns between cognitive task elements and pursuit tracking in chapter 3 (basic task set). Black arrows indicate the possible direction of interference. (B & C) potential interference patterns in chapter 4 (EF load modulation) and chapter 5 (Stimulus similarity modulation). Coloured arrows indicate possible direction of interference for low and high load conditions. (D) the measures considered across each cognitive task elements. A selection of measures are considered indicative of the individual cognitive task elements (presented in each box), while other measures were considered across the timeline of the task (presented below the boxes).

Chapter summaries

This thesis presents three experiments, and considers interference patterns across cognitive task elements during simultaneous CSC, both during basic task demands and during more challenging variations. Figure 1.1 presents a schematic for each of the three experiments, with indications as to where (and in which direction) the potential interference patterns may manifest. The methodological details common to all the experiments are provided in Chapter 2. Details of specific measures and hypotheses associated with each of the experiments are provided in the introductions of Chapters 3, 4 and 5.

Briefly, the first experiment (Chapter 3) explores the fundamental interference patterns across both tasks when the cognitive task demands are low in terms of the attentional load of identifying the target stimulus (i.e., target and standard stimuli are easily differentiated) and what to do when the target is identified (simply to add one to a continuous count). The sensitivity of specific cognitive task operations to the addition of the CSC task is inferred from electrophysiological measures: detecting the stimulus (P1), template matching (P2), response acknowledgement (P3b, parietal alpha ERD), and updating the count (frontal alpha ERS). Alongside these measures, tracking deviations (rho & theta), fronto-parietal alpha coherence, and the spectral behaviour of the motor cortices are monitored throughout each cognitive task element to understand the impact of the cognitive task on the CSC task.

The second experiment (Chapter 4) explores the impact of increasing the EF load of the task: when a target is detected, reduce the target count by either one (low load) or three (high load), starting from a random integer displayed at the beginning of each block. The physical properties of the stimuli used are identical to those of the first experiment (Chapter 3). The same measures described above are used to observe any changes in interference patterns as a result of the EF load manipulation.

The third experiment (Chapter 5) explores the impact of increasing the attentional load of the oddball task by modulating the physical similarity of the target and standard stimuli. The response requirements are identical to those in the first experiment (add one on the detection of a target). The objective is to observe what differences in interference patterns occur as a result of manipulating the attentional load of the cognitive task.

The final chapter (Chapter 6) summarises the full set of results, discusses implications and considers limitations and future directions.

Chapter 2: General Methods

Opening

This chapter will detail the tasks and analyses used to test the aforementioned hypotheses. A thorough description of the hardware used and the algorithms developed to process the data will be presented. All of the methods presented will be relevant for each of the subsequent chapters in this document. Any additional task manipulations and analyses relevant to each of the subsequent chapters will be included in said chapters. Any computer code that was developed to present stimuli and perform signal processing and analyses is available on request.

The tasks and their components

The tasks described herein were developed using PsychoPy (Peirce, 2009), an experiment design software suite that is based on the Python programming language. Many of the PsychoPy functions and objects were used in scripts that were developed to present stimuli and record data in all of the task combinations. These scripts will be available on request. This section will describe the tasks and how they were developed in detail.

Visual oddball task

To observe the effects of CSC on cognitive processing, a number of variants of a visual oddball task were used. A visual oddball task involves the presentation of rare target stimuli (oddballs) amongst a train of more common non-target (standard) stimuli. The target and standard stimuli differ on some physical property, usually contrast, shape, or size, and are separated in time. Typically, participants are required to respond with a keypress or mouse press when a target is detected and to ignore the non-target stimuli. The oddball tasks used here did not require a keypress on the detection of a target; instead, an alternative non-physical response was required (to constrain any motor related activity to the CSC task described below). The operation required following the detection of a target stimulus differed across experiments and will be described in the relevant chapters. The ratio of target to standard stimuli is considered an influencing factor in the magnitude of the brain’s response to detecting target stimuli, where a larger standard to target ratio increases the magnitude of the P3b response (Polich, 1987; 2007). For the current experiments, the probability of a stimulus being a target was .25. This was concluded to be a sufficient probability for allowing the accurate detection of the ERP components investigated in the current experiments, based on pilot data and the prevalence of studies that use such a probability (e.g. Gonsalvez et al., 1999; Furdea et al., 2009). The number of blocks in the oddball task varied across experiments, with each block presenting randomized sequences of targets and standards. At most, 12 targets were presented in a block. Stimuli were presented for 200 ms with a jittered inter-stimulus interval (ISI) set at 2500 +/- 100 ms. Introducing a random jitter to the duration of the ISI allowed for the avoidance of unwanted alpha band phase locking and prevented the participants' from predicting the onset of the stimuli. During the ISI, a fixation cross was presented in the centre of the display. The physical characteristics of the target and standard stimuli differed across experiments presented in this thesis and will be described in the relevant chapters and below. The method by which oddball task performance was measured also differed across the set of experiments and will be subsequently described in the relevant chapters.

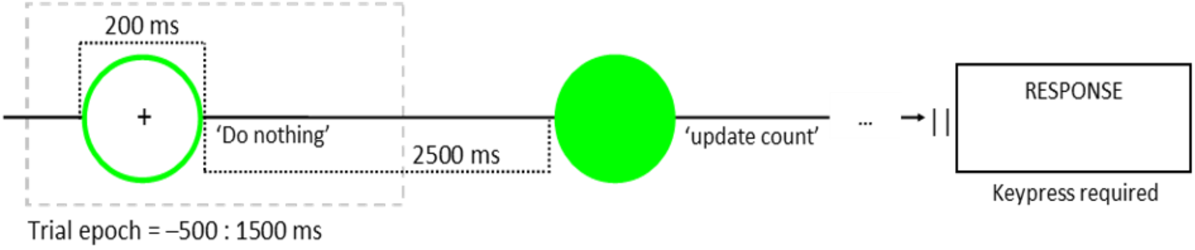


Figure 2.1. Temporal composition of an experimental trial. A schematic representation of 2 trials in sequence, detailing stimulus durations and action requirements. A keyboard response is required at the end of a block. EEG epochs are shown as a dashed box around the first stimulus.

In Chapter 5, the stimuli presented in the oddball task differ to those of the other experiments (see figure 2.1). Here, gabor patch stimuli replace the simple filled and unfilled green circles used in chapters 3 and 4. The perceptual-attentional load of the oddball task is increased, whereby the degree of similarity (spatial frequency) between the standard and target stimuli differs across load conditions

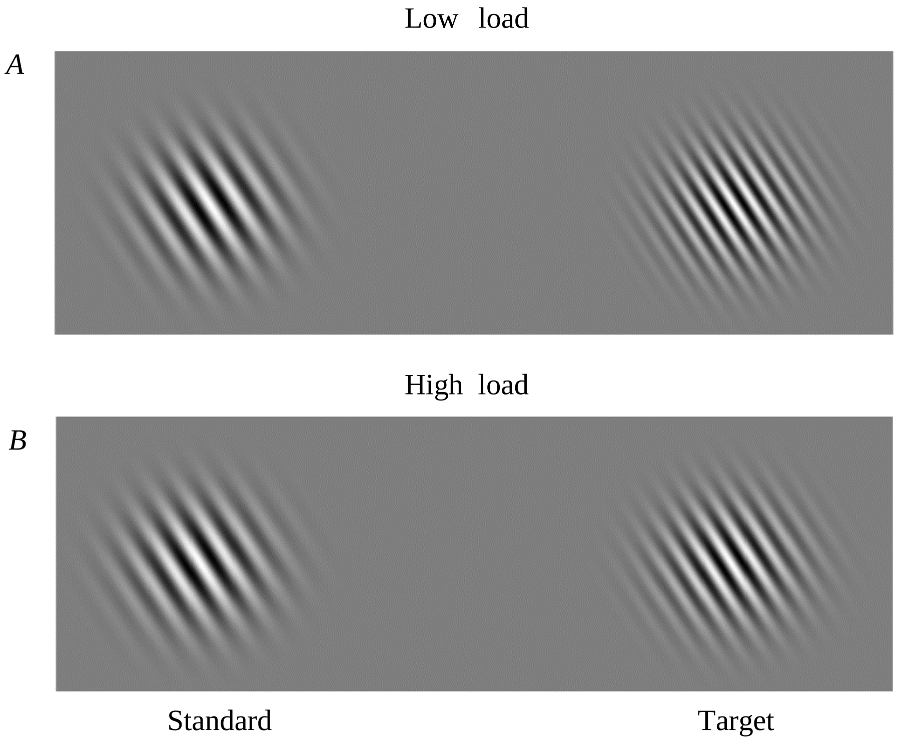


Figure 2.2. Gabor patches used in Chapter 5. A) stimuli in the low load condition. Left is the standard stimulus with a spatial frequency (SF) of 10, while the target (right) has a spatial frequency of 15. B) stimuli in the high load condition. The standard stimulus (left) has a SF of 10, while the target (right) has a SF of 13.

Motor configuration task

Prior to the pursuit tracking task (described below), a motor configuration task was completed by all participants in order to establish a suitable tracking velocity for the main pursuit tracking task. The reason for setting a participant-specific velocity was to avoid ceiling and flooring effects in the main task. By configuring a task environment that challenged the participant, it was expected that any dual-task interference due to the presence of stimuli from the oddball task would be magnified/measurable. If the tracking velocity in which a participant gave their best performance in the configuration task was used in the main pursuit tracking task, then any tracking errors due to the presentation of oddball stimuli may have been negligible. The tracking velocity selected was the participant’s third best performance (described below).

Participants were asked to maintain fixation at the centre of the screen whilst using a Wacom Intuos Pro digitizing tablet and stylus (Saitama, Japan) to pursue a cyan shaded circle with a diameter of 25 pixels (leading dot) which rotated clockwise in a circle (r=130 pixels, 36mm) around a fixation cross. Participants were sat so that their eyes were approximately 800-850 mm from the fixation cross, so that the lead dot's track subtended a visual angle of 2.42° -2.57°. The ability to divide covert attention between locations has been tested up to 3.5° of eccentricity from the centre of the screen (e.g., McMains & Somers, 2004). The stylus's position was presented on the display as a black circle with a diameter of 20 pixels (controlled dot) and the participant's task was to move the stylus across the tablet so as to keep the controlled dot as close as possible to the leading dot throughout the duration of the trial. Seven trials (each with a 10 second duration) were presented sequentially in which the angular velocity of the leading dot increased from 84 degrees per second (dps) in the first trial to 168 dps in the last trial (increasing in 12 dps increments). The sequence of trials were then presented in a reverse order. For each velocity, the final 7 seconds of the trial was used to calculate a percentage of the number of frames in which the two dots overlapped (shared some coordinate space). The angular velocity which had the third highest percentage was chosen as the velocity to be used in the main pursuit tracking task. The spatial dimensions of the tablet differed from that of the display, and so a scaling factor was used within the code to ensure that the coordinates of the tablet matched those of the display.

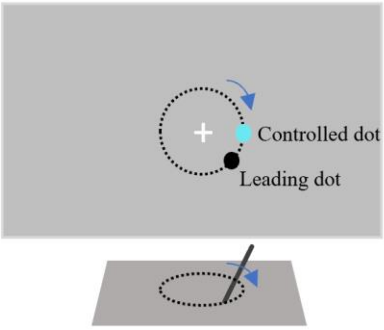


Figure 2.3. Pursuit Tracking Task. The leading dot moves clockwise on a circular trajectory and the participant tracks it with a stylus on a pressure-sensitive tablet. The stylus position is represented on screen as the controlled dot.

Pursuit Tracking Task

In order to examine the effects of oddball stimuli on pursuit tracking (in the dual-task condition), it was necessary to test participants on their ability to pursue the leading dot in the absence of any additional task loads. This was achieved by presenting 8 blocks (each ~2 minutes in duration) of simply pursuing the leading dot with an angular velocity chosen by the performance of the previous configuration task. The physical properties of both dots and the trajectory of the leading dot were identical to that of the configuration task. A block began (the lead dot started to move) when the participant placed the controlled dot on top of the leading dot. After 3 seconds, both X and Y coordinates of both dots were recorded in a text file. Participants were instructed to fixate on the fixation cross at the centre of the screen at all times. The code that ran this task also recorded triggers when a target or non-target was presented. Although neither target nor standards were physically presented in this task, the triggers served as a means of epoching the tracking data, so that time-locked tracking deviations could be compared alongside deviations in the dual-task.

Dual-task

The dual task consisted of the performance of both the visual oddball task and the pursuit tracking task simultaneously. That is, participants were required to maintain positional overlap of both dots during the presentation of target and standard stimuli. The block and trial structure were identical to that of the single visual oddball task. The trajectory of the leading dot rotated at the selected angular velocity around the fixation cross and at 25 mm beyond the boundary of the oddball stimuli. On each frame, the coordinates of both dots, type of stimulus and stimulus onset time was recorded in a text file.

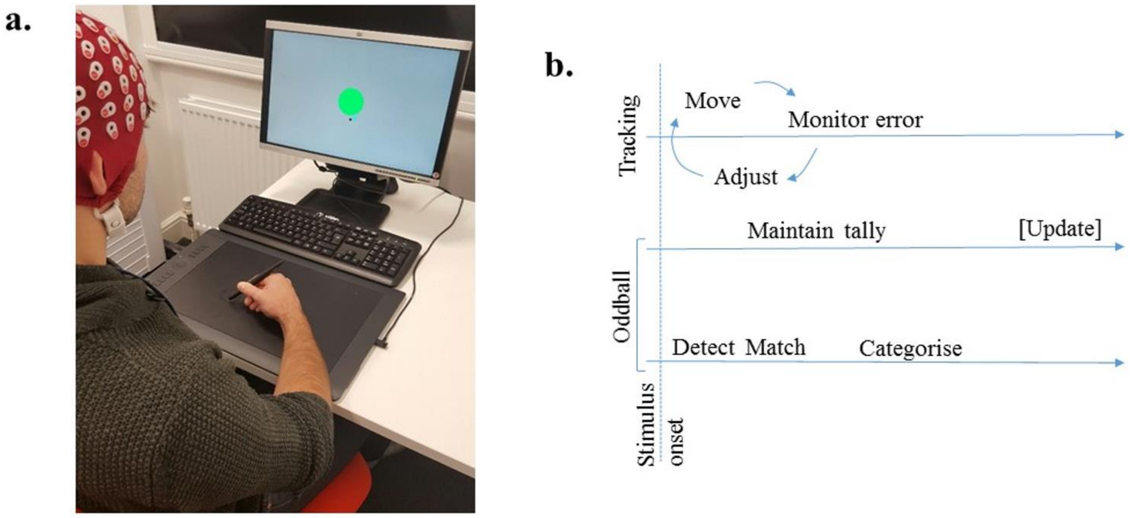


Figure 2.4. Dual-task arrangement and potential task components. (a) The oddball stimulus is either an unfilled (standard) or filled (target) circle in the centre of the screen. The black dot circles the oddball stimulus clockwise. The participant tracks it using a stylus on the pressure-sensitive tablet. The blue dot displays the stylus position on the screen. (b) Schematic representation of the relative timing of the potential components of the two tasks.

Procedure

Participants sat comfortably approximately 80cm from a 19 inch (1600 x 900 pixels) LCD monitor (60 Hz) and were asked to remain in position for the duration of the recording session. Participants received information sheets and were asked to sign consent forms. Once the EEG apparatus had been set up, and the electrodes applied to the EEG cap, participants completed the motor configuration task described above. Once completed, either the single visual oddball, single tracking, or dual-task was presented one after another (the order of which was counterbalanced across participants). Each task was preceded by 3 minutes worth of practice trials, in which participants became familiar with the task set up. In experiments 2 and 3, a number of other conditions were also presented (see relevant chapter). Following all the tasks, participants were debriefed and were credited with a £20 amazon gift voucher.

The following section will detail all of the measures considered in each of the three experiments and how they were derived. More specifically, data acquisition and signal processing parameters will be detailed for electrophysiological measures including a description of a virtual electrode technique by which an EEG signal was constructed by considering the maximum value (µV^2) at each time point throughout an epoch across a selection of EEG channels. Said channels were chosen based on local maxima observed in the distribution of voltage across the scalp within certain time windows of interest. Also detailed are the steps taken to analyse the pursuit tracking data in order to observe time-locked perturbations in tracking performance relative to the onsets of stimuli in the oddball task.

EEG data acquisition

In order to observe the activity of the CNS during the performance of all task combinations, a 128 channel Biosemi AciveTwo EEG system (Amsterdam, the Netherlands) was used. Electrodes were placed in the Biosemi ABC configuration and fixed to an elastic cap that fitted the participant. A conductive gel was applied to all the holes in the cap in order to facilitate the transition of the EEG signal from the scalp to the electrode surface. EEG data were collected using 128 Ag/AgCl active pin electrodes at 2.04 KHz and digitized in 24-bit resolution. Electrodes were referenced online using a common-mode sense (CMS) and driven-right leg (DRL) feedback loop with an online low pass filter performed in the analogue-digital converter (5th order sinc response with a -3 dB point at 1/5th of the sampling rate). Using an active system (online detection and rejection of common-mode signals such as line noise) allows for cleaner EEG data relative to passive systems. Electrode offsets (the difference (µv) between each channel and the CMS electrode) were examined after the electrodes were attached to the cap. If the offset exceeded |20| µv, then more gel was applied. If applying additional gel did not rectify the problem, electrodes were noted down and interpolated during pre-processing. Digital markers (triggers) were inserted into the EEG data via a DB25 cable though a USB-parallel port interface (Neurospec AG, Switzerland) that were sent by the computer running the task using pyserial, a serial port interface for python. These triggers indicated the onset and type of each of the oddball stimuli presented. EEG data were saved as a Biosemi Data Format (BDF) file and copied from the EEG computer for analysis.

Pursuit Tracking data acquisition

In order to detect spatial deviations during pursuit tracking, instantaneous positional coordinates (X and Y) were recorded for both controlled and leading dots from a Wacom Intuous Pro digitizing graphics tablet (Saitama, Japan) for each frame during a task. The tablet had a sampling rate of 60 Hz and an active area of 311 x 216 mm. Participants were instructed to use their right hand to hold the stylus as they would a normal pen and to continuously pursue the leading dot. The positional coordinates for both dots on each frame were saved as a line in a text file. These coordinates were then used to calculate a number of measures offline (see below).

Measures and Analyses

This section of the chapter will detail all of the processing steps for the tracking and EEG data, and will detail all of the measures used from each of the tasks in order to test the hypotheses. All the details presented are relevant to all of the chapters in this thesis.

EEG signal processing

Continuous EEG data were imported and processed in MATLAB (Mathworks, US) using functions from EEGLAB (Delorme & Makeig, 2004), an open source EEG/ERP analysis toolbox. A number of scripts were developed to import, process, analyse, and plot data. Raw EEG waveforms were down-sampled to 256 Hz and a linear finite impulse response (FIR) filter was applied to attenuate frequencies below 1 Hz and above 50 Hz. Line noise (50 Hz) was estimated and reduced from each channel using CleanLine (Mullen, 2012), an EEGLAB data processing plugin. The DC component of each channel was removed by calculating the mean and removing it from each sample point. Noisy channels were identified for each participant by visual inspection for unwanted high frequencies and extreme values. Any channels with kurtosis over 5 standard deviations from the mean kurtosis of all channels were also removed. Spherical interpolation was applied to any noisy channels following the decomposition of the data by Independent Components Analysis (ICA) (Bell & Sejnowski, 1995), this will be described below. If more than three neighbouring channels were considered to be noisy across the duration of a recording, then interpolation was not applied.

EEG epochs were generated by extracting 500 ms worth of sample points that preceded each event (oddball stimulus onset) and 1500 ms worth of sample points following each event. Epochs were then inspected and removed if they contained residual low frequency drift or intermittent high frequency segments that were considered to be caused by biomechanical mechanisms (e.g., jaw movements and ocular artefacts). All channels were re-referenced to an average reference (an average of all values at each time point) and a single channel (D32) was then removed. Removing a single channel following the re-referencing procedures corrects for the data rank issue (reduces rank to n-1) that is produced from using an average reference. If a channel is not removed, it is possible that the ICA algorithm can produce artefactual and/or duplicate components.

Following the steps described above, ICA was applied to epochs in each dataset. ICA involves the linear de-mixing of observed data so as to describe the contributing components of a signal. ICA attempts to model maximally temporally independent components of a signal in order to observe its constituent parts. The output of an ICA algorithm is a set of components, each with its own time series, that when summated perfectly produces the observed signal. It is possible, therefore, to model the components of a signal, identify specific components of interest (e.g., a source of noise), remove their contribution to the signal, and back-project the activity of all the remaining components. This results in the original signal, with the noise components' contribution removed. Given that EEG is mostly the product of the linear summation of signals from within the cortex, ICA is a powerful method of isolating and removing artefacts such as eye and jaw movements. Component properties such as spectra, topography and trial by trial component time series, were examined in order to identify the source of ocular and muscle artefacts. Ocular artefacts such as blinks were identified by low-frequency, non-time-locked fluctuations in the EEG trials with strong power at the front of the scalp. In some cases, ocular activity was time-locked to the stimuli, presumably presenting a startle response to the onset of the stimulus. If a component presented this, but with concentrated activity at the front of the head, it was considered artefactual and removed. Muscle components were identified by high frequency activity with activity close to the jaw. Any components that were identified as such, were modelled out of the observed signal.

EEG measures

A number of measures derived from the EEG time series were used to examine the effects of dual-tasking on the nervous system. These measures will be described herein.

Event-Related Potentials (ERPs)

A description of each of the ERPs evaluated in this thesis is included in the introduction chapter. All epochs were baseline corrected by calculating the mean of each channel before stimulus onset (-500 ms to 0 ms) and removing this value from all of the samples in the epoch. This process zero-normalises each signal and removes the average of non-task related activity (baseline) from the signal, resulting in a waveform with an average of the noise (non-task related activity) removed.

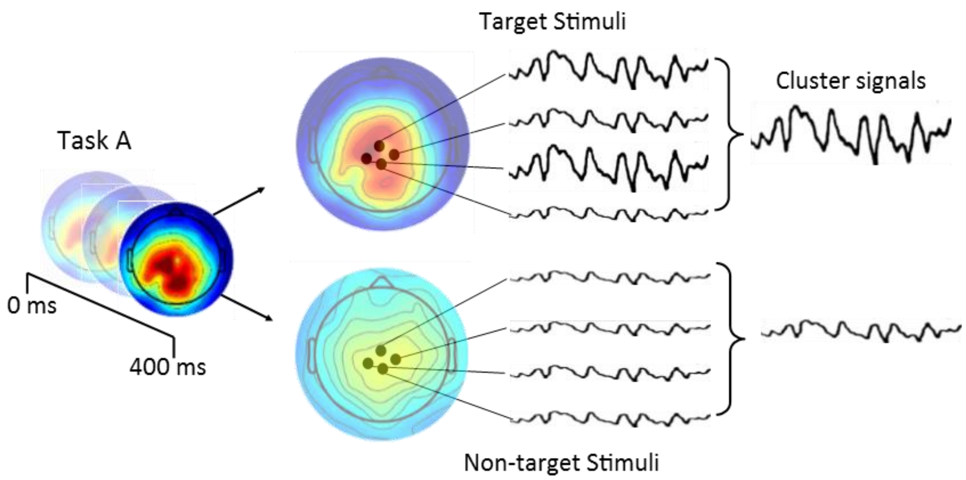
Generation of Cluster Signals for ERP Extraction

In order to derive a single time series from a cluster of electrodes (and thus measure its peak), a virtual electrode approach was used (Baker et al., 2018; Foxe & Simpson, 2002; Rousselet et al., 2010). This involves computing a 'virtual' signal that is a product of the maximum value across all electrodes in a cluster at each time point. This approach is sensitive to individual differences in the location of the maximum response to stimulation (Rousselet et al., 2010).

To identify clusters of electrodes in which to extract ERP values, a series of animations was created in order to plot scalp topography as a function of time. Grand average (all participants) topography was plotted every 5ms from stimulus onset (time 0) to 1000 ms post-stimulus onset. Once stitched together, the animation displayed clusters of electrodes that were maximally active in the time windows 80-120 ms, 180-220 ms, and 380-420 ms post stimulus onset. The electrode clusters which displayed the maximum value within each of these time windows were used for the extraction of ERP component measures. Electrode labels are given in Biosemi coordinates (see figure 2.5), and corresponding 10-5 labels are provided where possible (Oostenveld & Praamstra, 2000). The cluster of electrodes used for the quantification of P1 magnitude was B7 (PO8), B8, B9 (PO10), A26 (I2), A27 and A28 (O2) electrodes. For P2 magnitude, C26 (AFF3H), C20 (AFz), C13 (AFF4H), C25

(F1), C21 (Fz) and C12 (F2) electrodes were used. Finally, P3 magnitude was quantified using electrodes A5 (P1), A19 (Oz), A32 (P2), A18 (PPO3H), A20 and A31 (PPO4H).

A



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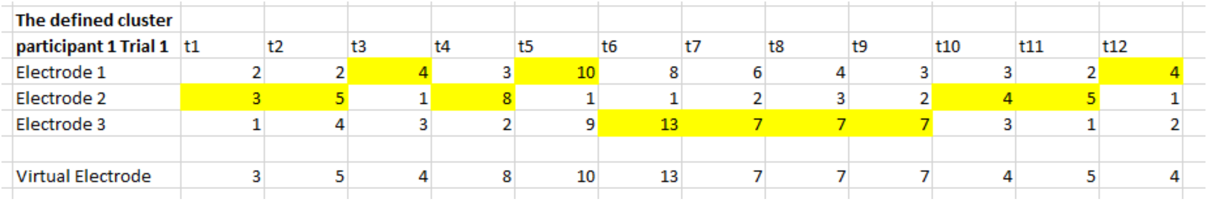

The defined cluster												
participant 1 Trial 1	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
Electrode 1	2	2	4	3	10	8	6	4	3	3	2	4
Electrode 2	3	5	1	8	1	1	2	3	2	4	5	1
Electrode 3	1	4	3	2	9	13	7	7	7	3	1	2
Virtual Electrode	3	5	4	8	10	13	7	7	7	4	5	4

C

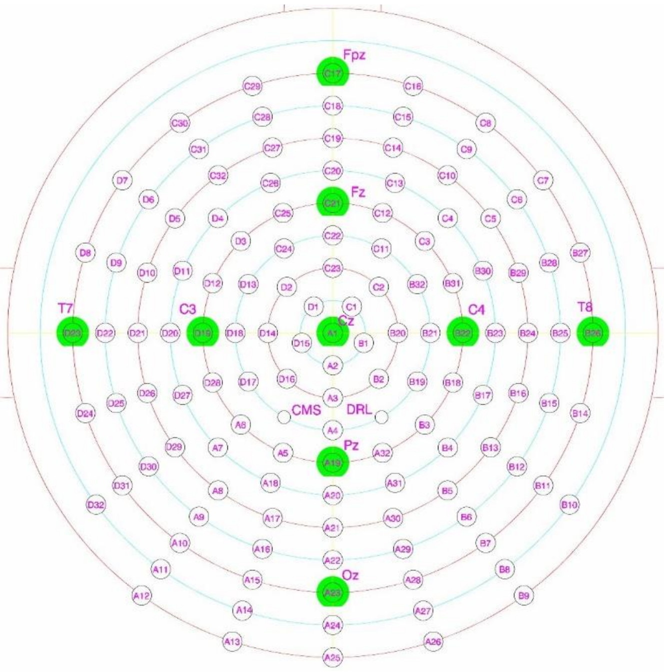

Figure 2.5. Process for deriving cluster signals and Biosemi coordinate system. (A) The grand average scalp topography at a given latency (here 400 ms) is visual inspected for the cluster of electrode positions with maximal response. (B) The assignment of virtual electrode response magnitude at each of several time points (t1 … t12) across the timeline of a hypothetical trial. The maximal response in the electrode cluster (highlighted in yellow) is assigned to the virtual electrode at each time point. (C) Biosemi coordinate labelling system.

Event-related Spectral Perturbations and Cross-Channel Coherence

In order to examine the effects of oddball stimuli on the ongoing frequencies present in the EEG, event-related spectral perturbations (ERSP) were computed for each trial type using the newtimef function in EEGlab (Delorme & Makeig, 2004). ERSPs allow for the analysis of time-locked power (magnitude) and phase changes in frequency space as a function of trial type. Modulations in ongoing frequencies were measured using moving window, zero padded fast Fourier transforms (FFTs) with hanning window tapering. FFTs involve convolving the observed signal with an artificial sine wave at a number of frequencies. The sine wave is defined with a given length and moved across the EEG time series. Within each window, the dot product between a pair of vectors of the same length (observed EEG and artificial sine wave) is calculated by point-wise multiplication of values at each time point. By summing these values, it is possible to identify the frequency at which the EEG signal is oscillating. By sliding a window across the EEG time series and computing an FFT within each window, it is possible to observe the dynamics of EEG spectral power over time.

For each participant, a time x frequency matrix was produced containing log power (dB) values of 100 frequencies (between 3 and 45 Hz) across time windows spanning -150 to 1500 ms post stimulus onset for each EEG epoch. Average log power in the 7-13 Hz range for each trial type was taken as alpha-band power over parietal cortex, and alpha/low-beta-band power as the average across 13-22 Hz over frontal cortex. A bandwidth spanning both alpha and low-beta activations was considered as previous studies (e.g. Onton & Makeig, 2005; Deiber et al., 2007) have examined frontal WM mechanisms in the context of overlapping alpha and beta bandwidths. Power values at each time window across all epochs were averaged to produce mean log power as a function of time. All power values computed were relative to the relevant power in the baseline period.

Power at each frequency is returned as a log value. That is, absolute power is decibel (dB) normalised so as to scale power values to each frequency. In many biological systems, power is inversely proportional to frequency, in that lower frequencies have higher power. This is known as pink noise, or 1/f noise. This phenomenon causes the visualisation of power across multiple frequencies difficult to do simultaneously. Also, absolute power is not normally distributed, and so parametric statistics are limited. Decibel normalisation provides a means of power-law scaling and attempts to correct for said noise. Therefore, relativized power measures are given as; power(dB)=10*log$_{10}$(signal/baseline).

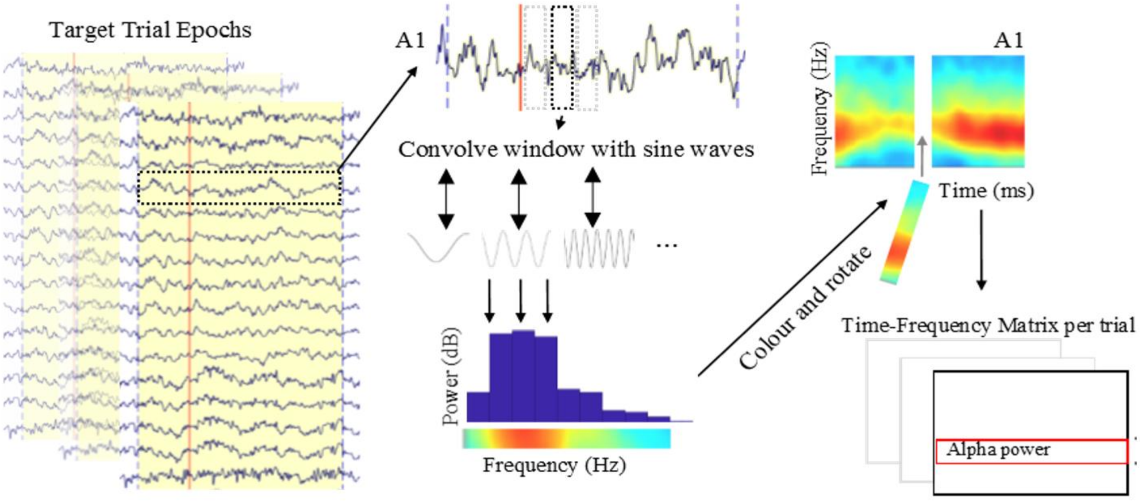

Figure 2.6. Steps in the time-frequency analysis. Time-frequency decomposition of EEG time series data. See text for details.

Cross-channel coherence was measured in order to observe the instantaneous coupling of the amplitude and phase of alpha oscillations between frontal and parietal regions of the cortex. The newcrossf function (EEGLAB) was used to generate coherence matrices for alpha power and phase between C21 and A19 electrode sites during a number of time windows throughout EEG epochs. Coefficients between said electrodes within the alpha frequency range were averaged across all trials for each time window in order to quantify the dynamic spectral relationship between frontal and parietal regions during each of the task conditions.

Spectral decomposition of motor cortex activation

In order to examine the effects of oddball task stimuli on the continuous rhythmic activity of the motor system (involved with performance of the pursuit tracking task), the spectopo function (EEGLAB) was used to derive alpha and beta power spectral density (PSD) at both left (D19) and right (B22) electrode sites during the pursuit tracking task, and target and non-target trials in the dual-task and single task (oddball only). The spectopo function involved the application of a discrete time

Fourier transform (DTFT) across the length of each EEG epoch, in order to observe any increases or decreases in alpha/beta power as a function of trial type. In the case that power changes occurred at smaller time scales, DTFTs were also computed for 6 time windows (0-200, 200-400, 400-600, 600-800, 800-1000, and 1000-1200 ms post stimulus onset) in each EEG epoch for all trial types. The Spectopo function produced a single vector (power spectral density for each frequency ranging from 3-45 Hz) for each trial for both D19 and B22 electrodes. Mean alpha (7-13 Hz) and beta (14-30 Hz) was calculated for each trial type for each electrode by averaging across all trials in the same condition. Power spectral density provides a relativized value, proportional to the frequency of the obtained absolute power value. It is given as; $psd=(10*\log_{10}(\mu V^2))/Hz$.

Pursuit Tracking signal processing and measures

To observe the effects of oddball task stimuli on pursuit tracking performance, instantaneous tracking deviation (positional discrepancy between leading dot and controlled dot at each time point) was calculated for each trial type (pursuit tracking, dual-task target and non-target trials). The experiment produced a text file with the coordinates (X and Y) of both the leading and controlled dot on each frame (60 samples per second). Also included in the text file was an indication as to the onset of each oddball stimulus so as to enable epoching of the tracking data around the oddball stimuli. Pursuit tracking deviations were quantified in two different ways; in polar and in cartesian space. For analyses in polar space, the coordinate at each time point (i) was converted to polar coordinates so as to obtain angle (theta) and radius (rho) values. For theta, the four-quadrant inverse tangent of coordinates Y(i) and X(i) was derived using the MATLAB atan2 function. For rho, the square root of coordinates $X(i)^2 + Y(i)^2$ with the origin of the circle as X=0,Y=0 was used. To calculate the instantaneous difference (deviation) between the lead and controlled dots theta values, the controlled dots theta value was subtracted from the lead dots theta value. For the rho difference, the lead dots rho value was subtracted from the controlled dots rho value. Deviation samples were epoched around the oddball stimulus onset (-200 to 2500 ms).

Following the generation of rho and theta tracking deviation vectors for each trial, epochs were zero normalized by removing the value observed at the timing of the P3b peak in the relevant condition, from all samples in the epoch. This presented deviation patterns relative to tracking performance at the timing of P3b. It was agreed said normalizing procedure was to be used, as findings discussed in the first experimental chapter (chapter 3) demonstrated significant deviation patterns post P3b, and that zero normalizing to values at the timing of P3b, would highlight said patterns. These normalized epochs were then smoothed using a moving average (8 samples). The resulting vectors were averaged across trials of the same type for each participant to produce participant-level averaged tracking deviation vectors (for both rho and theta). Deviation quantities (for both rho and theta) was then calculated for each condition by extracting the value at 5 separate times following the timing of the P3b peak (300, 600, 900, 1200 and 1500 delay periods). Analysing tracking performance in polar space was the primary method of demonstrating interference of the oddball task on CSC and this is presented in the main body of the experiment chapters.

Tracking performance was also analysed in cartesian space, that is, deviations were calculated on each frame using quadrant-specific and dimension-specific arithmetic, so that deviation was negatively signed when the controlled dot was trailing behind the leading dot, and positively signed when the controlled dot was in front of the leading dot. For example, for the horizontal (X) axis, deviation(X)=controlled(X)-lead(X) in quadrants I and IV, but deviation(X)=lead(X)-controlled(X) in quadrants II and III).

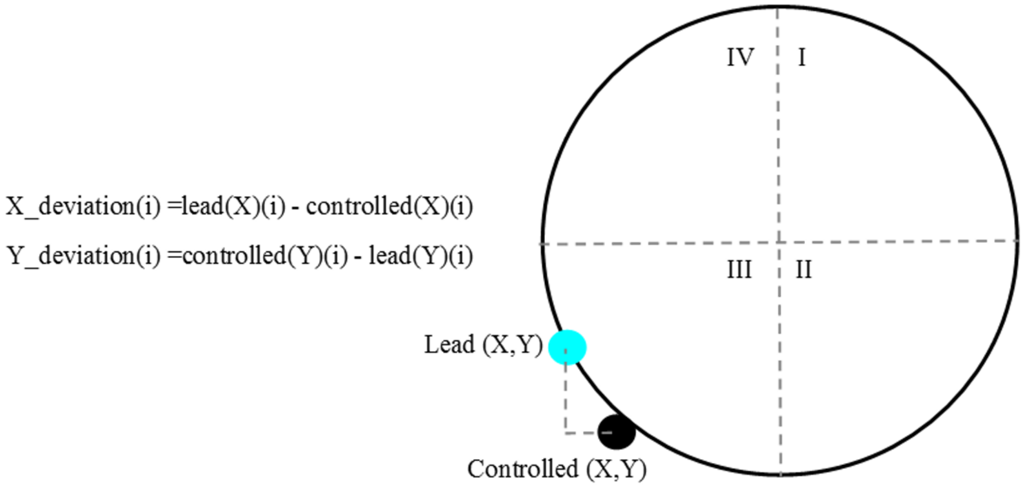

Figure 2.7. Cartesian analysis of tracking deviations. An example of how horizontal (X) and vertical (Y) deviation values are derived from cartesian coordinates where both leading and controlled dots are situated in quadrant 3 of the circle. See text for details.

Tracking deviation values were epoched around the onset of the oddball stimuli (-150 to 1500 ms post stimulus onset). In the case of the pursuit tracking task (single task), samples were epoched around the onset of oddball stimuli, even though no physical stimuli were presented. This provided a control condition in order to compare deviation during the presentation of oddball stimuli.

Following the generation of X and Y tracking deviation vectors for each trial, epochs were baseline corrected by removing the mean of pre-stimulus values (-150 to 0 ms) from all samples in the epoch. Baseline corrected epochs were then smoothed using a moving average (8 samples). The resulting vectors were averaged across trials of the same type for each participant to produce averaged tracking deviation vectors (for both X and Y). Maximum deviation (X and Y) was then calculated for each condition by extracting the timing (and value) of the maximum value within 6 separate time windows (0-200, 200-400,400-600,600-800,800-1000 and 1000-1200 ms post stimulus onset).

In order to visualise spatial deviations due to the onset of target and non-target stimuli, both X and Y deviation values were added or subtracted (depending on the sign of deviation) to the absolute X and Y coordinates of the leading dot. This allowed for the plotting of instantaneous deviations relative to the position of the leading dot, resulting in a spatial (X by Y) plot of tracking deviation in each condition.

Chapter 3: Experiment 1: Asymmetric interference between cognitive task components and concurrent sensorimotor coordination

Introduction

The objective in this thesis is to investigate motor-cognitive interference using an experimental paradigm in which the neurophysiological resourcing of the cognitive task's functional elements could be tracked alongside the instantaneous error levels in the concurrent motor task (Figure 3.1). The functional elements of the chosen oddball detection task are (1) stimulus detection, (2) template-matching, (3) response relevance judgment, and (4) updating the target tally. The resourcing of elements (1) – (3) could be estimated using the ERP components P1, P2 and P3, respectively. The performance of element (4) can be measured as tallying accuracy. Time-frequency analysis of the EEG signal's alpha and alpha/low- beta bands can provide additional resourcing information: attentional resourcing of element (3) in the level of parietal alpha-band desynchronization (Sutoh, 2000), the working memory load associated with element (4) in frontal alpha/low-beta power (Manza et al., 2014), and the strength of the fronto-parietal network underpinning the task set can be estimated in the alpha-band coherence between parietal and frontal sites (Kwon et al., 2015). The experimental paradigm also eliminates strategic adjustment of dual task loading by slowing down motor task performance or making use of the motor task's inherent error tolerance. It does this by requiring a constant speed and making any spatio-temporal deviation visible to the motor task's performance analysis. The purpose of the first experiment reported in this chapter is to test the proposed paradigm's ability to expose the details of dual-task interactions before exploring manipulations of the loading of elements (3) and (4) in subsequent chapters. The oddball task in this experiment employs a simple visual difference between the standard (an unfilled circle) and target (filled circle) stimuli, and the motor-tracking task requires participants to maintain a constant speed set at their respective comfort level.

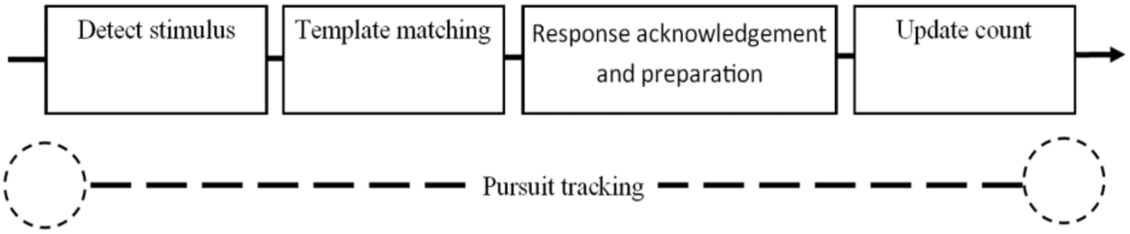

Figure 3.1. The functional elements of the oddball task. The demands of the pursuit tracking task are continuously concurrent.

It was hypothesised that performing the tracking task concurrently with the oddball task would not affect the oddball task at the P1 timescale, but would attenuate P2 and P3 amplitudes, indicating reduced attentional resourcing of oddball task performance. This is based on evidence that P1 is not sensitive to global attentional demands (Capizzi et al., 2013; Gherri & Eimer, 2010), though P3b (Matthews et al., 2005; Pratt et al., 2011; Ross et al., 2018) has been shown to be sensitive to dual-task interference. There is inconclusive evidence as to whether pursuit tracking would attenuate P2 amplitude, though P2 has been shown to be sensitive to attention (Hillyard et al., 1973). As such, if pursuit tracking was to modulate resourcing to cognitive operations associated with P2, then it was expected that an attenuation would be observed.

It was also expected that dual-tasking would attenuate parietal alpha-band ERD, indicating impaired target detection in the oddball task (Sutoh, 2000). Further, an increase in frontal alpha power (and lower accuracy) in the dual-task target condition was expected, confirming an overall increase in WM load in that condition (Manza et al., 2014). Also, it was expected that a reduction in fronto-parietal alpha-band coherence in the dual-task condition would occur, indicative of degraded resourcing in the dual-task condition (Kwon et al., 2015).

The above hypotheses were derived from the expectation that the concurrent tracking task would impede resourcing of the oddball task. In the reverse direction, if the cognitive task load interfered with tracking, it was expected that positional errors would develop at the time periods of this interference. Also, if the concurrent oddball task negatively impacted resourcing of the tracking task, it was expected that weaker ERD over contralateral motor cortex in the dual-task condition would be observed.

The key interest in this work lies in the symmetry and synchrony of the expected interference. If the component of the oddball task that had a negative impact on tracking was also the task component that was impaired by tracking, reciprocal effects were expected to be synchronous. On the other hand, if, say, tracking affected the attentional components of the oddball task, but it was the later executive function component of the oddball task that impaired tracking, then temporally separated directional effects on electrophysiological components and task performance were expected.

Methods

The methodological details general to all the reported experiments are provided in Chapter 2. Information specific to this experiment is provided in this section. Each experiment presented in this thesis included different groups of participants (i.e. there was no overlap in the cohorts tested).

Participants

The participants were 24 self-reportedly right-handed adults (13 females; mean age = 25.6 years, SD=6.13, range 19-42), with normal or corrected to normal vision, no current prescribed medication, and no history of sensorimotor or cognitive deficits. They were recruited through a research participation scheme for students and given research credits in return for their participation. The participants gave informed consent before the session and were fully debriefed at the end. Ethical approval for the research reported in this paper was granted by the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee.

Tasks

Participants first completed the motor configuration task as described in Chapter 2. This allowed the selection of a comfortable tracking speed. Participants then carried out the visual oddball task, visuomanual tracking task, and the dual task, in counterbalanced order.

Oddball Task Variant

The participants fixated at the centre of the screen while a sequence of shaded (target) or non-shaded (standard) circles (r = 100 pixels) were presented, centred on the fixation cross. These stimuli were presented for 200 ms, with a jittered ISI of 2500 +/- 100 ms. The ratio of target to standard stimuli was 1:4, and there were at most 12 targets presented in each block (the number of trials per block varied between 40 and 60). The participants’ task was to silently count up the number of targets presented in a block and report it via the keyboard once the block had finished. There were 8 blocks of trials in total and the number of blocks in which the number of targets were counted correctly was recorded, as were the participants’ EEG data. Accordingly, accuracy on the oddball task was recorded as either a 1 (accurately reported the number of targets in the block), or 0 (did not report the correct number of targets in the block), for each of the 8 blocks.

Dual task

The participants also performed the visual oddball task whilst concurrently performing the visuomanual tracking task. Each of the 8 blocks of trials started with the leading and controlled dots in an overlapping position. As the leading dot started moving, and the oddball task got under way, the participants' task was to maintain the positional overlap between the dots while performing the oddball task. The coordinates of the controlled and leading dots, the target count and the EEG data were recorded. As in the single-task conditions, the instruction throughout was to maintain eye fixation on the cross at the centre of the screen.

Signal Processing and Data Handling

A detailed description and explanation of all the signal processing procedures for the electrophysiological and pursuit-tracking deviation measures has been presented in Chapter 2. This section provides a brief description of the procedures used specifically in this experiment.

Oddball Detection Accuracy

Performance on the oddball task was the proportion of blocks in an experimental condition for which the participants reported the correct number of target stimuli presented.

EEG signal processing and measure extraction

EEG waveforms were down-sampled to 256 Hz and an FIR filter was applied to attenuate frequencies below 1 Hz and above 50 Hz. Mains interference (50 Hz) was estimated for each channel and removed using Cleanline (Mullen, 2012). The DC component of the signals were removed by calculating the mean and removing it from each sample period. Noisy channels were identified by visual inspection for high frequencies and extreme values. Any channels with kurtosis over 5 standard deviations from the mean kurtosis of all channels were removed. Spherical interpolation was applied to noisy channels following the decomposition of the data by ICA. Epochs were generated using 500 ms of samples preceding each oddball stimulus, to 1500 ms following the onset. Epochs were then inspected and removed if they contained residual low frequency drift or intermittent high frequencies that were considered to be biomechanical in their origin. Data were then average-referenced and subjected to ICA. Once decomposed, ICA components were inspected and removed if considered to be eye or muscle related. Finally, the residual components were back-projected on to the scalp.

Generation of ERP measures

Once the signal was generated for a given cluster for each trial type and task type, difference waves were computed (target stimulus minus non-target stimulus). This resulted in a waveform that represents the difference in target and non-target stimulus processing (i.e. the residual waveform displaying target-specific processing).

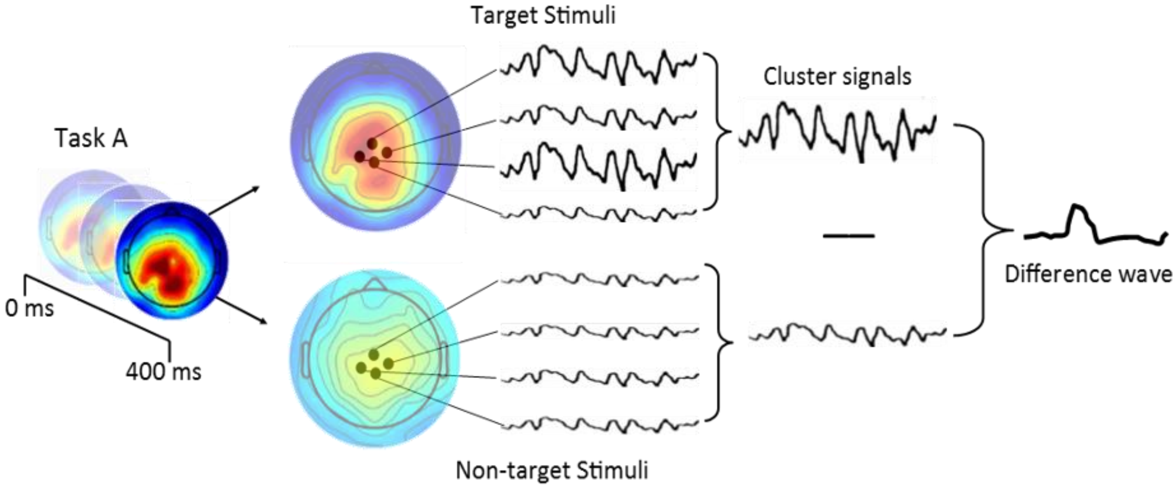

Figure 3.2. Generation of cluster signal difference waves. Cluster signals were generated from the maximum value at each sample period over a cluster of electrodes (see Figure 2.4). Non-target cluster signal activity was subtracted from the target cluster signal, resulting in target-minus-standard difference waves.

Once cluster-level difference waves were produced, P1, P2, and P3b component amplitudes were extracted from the relevant resulting waveforms. The cluster of electrodes used for the quantification of P1 parameters was B7, B8, B9, A26, A27 and A28 electrodes. For P2, C26, C20, C13, C25, C21 and C12 electrodes were used. Finally, P3b was quantified using electrodes A5, A19, A32, A18, A20 and A31.

Event-related Spectral Perturbations and Fronto-parietal Coherence

For frontal and parietal alpha ERSP measures, the EEGlab newtimef function was used, in which time-frequency time series were generated using moving window, zero padded fast Fourier transforms (FFTs) with hanning window tapering. Frontal ERSPs were extracted from electrode C21 (Fz), and parietal ERSPS from A19 (Pz). Once generated for each participant, alpha power (7-13 Hz) was extracted for 20 separate time bins following stimulus onset for each condition. For fronto-parietal coherence measures, the newcrossf function was used to generate coherence matrices for alpha power and phase between C21 and A19 electrode sites during a number of time windows throughout EEG epochs. Coefficients between these electrodes within the alpha frequency range were averaged across all trials for each time window in order to quantify the dynamic spectral relationship between frontal and parietal regions during each of the task conditions.

Pursuit Tracking Deviation processing and analysis

In order to quantify deviation patterns in the pursuit tracking task, X and Y coordinates of both the leading dot and the controlled dot were recorded and tracking deviation time series were analysed in two ways, in Cartesian and polar coordinates. Chapter 2 provides a detailed description of how these time series were derived. Once the time series were produced, they were epoched around each presentation of the oddball stimulus.

Spectral decomposition of motor cortex activation

The spectopo function (EEGLAB) was used to derive alpha and beta power spectral density (PSD) at both left (D19) and right (B22) electrode sites during the pursuit-tracking task, and target and non-target trials in the dual and single (oddball only) task. In case power changes occurred at smaller time scales, DTFTs were also computed for 6 time windows (0-200, 200-400, 400-600, 600-800, 800-

1000, and 1000-200 ms post stimulus onset) in each EEG epoch for all trial types. The spectopo function produced a single vector (power spectral density for each frequency ranging from 3-45 Hz) for each trial for both D19 and B22 electrodes. Mean alpha (7-13 Hz) and beta (14-30 Hz) power was calculated for each trial type for each electrode by averaging across all trials in the same condition.

Statistical Analysis

Statistical analysis for all measures were based on tests from the general liner model framework. Below I detail which tests were used for each measure in order to examine the effects of dual-tasking on single-task performance.

Oddball target detection accuracy: In order to test the effects of dual-tasking on the oddball task on a behavioural level, a paired-samples t-test was used in order to compare target detection performance between single and dual-task conditions. If target detection performance was to decline in the dual-task condition, then oddball task performance was interfered by the simultaneous pursuit-tracking task.

*ERP components:*P1, P2, and P3b ERP component amplitudes were compared between single and dual-task conditions using paired-samples t-tests. If P1 amplitude was to be decrease in the dual-task condition, then pursuit tracking would be shown to impede low-level stimulus processing. If P2 was to decrease, then pursuit tracking would be shown to reduce attention allocation to the process of template matching. Finally, if P3b was to decrease under dual-task conditions, then a reduction in attention allocation to response preparation processes would be inferred.

ERSP and fronto-parietal coherence: So as to test the effects of dual-tasking on parietal alpha power, frontal alpha/low-beta power, and the coordination of the fronto-parietal network, a repeated measures ANOVA with condition (single task, dual-task), stimulus (standard, target) and time bin (0 to 1000 ms in 20 time bins) were considered as main factors. For parietal alpha, if the power that is typically reduced during target processing (alpha ERD) was attenuated, then dual-tasking would be shown to interfere with the processing of spatial representations in WM and the preparing of a suitable response. As for frontal alpha/low-beta, if power was to be increased in the dual-task condition specifically after 500 ms following target onset, then the presence of pursuit tracking would be shown to increase the attentional demands associated with updating the target count. Finally, for fronto-parietal coherence, if dual-tasking was shown to reduce alpha coherence magnitude or phase, then the fronto-parietal network set up to maintain the performance of the oddball task would be shown to be hindered.

Pursuit-tracking: Pursuit tracking measures are reported in both cartesian and polar coordinates. For both, a repeated measures ANOVA with task (single, dual, motor-only) and time bin (0 to 1200 ms in 200 ms time bins) was used in order to compare vertical and horizonal tracking deviations (cartesian) and rho and theta tracking deviations (polar) in single task, dual-task, and motor-only conditions. For the cartesian analysis, a negative vertical deviation at a certain time would indicate that an individual presented spatial deviations on the vertical axis (above or below the leading dot), whereas deviations on the horizontal axis would reveal spatial deviations to the left or to the right of the leading dot. The timing of these deviations would reveal which, if any, the effects of a specific concurrent cognitive operation involved in the oddball task. Deviations in polar space were also analysed in the same way, however the measures rho and theta allow for the analysis of radial and angular deviations at specific time-points throughout the processing of oddball task stimuli. If theta was to assume a negative value at a certain time point, then the controlled dot could be considered to be lagging behind the leading dot, whereas a negative rho value would indicate that the controlled dot was positioned inside the trajectory set by the controlled dot. If values were to be positive in theta, then the controlled dot would be positioned further ahead than the leading dot, and a positive rho value would indicate that the controlled dot had extended beyond the boundary set by the leading dot. Again, the timing of such deviations would be informative as to the contributing cognitive operation in the decline in motor performance.

Modulations in motor cortex activity: It was expected that performing a motor task would reduce alpha and beta power over the left motor cortex (indicative of the involvement of the primary motor cortex in the coordination of positioning the controlled dot). A repeated measures ANOVA with hemisphere (left, right) and task (motor-only, single task standard and target, dual-task standard and target) as factors was used with alpha and beta power as the dependent measure (performed separately for each). If either alpha or beta ERD was to be reduced in the dual-task condition relative to the motor-only condition, then it would be demonstrated that the processes involved in the oddball task interfere with activations of the motor cortex

Results

Oddball target detection accuracy

A paired-samples t-test using an empirical logistic transformation (c=0.001) was conducted to compare target detection accuracy (%) in both single and dual-task conditions. Accuracy was greater in the single (*M*=72.17, *SD*=16.65) than dual-task condition (*M*=48.21, *SD*=20.39); *t*(23)= 2.81, *p*<.001. M1-M2 (back-transformed) = 0.78, CI [0.58 0.91].

ERP components

The effects of dual-tasking on the amplitude of P1, P2 and P3b difference waves were analysed using paired sample *t*-tests.

P1: For P1, the difference wave amplitude did not differ between single and dual task conditions (*t*(23) = 1.36, *p*=.19). As standard and target stimuli (unfilled and filled circles, respectively) differed in bottom-up stimulus characteristics such as brightness and contrast, a stimulus effect on P1 was expected regardless of task conditions. This difference was significant under both single-task (*t*(23) = 7.58, *p*<.001) and dual-task (*t*(23) = 4.43, *p*<.001) conditions.

P2: For P2, the difference wave amplitudes were smaller during dual tasking (*t*(23) = 4.02, *p*<.001).

P3b: For P3b, the difference wave amplitudes were also smaller during dual tasking (*t*(23) = 4.03, *p*<.001).

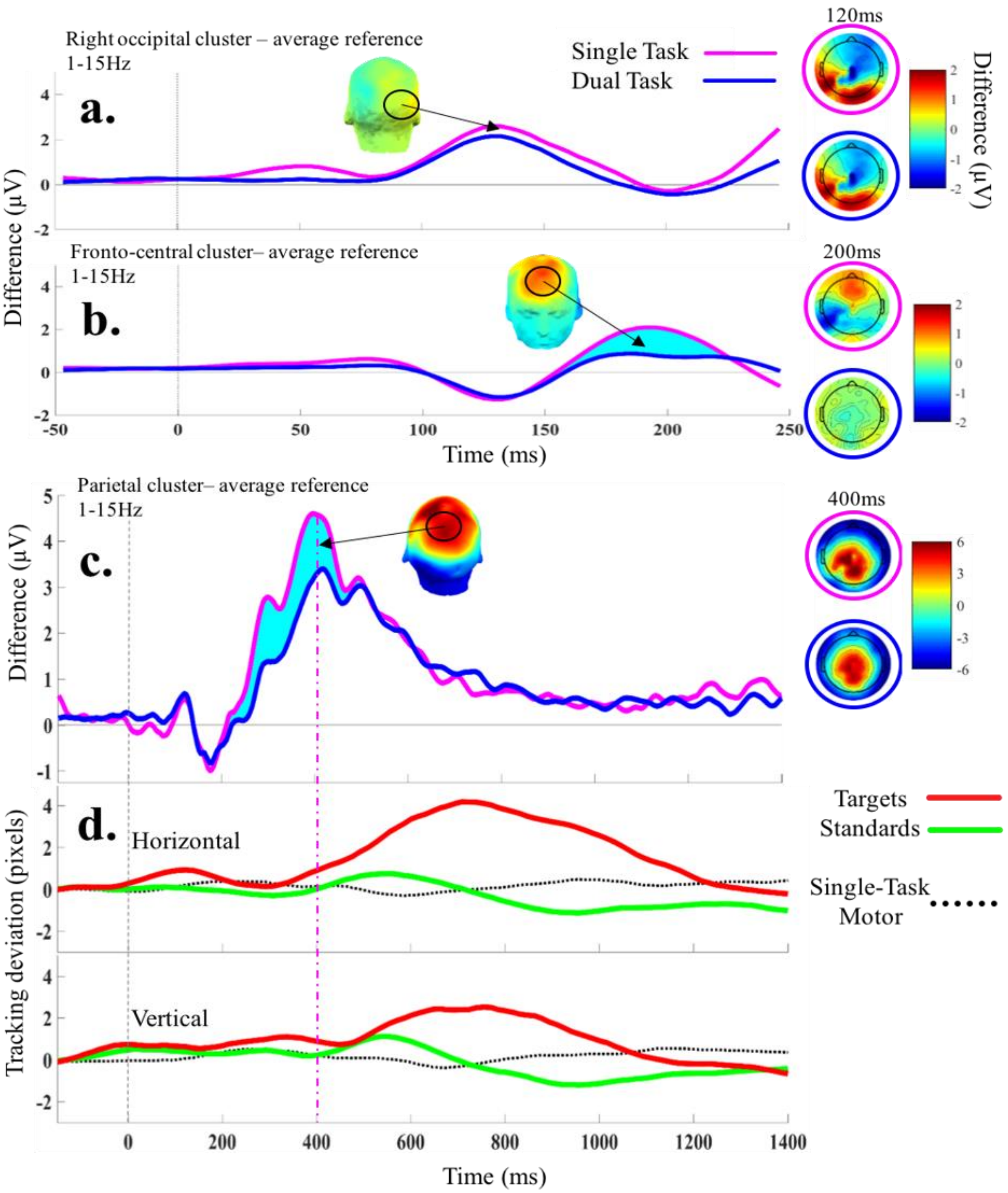

Figure 3.3. Event-Related Potentials. a-c: ERP difference waves derived from (a) right occipital, (b) fronto-central, (c) parietal electrode clusters, showing, respectively, P1, P2 and P3b waveform differences (target–standard) in single and dual task conditions. Areas shaded in blue show statistically significant differences. No significant differences between single and dual-tasks were found for P1 (a). Both P2 and P3b show statistically significant differences between single and dual-task difference waves (b, c). Scalp topographies are of difference waves at 120, 200, and 400 ms post stimulus-onset. (d) Epoched tracking in the horizontal (top) and vertical (bottom) axes. The dotted vertical line at ~400ms indicates mean P3b peak latency. Both vertical and horizontal tracking deviation increased for dual-task target trials in the 600-800 ms and 800-1000 ms periods.

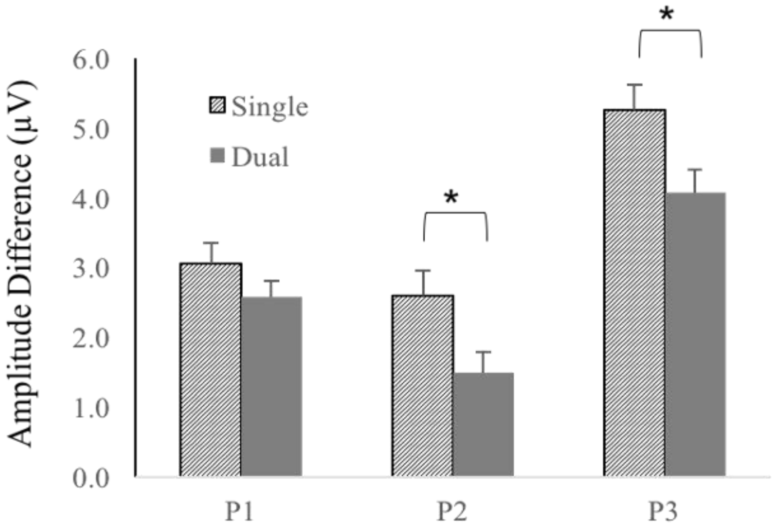

Figure 3.4. Component Amplitude Differences. (a) Mean P1, P2 and P3b ERP component amplitude differences (target-standard) for both single and dual task conditions. Both P2 and P3b difference wave amplitudes were significantly attenuated in the dual-task condition. Error bars show standard errors.

Relationship between P2 and P3b amplitude and tracking speed

As participants differed in their preferred tracking speed (speed ranged from 96 to 144 dps), correlations between P2 and P3b component amplitudes and tracking speed were performed, in order to investigate whether component amplitude was related to tracking speed . Neither P2 (*r*=.06, *p*=.77) nor P3b amplitude (*r*=-.07, *p*=.77) was significantly correlated with tracking speed.

Event-related Spectral Perturbations and fronto-parietal Coherence

Experimental effects on parietal and frontal alpha-band power, and fronto-parietal alpha-band amplitude and phase coherence were analysed using a 2 (Task: single, dual) x 2 (Stimulus: standard, target) x 20 (time) repeated measures ANOVA. Time bins were of 50 ms duration and spanned 0-1000 ms post stimulus onset. Frontal alpha/low-beta band power was analysed over the 550-1000 ms time period (as previously discussed).

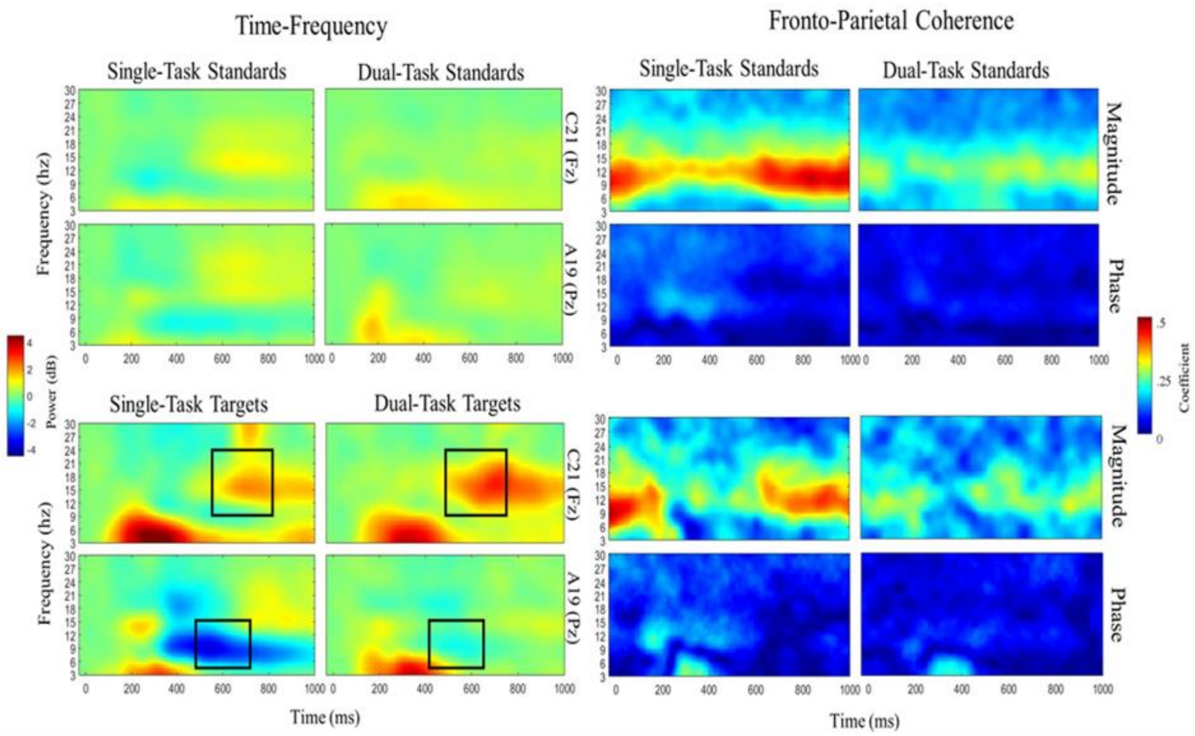

Figure 3.5. *Grand average time-frequency representation and fronto-parietal coherence. Left panels: spectral power changes (dB) as a function of time for standard (top) and target (bottom) trials at C21 (frontal) and A19 (parietal) electrodes; Right panels: event-related spectral coherence (ERSCoh) between C21 and A19 for standard (top) and target (bottom) trials. Parietal alpha desynchronization is shown for single-task target trials relative to dual-task target trials in the bottom two cells of the left panel. Frontal alpha synchronization for dual-task target trials relative to single-task can also be seen in the bottom left panel. Fronto-parietal alpha magnitude and phase coherence (right panel) can be seen to decrease during dual-task standard and dual-task target trials relative to single-task trials.*

Parietal alpha-band power

On parietal alpha-band power, there were significant main effects of task ($F(1, 23) = 4.75$, $p<.05$, $\eta_G^2= .031$), stimulus ($F(1, 23) = 70.13$, $p<.01$, $\eta_G^2= .021$), and time ($F(19, 437) = 20.62$, $p<.001$, $\eta_G^2= .132$), and significant task x stimulus ($F(1, 23) = 6.04$, $p<.05$, $\eta_G^2= .010$), task x time ($F(19, 437) = 3.48$, $p<.001$, $\eta_G^2= .013$), stimulus x time ($F(19, 437) = 12.51$, $p<.001$, $\eta_G^2= .038$), and task x stimulus x time ($F(19, 437) = 5.97$, $p<.001$, $\eta_G^2= .011$) interactions. As shown in Figs. 3.5 and 3.6, the desynchronization in the 450-650 ms period that was observed for target stimuli in the single task was attenuated in the dual task. There was no corresponding pattern in the case of standard stimuli.

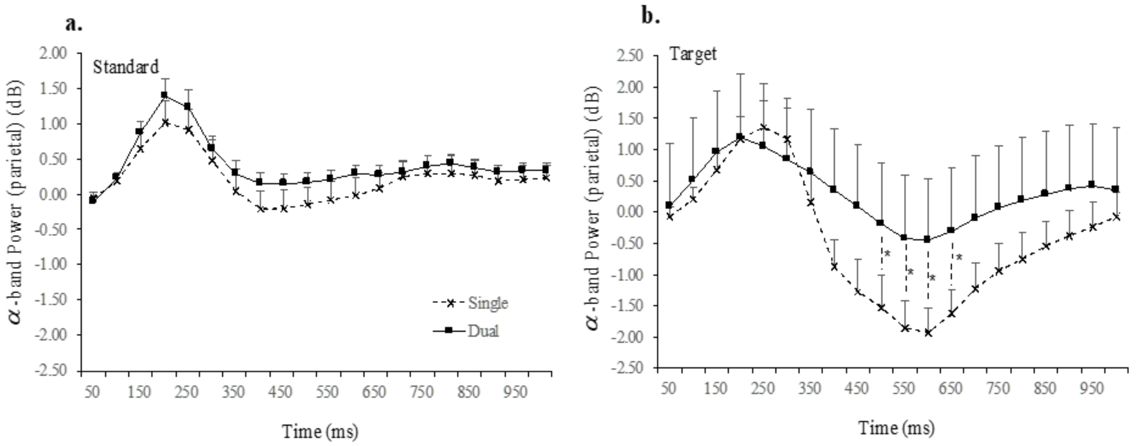

Figure 3.6. Parietal Alpha Power over Time. Mean parietal alpha power for standard and target trials in single and dual task conditions. (Bonferroni-corrected significant difference). Parietal alpha power decreases for single-task target trials (alpha desynchronization) in the 500-700ms period relative to dual-task targets. Error bars show standard errors.*

Frontal alpha-band power

On frontal alpha-band power, there were significant stimulus x time (*F*(9, 207) = 2.28, *p*<.05, $\eta_G{}^2$= .006), and task x stimulus x time (*F*(9, 207) = 3.17, *p*<.001, $\eta_G{}^2$= .005) interactions. Frontal alpha-band power was greater in the dual than single task for target stimuli, particularly in the 650-750 ms period (Figs. 3.5, 3.7). There was no corresponding difference for the standard stimuli.

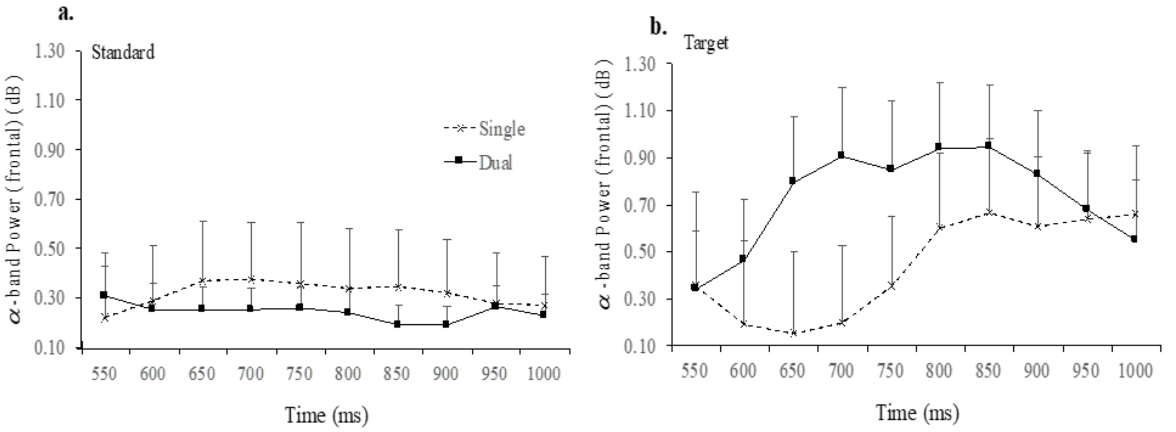

Figure 3.7. Frontal Alpha Power over Time. Mean frontal alpha power (dB) for both standard and target trials in single and dual task conditions at 10 time points from 550 to 1000 ms. Frontal alpha power increases for dual-task target trials (alpha synchronization) in the 650-750 ms period relative to single-task targets. Error bars show standard error.

Fronto-parietal alpha-band coherence

On amplitude coherence, there were significant main effects of task ($F(1, 23) = 31.99$, $p<.001$, $\eta_G^2= .014$) and time ($F(19, 437) = 6.25$, $p<.001$, $\eta_G^2= .011$), and significant interactions between task and time ($F(19, 437) = 2.72$, $p<.001$, $\eta_G^2= .037$) and stimulus type and time ($F(19, 437) = 2.17$, $p<.001$, $\eta_G^2= .003$). The time profile of amplitude coherence was similar in single and dual task, with a period of attenuation centred around 500 ms post stimulus-onset, but overall, coherence amplitude was lower during dual tasking (Figs. 3.5, 3.8a). In the case of phase coherence, there were main effects of task ($F(1, 23) = 13.29$, $p<.001$, $\eta_G^2= .004$), stimulus ($F(1, 23) = 59.11$, $p<.001$, $\eta_G^2= .016$) and time ($F(19, 437) = 10.01$, $p<.001$, $\eta_G^2= .017$), and significant task x time ($F(19, 437) = 1.79$, $p<.001$, $\eta_G^2= .015$) and task x stimulus x time ($F(19, 437) = 2.5$, $p<.001$, $\eta_G^2= .001$) interactions. The three-way interaction was due to the spike in phase coherence that occurred for target stimuli in the single task, but that was not matched during dual-tasking (Figs. 3.5, 3.8a).

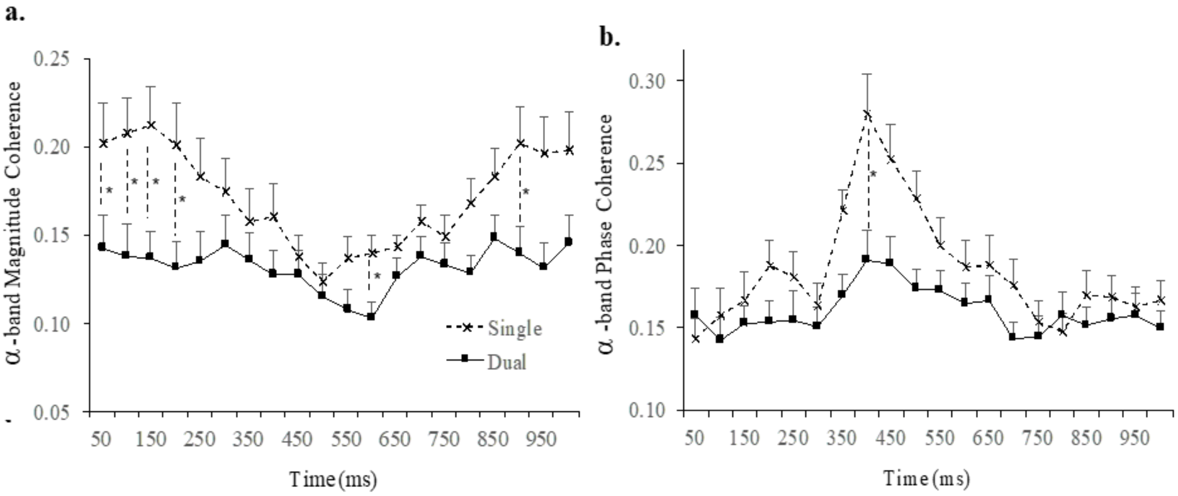

Figure 3.8. Fronto-Parietal Alpha Magnitude and Phase Coherence. Mean fronto-parietal magnitude (a) and phase (b) coherence for target stimuli in both single and dual task conditions at 20 time points from 50 to 1000 ms (Bonferroni-corrected significant difference). Fronto-parietal alpha magnitude and phase coherence are attenuated during dual-task target trials relative to single-task target trials. Error bars show standard errors.*

Visuomanual Tracking Deviation

Cartesian Analyses

Initially, analyses were performed in Cartesian coordinates (see Baker et al., 2018). Tracking deviation during the single and dual task conditions is shown on the timeline in Fig. 3.9). It can be seen that, in the dual-task trials that presented the target stimulus, the controlled dot developed a lead (positive deflection) over the lead dot in both the horizontal and vertical directions during the 600-800 and 800-1000 ms periods post stimulus-onset. Fig. 3.10 shows the spatial pattern of the controlled dot's trajectory in the single-task motor, and dual-task target- and standard-stimulus conditions by superimposing the deviation patterns onto the lead dot's position. The main figure shows that the controlled dot's trajectory deviates prominently in the dual-task, target-stimulus condition only. A magnified inset shows this deviation pattern in six representative participants.

Both the horizontal and vertical components of this deviation pattern were quantified using a 3 (task: motor-only single task, dual task with standard stimulus, dual task with target stimulus) x 6 (time: 0-

200, 200-400, 400-600, 600-800, 800-1000, 1000-1200 ms) repeated measures ANOVA. In the case of horizontal deviation, the main effect of task was significant ($F(2, 46) = 7.72$, $p<.001$, $\eta_G^2 = .097$), as was the main effect of time ($F(6, 138) = 4.44$, $p<.001$, $\eta_G^2 = .062$). The interaction between task and time was also significant ($F(12, 276) = 6.12$, $p<.001$, $\eta_G^2 = .058$). Comparison of means indicated that horizontal deviation in the dual-task target condition differed significantly from the other conditions in the 600-800 and 800-1000 ms time periods. In the case of vertical deviation, the main effect of time ($F(6, 138) = 3.18$, $p<.01$, $\eta_G^2 = .041$) and the interaction between task and time ($F(12, 276) = 2.72$, $p<.01$, $\eta_G^2 = .043$) were significant. In post-hoc means comparisons, however, there were no significant differences between conditions in any of the time windows.

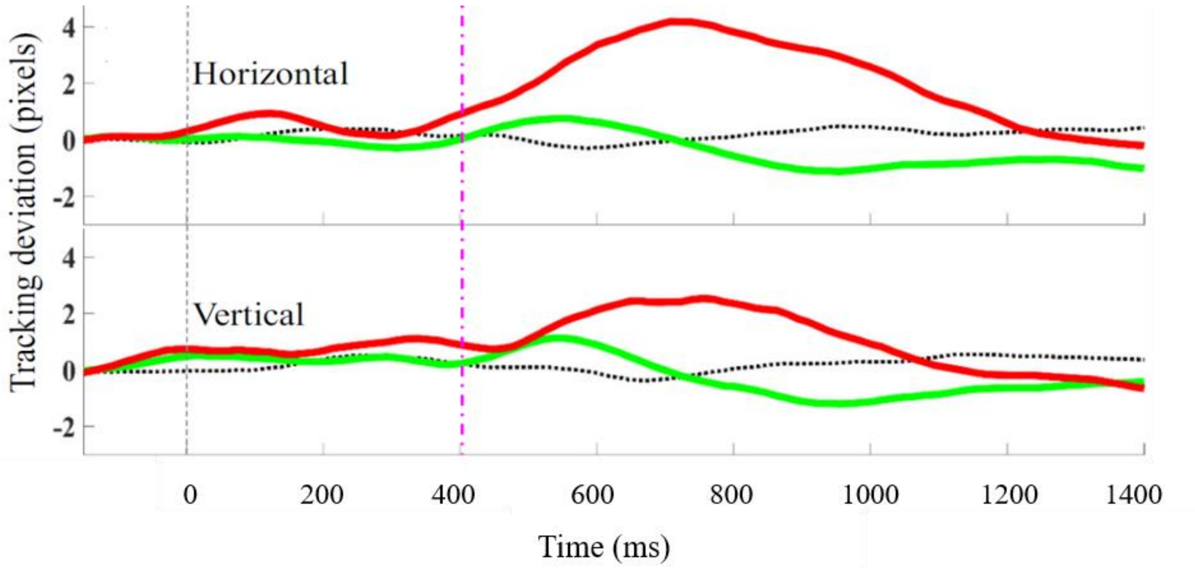

Figure 3.9. Tracking Deviations in Cartesian coordinates. Epoched tracking deviation (pixel difference between controlled and leading dots) in the horizontal (top) and vertical (bottom) axes. The dashed vertical line at ~400 ms indicates mean P3b peak latency. Both vertical and horizontal tracking deviation increased for dual-task target trials in the 600–800 ms and 800–1,000 ms periods. Tracking results are shown separately for the oddball task's standard and target trials and for the single-task condition in which participants only performed the tracking task.

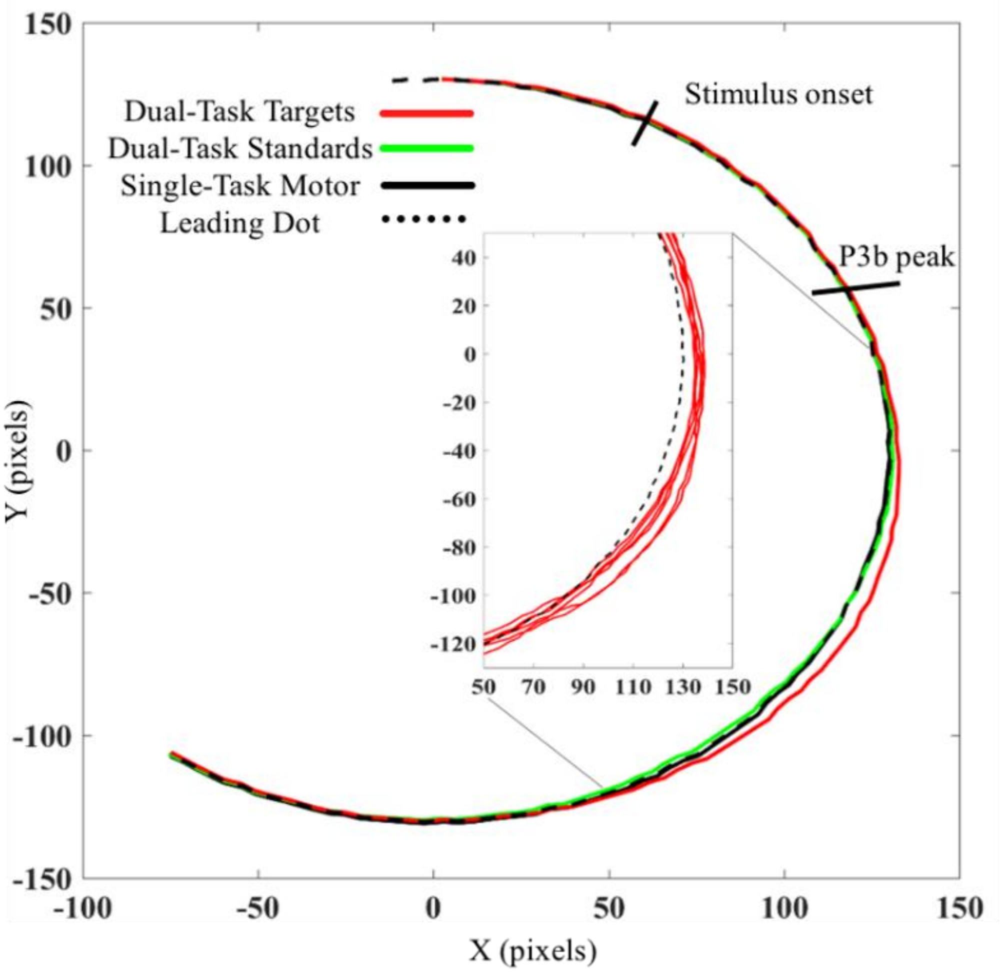

Figure 3.10. Spatial representation of tracking deviations. Grand average epoched horizontal (X) and vertical (Y) deviation (pixels) in the manual tracking task. Stimulus onset time and mean P3b peak latency are marked by black lines crossing the time series. The insert shows a magnified view of X and Y deviation for dual-task target trials for six representative participants. In the target trials, the controlled dot's trajectory extended beyond the circular trace of the lead dot, indicating that participants were impeded in their ability to keep their motion entrained to that of the lead dot.

Relationship between P3b amplitude and visuomanual tracking deviation

The dual-task target-stimulus condition produced a significant tracking deviation in the 500 ms time period following the P3b peak. As the P3b component corresponds to the recognition of the stimulus' task relevance, the observed trajectory deviation in fact occurred during the subsequent executive function of updating the target tally. To test whether tracking deviation may have been related to the P3b process, P3b peak amplitudes were correlated with the maximum horizontal and vertical tracking deviations that followed. Neither horizontal (r = .126, p=.56) nor vertical (r=-.06, p=.77) deviation were significantly correlated with the P3b peak amplitude.

Visuomanual Tracking Deviation: Polar Analyses

A limitation of analysing tracking deviation on a circular trajectory using Cartesian coordinates is that separable estimates for the angular lag (i.e., whether the controlled dot was ahead or behind the lead dot in terms of the angle subtended on a reference axis) and the radial deviation (whether the controlled dot deviated into or out of the circle defined by the lead dot) could not be obtained throughout each trial's epoch in the same way. A given set of horizontal and vertical deviation could result from different angular and radial deviations depending on the quadrant, and this resulted in the quadrant-specific calculations detailed in Chapter 2. This relationship was further complicated by the fact that trial epochs started and ended at different points (and hence traversed different quadrants) along the circular trajectory.

These issues were mitigated by analysing tracking deviation using polar coordinates whereby theta depicted the angular lag or advance and rho depicted the radial error. To examine the effects of stimulus type on both theta and rho deviations, a 3 (Task: motor-only, dual task standard, dual task target) x 5 (Post P3b-delay: 300,600,900,1200,1500 ms) repeated measures ANOVA was used. For theta, a significant main effect of time was found ($F(4, 92) = 6.73$, $p<.005$, $\eta_G^2= .227$), as was a significant interaction between task and time, which showed that target stimuli presented greater theta deviations than both standard and motor-only trials in the 300 and 600 ms post P3b delay periods. The theta deviations were positive, indicating an angular advance with respect to the lead dot's position (i.e., the controlled dot got ahead of the lead dot in angular terms). For rho, no significant main effects or interactions were observed.

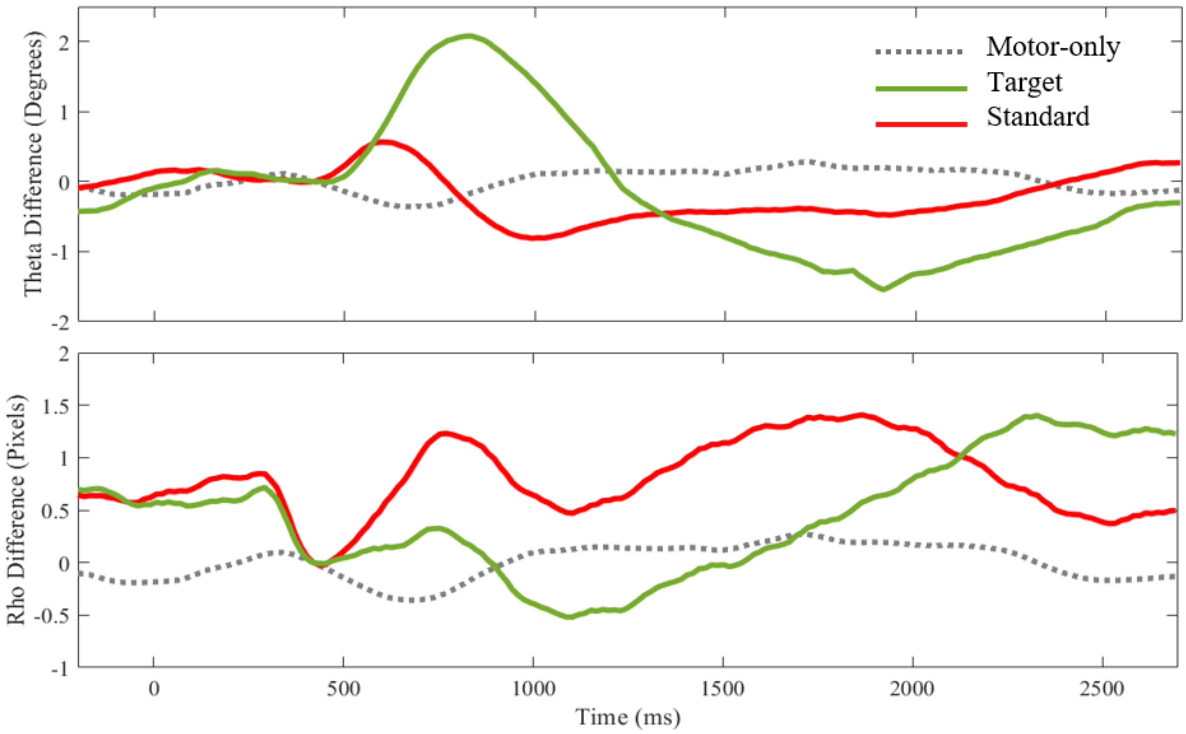

Figure 3.11. Tracking deviations in polar coordinates (theta, rho). The time series are zero normalized to the timing of the P3b peak (at 400 ms). Target-stimulus trials generated greater theta deviation than standard-stimulus trials and motor-only trials in the 700 to 1000 ms post stimulus-onset period.

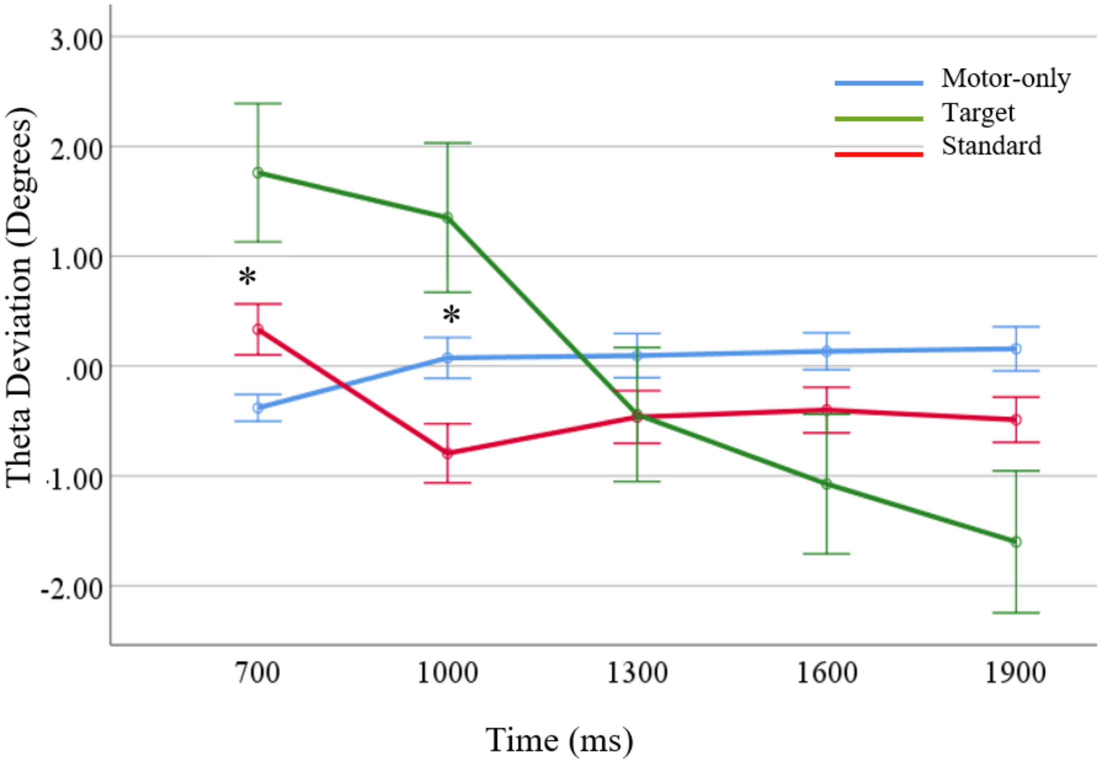

Figure 3.12. Theta deviation across the trial epoch for motor-only, standard-stimulus, and target-stimulus trials. The data are zero normalised to the timing of P3b. Significant differences were observed between target trials relative to motor-only and standard trials between 700 and 1000 ms post stimulus-onset). Error bars show standard error.

Polar Analyses: Pre P3b Period

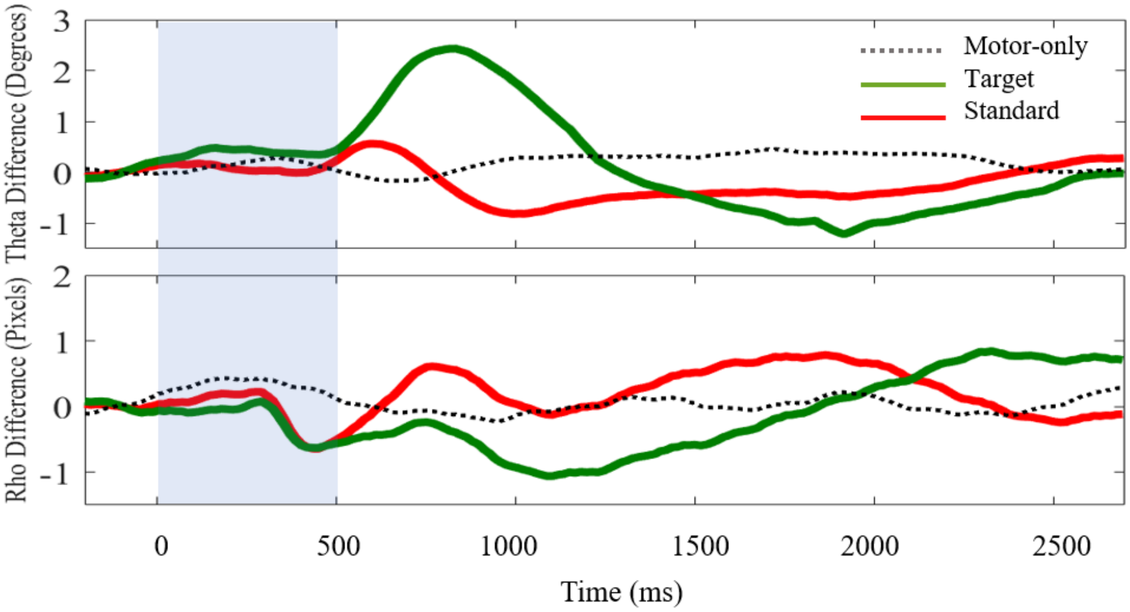

Figure 3.13. Rho/theta deviation time series with pre-stimulus baseline correction. The analysis period from 0-500 ms is shown shaded in blue.

In the case that tracking deviations manifested prior to P3b (i.e. when the additional load was present), a second analysis on rho/theta was conducted. Deviation time series were baseline corrected by calculating the mean of the deviation values in the pre-stimulus window for each condition, and removing said mean from each sample throughout the relevant epoch. Time series were subsequently separated into 100 ms bins, from time zero (stimulus onset) to 500 ms, and the means calculated within each bin, for each condition/stimulus. A 3 (stimulus: motor-only, dual task standard, dual task target) x 5 (time window: 0-100, 100-200, 200-300, 300-400, 400-500) repeated measures ANOVA was used, for rho and theta separately.

For theta, no main effects or interactions were found. For rho, a main effect of time was found (F,4,92)=6.60, p<.05, $\eta_G{}^2$= .015), whereby values at 500 ms presented more negative rho deviations than all other time periods. Note that the scale of this difference is in the order of sub-pixels.

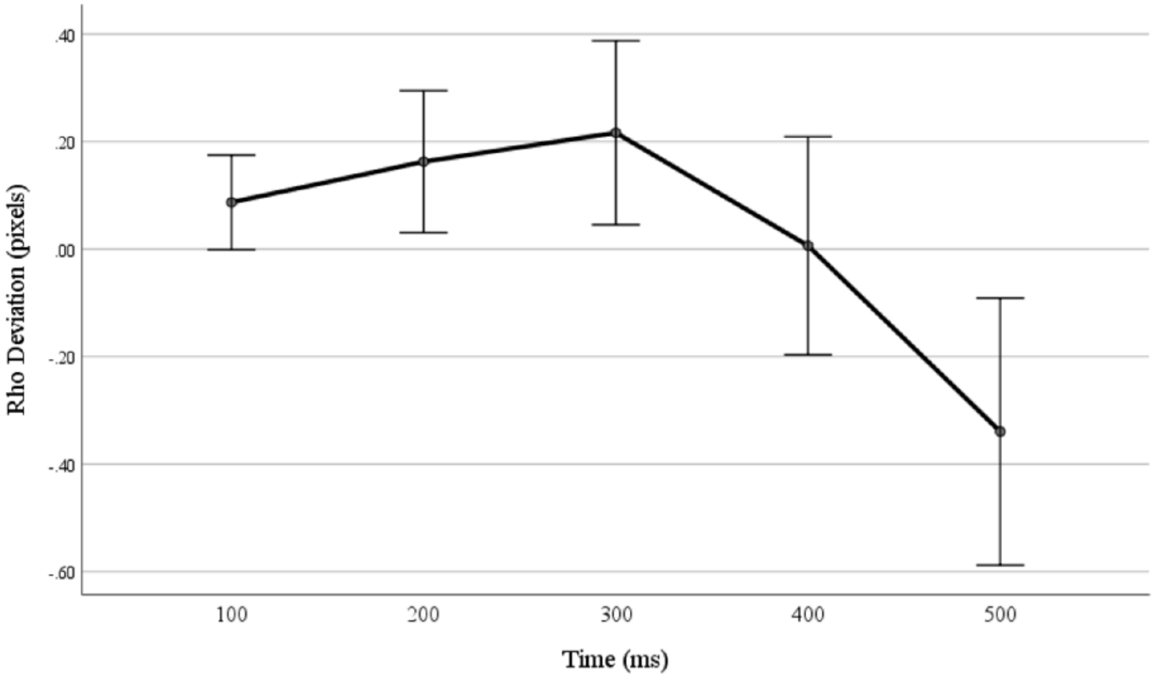

Figure 3.14. Rho Deviation over Time (Pre-P3b period). Rho deviations from 100 to 500 ms post stimulus onset for all trials. Values in the 500 ms period presented more negative rho values than the preceding time periods. Error bars show standard errors.

Effects of oddball task performance on spectral power over primary motor cortex

Visuomanual tracking occurred in three task conditions: motor-only, dual-task with the standard stimulus, and dual-task with the target stimulus. In these three conditions, It was expected that event-related desynchronization (ERD) would be observed over motor cortex relative to the single-task standard and target oddball conditions (where there was no motor activity). Additionally, recall that if performing the oddball task while tracking reduced motor resourcing, it was expected that less ERD (more spectral power) in the two dual-task conditions relative to the motor-only condition. Separately for alpha and beta power bands, a 2 (hemisphere: LH, RH) x 5 (task: single-standard, single-target, dual-standard, dual-target, motor-only) repeated measures ANOVA using absolute power as the dependent measure was used (Fig. 3.15).

For the alpha band (Fig. 3.15a), the main effects of hemisphere ($F(1, 23) = 14.09$, $p<.001$, $\eta_G^2 = .012$), and task ($F(4, 92) = 13.88$, $p<.001$, $\eta_G^2 = .092$) were significant, but the interaction between hemisphere and task was not. For the beta band also (Fig. 3.15b), the main effects of hemisphere

($F(1, 23) = 13.98$, $p<.001$, $\eta_G^2= .012$), and task ($F(4, 92) = 19.29$, $p<.001$, $\eta_G^2= .084$) were significant, but the interaction between hemisphere and task was not. As Fig. 9 indicates, spectral power over motor cortex was reduced (i.e., ERD occurred) in the three task conditions involving tracking. Post-hoc mean comparisons did not find differences between the dual-task and motor-only conditions in either band, which suggests that motor programming resourcing was not impacted as a result of concurrently performing the oddball task.

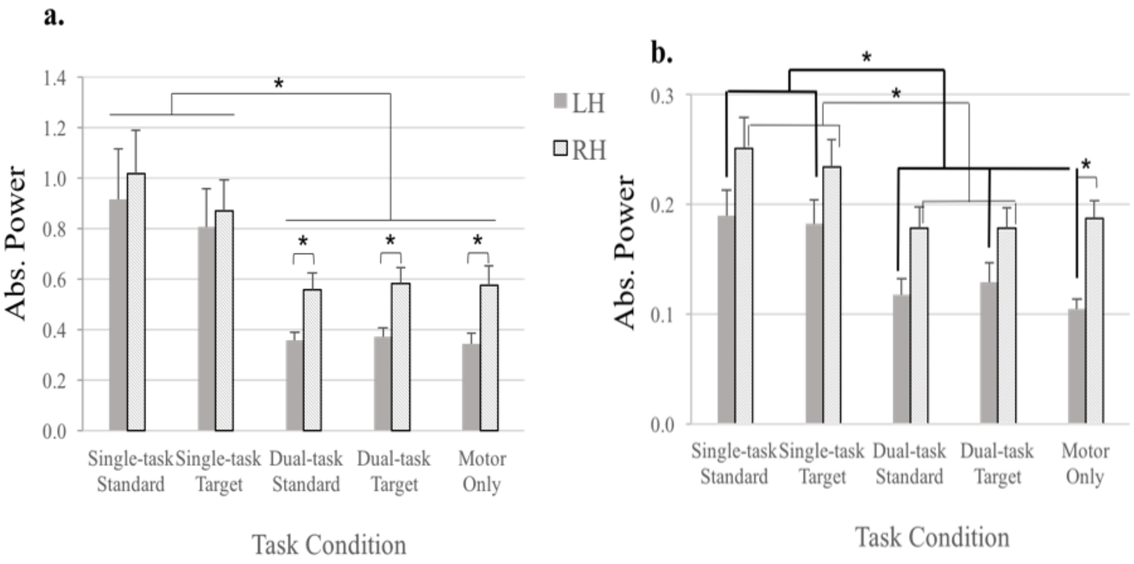

Figure 3.15. Alpha & beta-band power over motor cortices. Alpha (a) and beta (b) band power over left and right primary motor cortex during all single and dual task conditions. Power was attenuated in the dual-task and motor-task only conditions, indicating desynchronization linked to motor activity. Desynchronization was greater in LH (the motor task used the right hand), but did not differ in either frequency band between the dual-task and motor task-only conditions. Error bars show standard errors.

In case any power differences occurred over shorter durations and therefore could not be detected over the whole trial period, spectral power over left primary motor cortex (contralateral to the moving hand) using a 3 (task: motor-only, dual-standard, dual-target) x 6 (time: 0-200, 200-400, 400-600, 600-800, 800-1000, and 1000-200 ms) repeated measures ANOVA was used. There were no significant effects, indicating that spectral power over motor cortex did not change across the motor-only and dual-task standard and target conditions.

Discussion

The main aim of the current experiment was to assess the pattern of CMi during basic task settings. That is, without any load manipulations. Of specific interest was the timing and reciprocity of CMi across both cognitive and motor tasks when the demands of the cognitive task was to simply update a target count on detecting a salient target stimulus.

Performing the visual oddball task during visuomanual tracking reproduced performance deficits that are characteristic of dual-task interference. The participants made more errors in reporting the number of targets in the dual-task condition, and they also generated greater positional deviation in the tracking task, but only following the onset of target stimuli in the oddball task. Investigating these dual-task costs at the level of electrophysiological events generated significant new information, both about the possible selectivity of dual-task costs with respect to cognitive sub-processes, as well as asymmetry and asynchrony in reciprocal effects.

First, at around 100 ms, there was no dual-task effect on P1 component amplitude, confirming no effect of global attentional demands on P1 (Capizzi et al., 2013; Gherri & Eimer, 2010). Thus, there was no indication that tracking affected bottom-up perceptual processing of stimuli at this timescale. The stimulus effect (a larger P1 magnitude for the target stimulus which had greater contrast) under both single and dual task conditions also indicated that visual engagement in the tracking task did not compromise early-stage perceptual processing of the oddball stimulus. The P1 results suggest that the single and dual-task conditions were comparable in terms of participants' ability to visually detect the oddball stimulus. Note that participants' instructions throughout were to maintain eye-fixation at the centre of the screen region where task stimuli appeared. So, eye movements, such as pursuit of the leading dot during tracking, played a minimal role, if any.

At 200 and 300 ms post stimulus-onset, dual-tasking did affect top-down categorization/template-matching (P2) and task-relevance judgement (P3b) processes. The P2 component is thought to signify top-down processes involved in comparing the current stimulus to representations of previous ones, such as the templates of standard and target stimuli in this oddball task (Kim et al., 2008; Luck, 2005). The P3b is linked to the identification of the stimulus as a target, and hence its relevance to the response process (Luck, 2005; Polich, 2007). Attenuation of both component amplitudes during dual-tasking indicates that the resourcing of these top-down processes was compromised during concurrent performance of the tracking task. Attenuation of P3b has also been observed in other dual-task studies (Matthews et al., 2005; Pratt et al., 2011; Ross et al., 2018), demonstrating its susceptibility to the demands of concurrent tasks.

The results of time-frequency analysis of EEG corroborated the ERP evidence of reduced resourcing of the oddball task during dual-tasking. The comparatively rarer encounter with the target stimulus is a change in processing that should instigate a parietal alpha-band ERD around 400-600 ms post stimulus-onset (Sutoh et al., 2000). During dual-tasking, a significant reduction in this parietal ERD's magnitude in the 450-650 ms time bin (Fig. 3.5, bottom-left panel) was observed, indicating that the neural process of target identification was not as robust as in the single-task situation. This result was also reflected behaviorally in reduced target-detection accuracy in the dual-task condition. This reduction in alpha ERD could reflect changes in active cortical inhibition related to the additional demands of the pursuit tracking task.

In addition to the above, concurrent performance of the tracking task was also found to affect the strength of the fronto-parietal network (Corbetta & Shulman, 2002) that supports attention tasks such as oddball detection (Güntekin & Başar, 2010; Sadaghiani et al., 2012; Sauseng et al., 2006; Van Schouwenburg et al., 2017). The dual-tasking condition showed lower alpha-band magnitude and phase coherence between frontal and parietal networks, indicating that the large-scale cortical coordination that links bottom-up and top-down processes in attentional tasks was eroded when simultaneously performing the tracking task. Increased frontal alpha-band power in the dual-task condition was also obserbed, which confirms that overall WM load increased while dual-tasking relative to the single task, as has also been observed in imaging studies of cognitive-motor dual-task interference described in the introduction chapter (Doi et al., 2013; Holtzer et al., 2011; Leone et al., 2017; Meester et al., 2014).

These results show that concurrent visuomanual tracking had a negative impact on oddball task processes in the P2 and P3b time periods, suggesting that this type of CSC-cognitive dual-tasking reduces attentional resources available to the cognitive task. Reciprocally, however, no significant deviations in tracking accumulated during these time periods. Performing the tracking task reduced the accuracy of oddball target detection, which could have resulted from interference in the P2-P3b timescale (where the waveforms were magnitude-attenuated when dual-tasking) or later during the executive function of updating the tally, or both. In the reverse direction, the impact of oddball detection on tracking performance occurred only in the period after the P3b waveform, and then only in trials where the target stimulus was encountered. Moreover, the magnitude of tracking deviation was not correlated with that of the magnitude of the preceding P3b component. The fact that tracking deviation occurred only in the case of the target stimulus, which has also been observed previously (e.g., Gazes et al., 2010) and that its magnitude was unrelated to that of the preceding P3b, together preclude the possibility that an earlier, more general interference resulted in delayed effects in the post-P3b response stages. Rather, the observed pattern strongly suggests that it was the cognitive response triggered by the target stimulus (i.e., the executive function of updating the target tally) that interfered with tracking. In this sense, the updating process could be considered a (cognitive) perturbation to the tracking coordination. Note that the tracking errors observed following target stimuli amounted to a phase advance relative to the lead stimulus (Fig. 3.11), whereby the controlled cursor developed an angular advance relative to the lead cursor (i.e., its angular speed temporarily increased relative to the leading dot). This pattern suggests that the perturbation (due to the updating process in the target condition) differs from processes that resulted in pauses to tracking that were seen when postural perturbations were applied while visuomanual tracking was performed as a secondary task (McIlroy et al., 1999; Norrie et al., 2002). That is, a cessation of tracking performance was observed when postural perturbations were delivered, in contrast to an overcompensation in tracking performance observed here. This different could be due to the difference in nature of the perturbation (motor Vs. cognitive). For example, a motor perturbation may have been sufficient enough to completely stop performance in pursuit tracking, whereas a cognitive perturbation (as delivered in the current study), may have instigated a strategic compensation. Previous research has shown that reaction time to visual or auditory stimuli can be slowed when a perturbation is applied to a concurrent balancing function (e.g., Redfern et al., 2002). The angular advance seen here also represents a loss of entrainment to visual feedback, but by running ahead of it instead of falling behind. As the task did not allow any scope for accommodating resource demands by slowing down the tracking task's performance (as is often possible in driving or walking), the phase advance may have been a compensation strategy. That is, participants anticipated that they would become distracted and may potentially lag behind, and compensated by advancing ahead of the leading dot.

The interference pattern observed here shows that simply documenting reciprocal performance deficits at the behavioural level is not sufficient for understanding the micro-structure of interference between a CSC and a concurrent cognitive task. It is possible that, as in the present task combination, the CSC impacts the attentional components of the cognitive task, but it is an executive function component of the cognitive task that impacts the CSC. Also, these directional influences can occur at different times in the information-processing sequence. Such a finding was made possible in this study by the use of a multi-component cognitive task, and the deployment of neurophysiological methods to resolve interference effects to the specific time-scales of task components. The possibility or significance of such asymmetric and asynchronous CSC-cognitive interference has never been highlighted in the large and growing dual-tasking literature on everyday CSCs (e.g., driving, gait, or balancing). This is despite the fact that the vast majority of everyday cognitive tasks performed alongside common CSCs involve perception, attention, and executive functions, as well as a motor response in some cases.

Even using highly controlled laboratory tasks, it is rarely possible to ensure that the cognitive task only taps a single cognitive sub-process such as attention or EF. Everyday cognitive activities almost always combine a number of sub-processes. In addition, multiple simultaneous task demands activate executive attention processes that dynamically adjust cognitive resource allocation (Ridderinkhof et al., 2004). In the present study, performing the CSC alongside the oddball task evidently put pressure on available attentional resources, as indicated by attenuated P2, P3b, and parietal alpha-band ERD. However, this did not have a reciprocal effect on CSC performance in the same timescale. Thus, reduced resourcing of the cognitive task rather than the CSC was the preferred solution for dual-task demands at that timescale. This pattern is also seen in the context of whole-body CSCs such as gait or balancing, where priority is normally given to CSC maintenance at the expense of cognitive performance (e.g., the 'posture-first' principle) (Bloem et al., 2001). Although, this strategy is stable for healthy young adults, in older people, particularly neurological patients, prioritization in the face of dual-task pressure does not always favour the CSC (Yogev-Seligmann et al., 2008). Parkinson's (Bloem et al., 2001) and stroke patients (Huitema et al., 2006) may prioritize the secondary task over gait or balancing, and even healthy older adults can prioritize their planning of future stepping at the risk of losing balance (Chapman & Hollands, 2007). In this study, close inspection of the electrophysiological events associated with multiple cognitive sub-processes enabled the observation that CSC performance was maintained at the expense of resourcing the attentional component of the cognitive task in the 200-400 ms timescale, but this was not evident at the timescale of the EF component of the oddball task.

As previously outlined, there is converging evidence that CSC stability is most consistently impacted by concurrent EF tasks. Even though CSC performance in the present study remained unperturbed as the oddball task's attentional sub-processes came under resourcing pressure, CSC errors did occur later during the EF sub-process of the same task. As the present task setting did not allow strategic adaptations (e.g., reducing CSC speed), or utilization of the kind of error tolerance that is inherent in everyday CSCs such as driving or walking, it provided strong evidence that concurrent demands for EF operations may be at the heart of CSC-cognitive interference. There is not a universally accepted list of the types of cognitive operations that comprise EF. In the context of CSC-cognitive dual-tasking, Yogev-Seligmann et al., (2008) identified volition (formulating goals, initiating action), self-awareness, planning (identifying and organizing sub-tasks), response-inhibition (disregarding irrelevant information), response-monitoring (detecting errors with respect to task goals) and attention allocation (distributing available cognitive resources among competing demands) as aspects of EF. An alternative to this functional approach has been to associate EF with specific operations performed on information held in WM. Miyake and colleagues (Miyake et al., 2000; Miyake & Friedman, 2012) have proposed, for example, that EF involves updating (monitoring and altering WM contents), shifting (moving resources between task sets) and inhibition (suppressing effects of irrelevant information).

In terms of the latter approach, the EF component of the covert oddball task used in the present study was updating (the tally of target stimuli detected). CSC-cognitive dual-tasking studies have frequently addressed shifting (e.g., slowing down the CSC to accommodate cognitive operations) and inhibition (e.g., using Stroop tasks), but the effects of updating operations on concurrent CSC's performance have not been highlighted. It might be that detecting the impact of updating was only made possible by severely curtailing the opportunity for shifting (by preventing speed variation). Updating task-relevant information in WM is patently ubiquitous in everyday cognitive activity. Indeed, shifting between task sets must also involve large-scale updating of which information is currently task-relevant, and even inhibition is only possible when the current task-relevance of information is kept updated. Even as updating processes are recognized as fundamental to performing or switching between cognitive tasks, it is worth noting that frequently updating the state is also fundamental to the maintenance of any CSC. This form of state-updating must integrate sensorimotor information on a grand scale, be tailored to the current task goals held in WM, and, importantly, maintain a high enough frequency to ensure CSC stability or counteract perturbations to it. It is highly plausible that pre-frontal cortex activity detected during CSCs, such as walking (Harada et al., 2009; Suzuki et al., 2004), is associated with state-updating. The extent to which updating operations can be performed simultaneously with respect to more than one task could be a key point in understanding CSC-cognitive interference, and indeed, dual-task interference more generally. It has been shown that just like CSC-cognitive dual-task performance, updating performance in EF tasks also declines with age (De Beni & Palladino, 2004). The current results suggest that future research should focus on the possibility that the EF of updating is at the heart of CSC-cognitive interference.

Chapter 4: Experiment 2: The effects of executive function load on concurrent sensorimotor coordination

Introduction

The experiment presented in chapter 3 highlighted an asymmetric pattern of interference between the cognitive (oddball) task and the motor (pursuit tracking) task. The tracking task modulated cognitive processing as early as element 2 (template matching), while significant perturbations to tracking performance did not manifest until element 4 (target count updating) of the oddball task. As the tracking deviation occurred in the post-P3b period, and its level did not correlate with P3b magnitude, the tallying of detected oddball targets appeared to be the cognitive task component that interfered with the tracking task. To test this interpretation further, the experiment reported in this chapter manipulated the cognitive load associated with the updating element of the oddball task.

The successful updating of the target count is an executive function (EF) that involves maintaining the current count in WM, identifying the stimulus as a target, and changing the count according to the specified rule (Miyake & Shah, 1999). Both frontal and parietal processes support operations involved in the manipulation of numerical information. Frontal processes contribute to retrieval and updating (Delazer et al., 2003; Kazui et al., 2000) and parietal processes play an important role in calculations (Woo et al., 2009). Behavioural studies have reported longer reaction times for calculations with a greater ‘problem size’ (Ashcraft, 1992; Groen & Parkman, 1972). The magnitude of the calculation (e.g., adding five rather than adding two), determines the speed at which the calculation is performed (i.e., adding a larger number requires a more complex manipulation than adding smaller numbers, resulting in longer response times). Posner (1964) quantified the processing demands of a numerical manipulation task in information-theoretic terms as the amount of *information reduction* required to perform the calculation–task difficulty (i.e., processing demand) is proportional to the magnitude of information reduction (Posner & Rossman, 1965). The magnitude of information reduction in bits represents the availability of correct answers amongst the number set. For example, subtracting by seven has fewer correct outcomes than does subtracting by three.

The amount of information reduction is the difference between the quantity of information contained in the original population of numbers (say, for example, 0-80), and the quantity of information in the available set of correct answers. Repeatedly deducting three requires the selection of a third of the original information. The amount of information in a number population of 80 is $\log_2 80 = 6.321$ bits. The amount of information in the population of available answers (e.g. a third of the population) is therefore a third of the information in the original set, given as $(\log_2 80)/3 = 2.107$. Therefore, the operation involves the reduction of 4.21 bits of information. This reduction is greater (and more resource-intensive) than deducting two, where the information reduction level is only 3.16 bits.

Information reduction tasks (such as mental subtraction) have been used previously in motor-cognitive interference studies (Pellecchia & Turvey, 2001; Pellecchia, 2003), where a higher level of information reduction required by the cognitive task results in greater performance deficits in the motor task. As the aim of the current experiment was to increase the EF load associated with updating the target count, a subtraction task with two levels of information reduction (high load, 4.21 bits, and low load, zero bits) was chosen as the target-tallying task. As this manipulation only changed what was to be done once a target stimulus was detected, and did not affect the difficulty of detecting the target, it was not expected to directly impact the attentional load associated with elements 2 (template-matching) and 3 (response-relevance acknowledgement) of the oddball task. However, there was a possibility that increasing the difficulty of the tallying task could indirectly affect the earlier stages of the oddball task. First, participants could rehearse the current tally, or pre-calculate the new value in advance of identifying the stimulus as a target. Second, participants could reserve cognitive capacity in anticipation of the stimulus being a target and demanding EF resources. To mitigate these possibilities, the load was kept lower than typically used in information reduction tasks (subtraction by one or three rather than, for example, by three or seven as in Pellecchia, 2003).

It was recognised that increasing the required level of information reduction could lower accuracy (due to the increased cognitive load of tallying even though the load involved in identifying the stimulus as a target did not change). If reductions in P1, P2 or P3b amplitude occurred in the higher EF load condition, the manipulation would have affected the attentional requirements associated with identifying the target. If no such attenuation occurred, then it could be argued that target detection was unaffected, and the reduction in accuracy (if observed) was due to the increased load of the tally-updating operation. Based on Chapter 3's results, it was also hypothesised that increasing the difficulty of the post target-identification element of the oddball task would amplify the tracking deviations occurring in the post-P3b timeframe. It was also expected that tracking deviations would remain confined to the post target-identification timeframe as observed in Chapter 3.

Regarding the tracking task's effect on the oddball task, given the findings of Chapter 3, it was hypothesized that P2 and P3b amplitude (but not P1), and parietal alpha-band desynchronization would be attenuated during dual-tasking, and that this attenuation would not be modulated by the tallying task's difficulty. Given that the WM demands of the updating operation would be greater in the higher EF load condition, it was hypothesized that this condition would increase frontal alpha/low-beta power, as would the added load of dual-tasking itself. For fronto-parietal coherence, it was hypothesized that dual-tasking would again attenuate both magnitude and phase coefficients, and that this attenuation would be confined to time periods prior to element 4. It was unclear as to how the modulation of tallying difficulty would impact the fronto-parietal network involved in the task, but it was predicted that there would be no effect of EF load on coherence measures if the network measured is associated with the processing of the oddball task stimulus, and not the subsequent target-tally updating operation.

Methods

The methodological details general to all the reported experiments are provided in Chapter 2. Information specific to this experiment is provided in this section.

Participants

The participants were 24 self-reportedly right-handed adults (13 males; mean age = 28.6, SD=3.54, range 24-38), with normal or corrected to normal vision, no current prescribed medication, and no history of sensorimotor or cognitive deficits. They were recruited through a research participation scheme, and compensated with research credits. The participants gave informed consent before the session, and were fully debriefed following data collection. Ethical approval for the research reported in this paper was granted by the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee.

Tasks

Participants first completed the motor configuration task described in the general methods chapter. Following the selection of an appropriate tracking speed, participants were then subject to the visual oddball task (high and low EF load condition blocks separately), the tracking task, and the dual task (high and low EF load blocks separately), in a counterbalanced order.

Oddball task

The participants fixated at the centre of the screen while a sequence of shaded (target) or non-shaded (standard) circles (r = 100 pixels) were presented, centred on the fixation cross. These stimuli were presented for 200 ms, with an ISI of 2500 +/- 100 ms. The ratio of target to standard stimuli was 1:4, and there were at most 12 targets presented in each block (the number of trials per block varied between 40 and 60). Participants were presented with a random integer between 65 and 95 at the beginning of each block and were asked to keep deducting one or three (low EF or high EF load blocks respectively) every time they detected a target stimulus. There were 5 blocks of trials in both low and high EF load conditions. At the end of each block, participants were asked to enter the integer that they arrived at via a keypress. This response was logged, as were the EEG data.

Dual Task

The participants performed the oddball task (both low EF and high EF load variants) whilst also performing the visuomanual tracking task. Five blocks of each variant were presented. Each block of trials started with the leading and controlled dots in an overlapping position. As the leading dot started moving, and the oddball task got under way, the participants’ task was to maintain the positional overlap between the dots while performing the oddball task. The coordinates of the controlled and leading dots, the target count and the EEG data were recorded.

Statistical Analysis

Statistical analysis for all measures were based on tests from the general liner model framework. Below I detail which tests were used for each measure in order to examine the effects of dual-tasking on single-task performance and the influence of the load of the updating operation.

Oddball target detection accuracy: In order to test the effects of dual-tasking and the loading of the updating operation on the oddball task on a behavioural level, a repeated measures ANOVA with task (single, dual) and load (low, high) as factors was used. If dual-tasking was to impede oddball task performance, then a reduction in accuracy would be observed. It was also possible that the higher load condition would reduce accuracy in the oddball task, as the updating operation was made more difficult.

ERP components: P1, P2, and P3b ERP component amplitudes were compared using a repeated measures ANOVA with task (single, dual), stimulus (standard, target) and load (high, low) as factors. If P1 amplitude was to be reduced in dual-task conditions, then it would be inferred that pursuit tracking attenuated low level visual processing. It was also possible that the loading of the updating operation could modulate P1 amplitude, though this was not predicted as the load was intended to stress later processing operations. If P2 was to be reduced during dual-tasking, then it was inferred that attentional resources dedicated to categorising a stimulus was reduced. Again, it was possible that the updating load would modulate P2, however this was not predicted given that P2 is associated with categorising the stimulus and not with updating the target count. Finally, if P3b was to be attenuated, then it was inferred that attentional resources dedicated to response preparation was reduced. It was possible that the load manipulation introduced here could impact P3b amplitude, given that individuals could organise attentional resources in anticipation of a more difficult calculation.

ERSP and fronto-parietal coherence: So as to test the effects of dual-tasking and the updating load on parietal alpha power, frontal alpha/low-beta power, and the coordination of the fronto-parietal network, a repeated measures ANOVA with condition (single task, dual-task), stimulus (standard, target), load (high, low) and time bin (0 to 1000 ms in 20 time bins) were considered as main factors.

For parietal alpha, if the power that is typically reduced during target processing (alpha ERD) was attenuated, then dual-tasking would be shown to interfere with the processing of spatial representations in WM and the preparing of a suitable response. The introduced load could have potentially modulated parietal alpha ERD, given that individuals could organise attentional resourcing in anticipation of a more difficult calculation. As for frontal alpha/low-beta, if power was to be increased in the dual-task condition specifically after 500 ms following target onset, then the presence of pursuit tracking would be shown to increase the attentional demands associated with updating the target count. It was expected that an increased loading of the updating operation would modulate frontal alpha/low-beta ERS, in that an increase in power would be observed. Finally, for fronto-parietal coherence, if dual-tasking was shown to reduce alpha coherence magnitude or phase, then the fronto-parietal network set up to maintain the performance of the oddball task would be hindered. It was also possible that the more demanding variant of the updating operation would significantly modulate the behaviour of the fronto-parietal network.

Pursuit-tracking: Pursuit tracking measures are reported in polar coordinates in two separate analyses. The first analysis baselines the tracking timeseries at the timing of the P3b peak, whereas the second analysis using a pre-stimulus baseline. A repeated measures ANOVA with task (single, dual, motor-only), load (high, low) and time bin (300, 600, 900, 1200, 1500 ms post P3b) was used in order to compare rho and theta tracking deviations in single task, dual-task, and motor-only conditions under different loads in the first analysis. For the second analysis, the factors remain the same, however with 5 time bins (from 0 to 500 ms in 100 ms bins). Rho and theta allow for the analysis of radial and angular deviations at specific time-points throughout the processing of oddball task stimuli. If theta was to assume a negative value at a certain time point, then the controlled dot could be considered to be lagging behind the leading dot, whereas a negative rho value would indicate that the controlled dot was positioned inside the trajectory set by the controlled dot. If values were to be positive in theta, then the controlled dot would be positioned further ahead than the leading dot, and a positive rho value would indicate that the controlled dot had extended beyond the boundary set by the leading dot. The timing of such deviations would be informative as to the contributing cognitive operation in the decline in motor performance.

Modulations in motor cortex activity: It was expected that performing a motor task would reduce alpha and beta power over the left motor cortex (indicative of the involvement of the primary motor cortex in the coordination of positioning the controlled dot). A repeated measures ANOVA with hemisphere (left, right), load (high, low), and task (motor-only, single task standard and target, dual-task standard and target) as factors was used with alpha and beta power as the dependent measure (performed separately for each). If either alpha or beta ERD was to be reduced in the dual-task condition relative to the motor-only condition, then it would be demonstrated that the processes involved in the oddball task interfere with activations of the motor cortex. If alpha or beta ERD was to be modulated by the updating operation load, then it would be demonstrated that the updating load interfered with motor cortex activation.

Results

Oddball Target Detection Accuracy

To test the effects of dual-tasking and EF load on target detection accuracy, a 2 (Task: single, dual) x 2 (EF load: high, low) repeated measures ANOVA was used. There were no significant effects of task or EF load on oddball detection accuracy. The numerical trend was in the direction of lower accuracy during dual tasking.

ERP Components

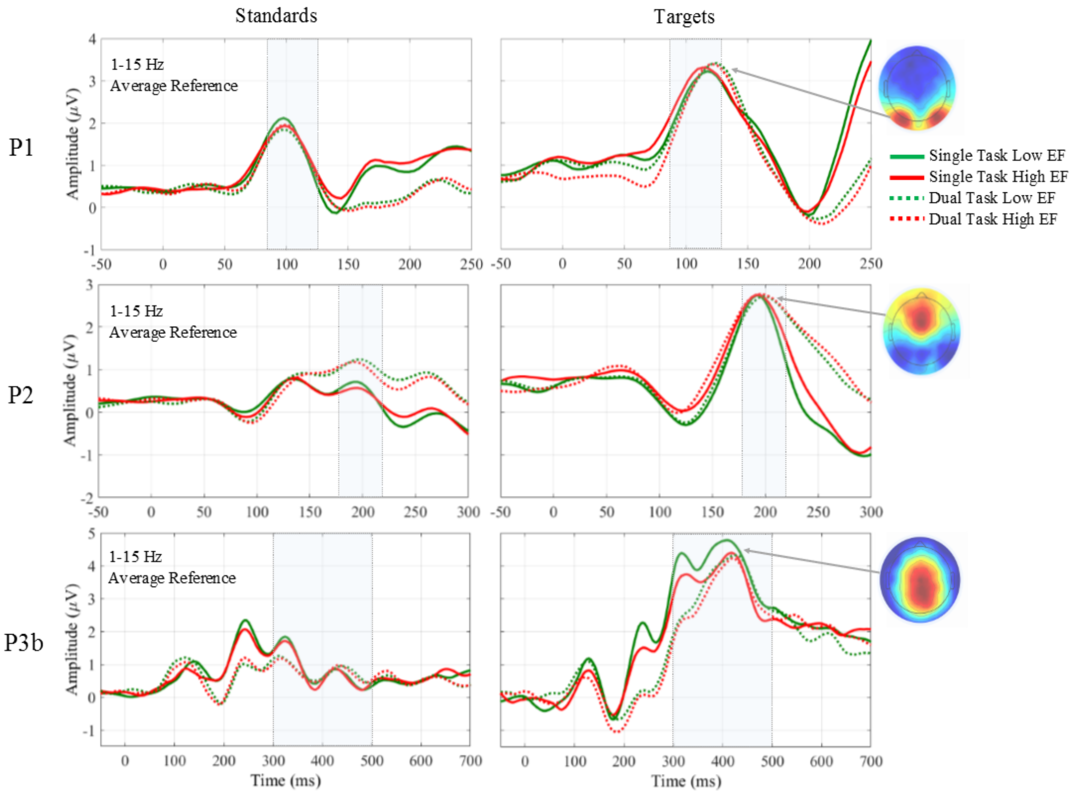

Figure 4.1. ERP component waveforms for P1, P2 and P3b for standard (left) and target (right) stimuli for single and dual task, and low and high EF load conditions. Waveforms are average referenced and show 1-15 Hz (for display purposes, amplitude values for statistics were derived from data between 1 and 50 Hz). Also shown are grand average scalp topographies for each ERP component. No significant differences between single and dual-tasks were found for P1. Both P2 and P3b show statistically significant differences between single and dual-task trials for target stimuli (dual-tasking reduced component amplitude). Only P3b showed an effect of EF load (higher EF load reduced P3b amplitude during target trials).

The effects of dual-tasking and EF load on the amplitude of P1, P2 and P3b component waveforms were analysed using a 2 (Stimulus: standard, target) x 2 (Task: single, dual) x 2 (EF load: high, low) repeated measures ANOVA.

P1: The main effect of stimulus was significant [$F(1,23) = 9.69$, $p<.01$, $\eta_G^2 = .06$; P1 amplitude was greater to the higher contrast target stimulus (Fig. 4.2)].

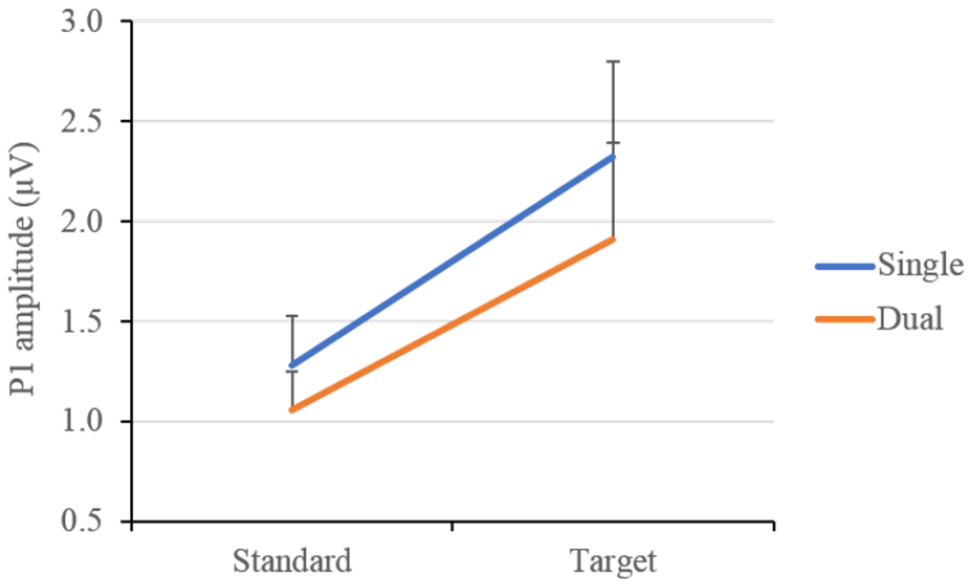

Figure 4.2. Grand average P1 amplitude condition means for standard and target trials in single and dual tasks. Target stimuli resulted in higher P1 amplitude than standard stimuli. There were no dual-task effects on P1 amplitude.

P2: The main effect of stimulus was significant [$F(1,23) = 43.29$, $p<.001$, $\eta_G^2 = .21$; P2 amplitude was greater to the target stimulus]. The interaction between task and stimulus was also significant [$F(1,23) = 6.10$, $p<.05$, $\eta_G^2 = .01$; P2 amplitude was greater to the target than standard stimulus in both the single and dual tasks, but the difference was reduced in the dual task condition (Fig. 4.3)].

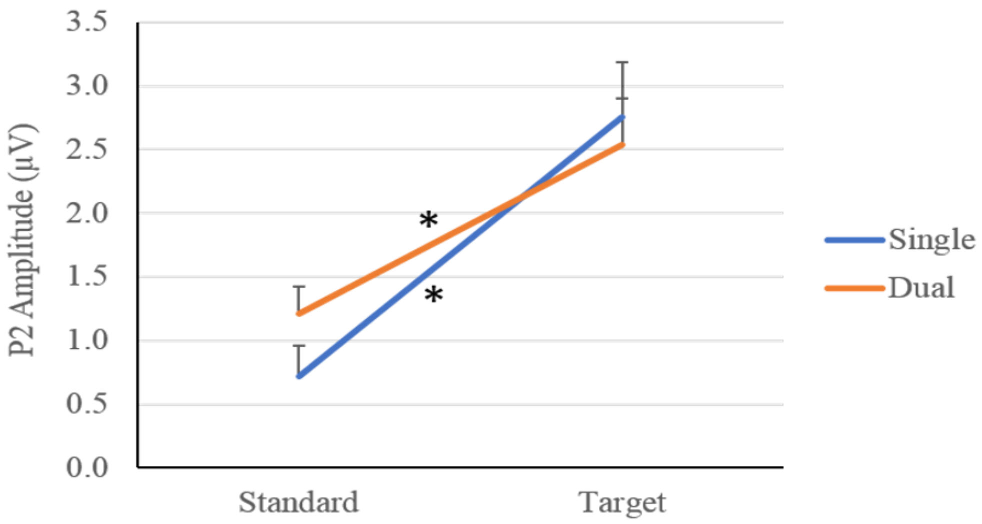

Figure 4.3. Grand average P2 amplitude condition means for standard and target trials in single and dual tasks. P2 amplitude was greater to the target than standard stimulus in both the single and dual tasks, but the difference was reduced in the dual task condition.

P3b: The main effect of task [$F(1,23) = 5.50$, $p<.05$, $\eta_G^2 = .03$; P3b amplitude was reduced during dual tasking], stimulus [$F(1,23) = 86.25$, $p<.001$, $\eta_G^2 = .48$; P3b magnitude was greater to the target stimulus] and EF load [$F(1,23) = 9.70$, $p<.01$, $\eta_G^2 = .007$; P3b magnitude was smaller when EF load was high] were significant. The interaction between task and stimulus was also significant [$F(1,23) = 6.78$, $p<.05$, $\eta_G^2 = .008$; P3b amplitude was higher for the target than standard stimulus in both task conditions, but for the target stimulus only, dual-tasking reduced P3b amplitude (Fig. 4.4, left)]. The interaction between EF load and stimulus was also significant [$F(1,23) = 5.38$, $p<.05$, $\eta_G^2 = .002$; P3b amplitude was greater for the target than standard stimulus in both EF load conditions, but for the target stimulus only, higher EF load reduced P3b amplitude, (Fig. 4.4, right)].

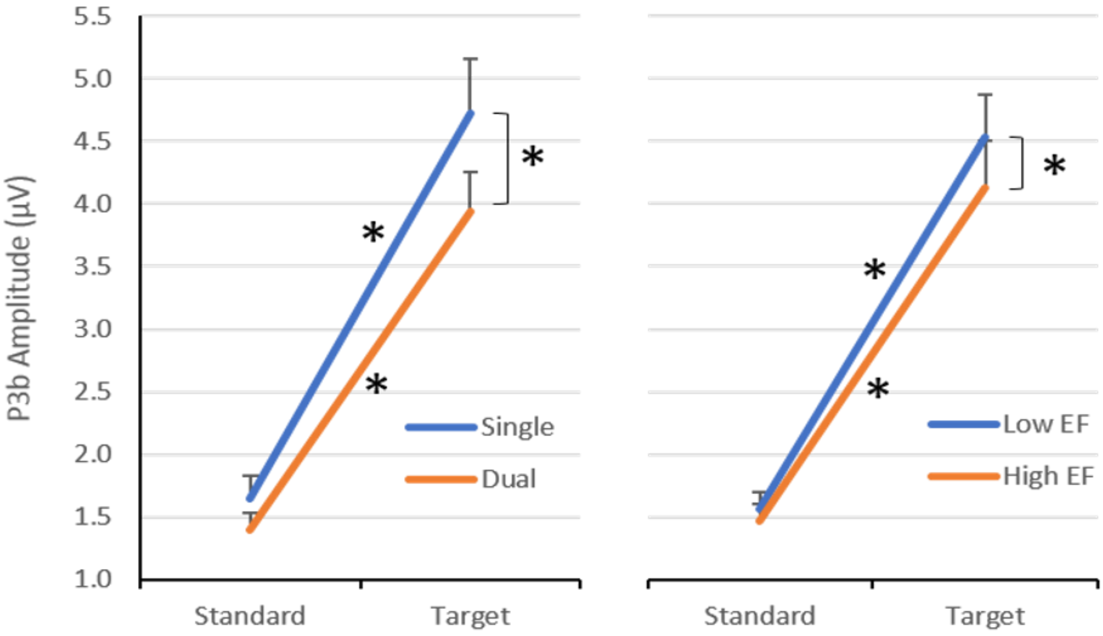

Figure 4.4. Grand average P3b amplitude. Left panel: P3b amplitude means for standard and target trials in single and dual tasks. Target stimuli showed higher amplitude than standard stimuli in both tasks conditions. Amplitude was reduced in the dual-task condition for target trials. Right panel: P3b amplitude means for standard and target trials in low and high EF tasks. Target stimuli generated higher P3b amplitude than standard stimuli in both EF load conditions. Amplitude for target stimuli was reduced in the higher EF load condition.

Event-related spectral perturbations and fronto-parietal coherence

Experimental effects on parietal and frontal alpha/beta-band power, and fronto-parietal alpha-band amplitude and phase coherence were analysed using a 2 (Task: single, dual) x 2 (Stimulus: standard, target) x 2 (EF load: low, high) x 20 (time) repeated measures ANOVA. Time bins were of 50 ms duration and spanned 0-1000 ms post stimulus onset. Frontal alpha-band power was analysed over the 550-1000 ms (post stimulus-onset) time period.

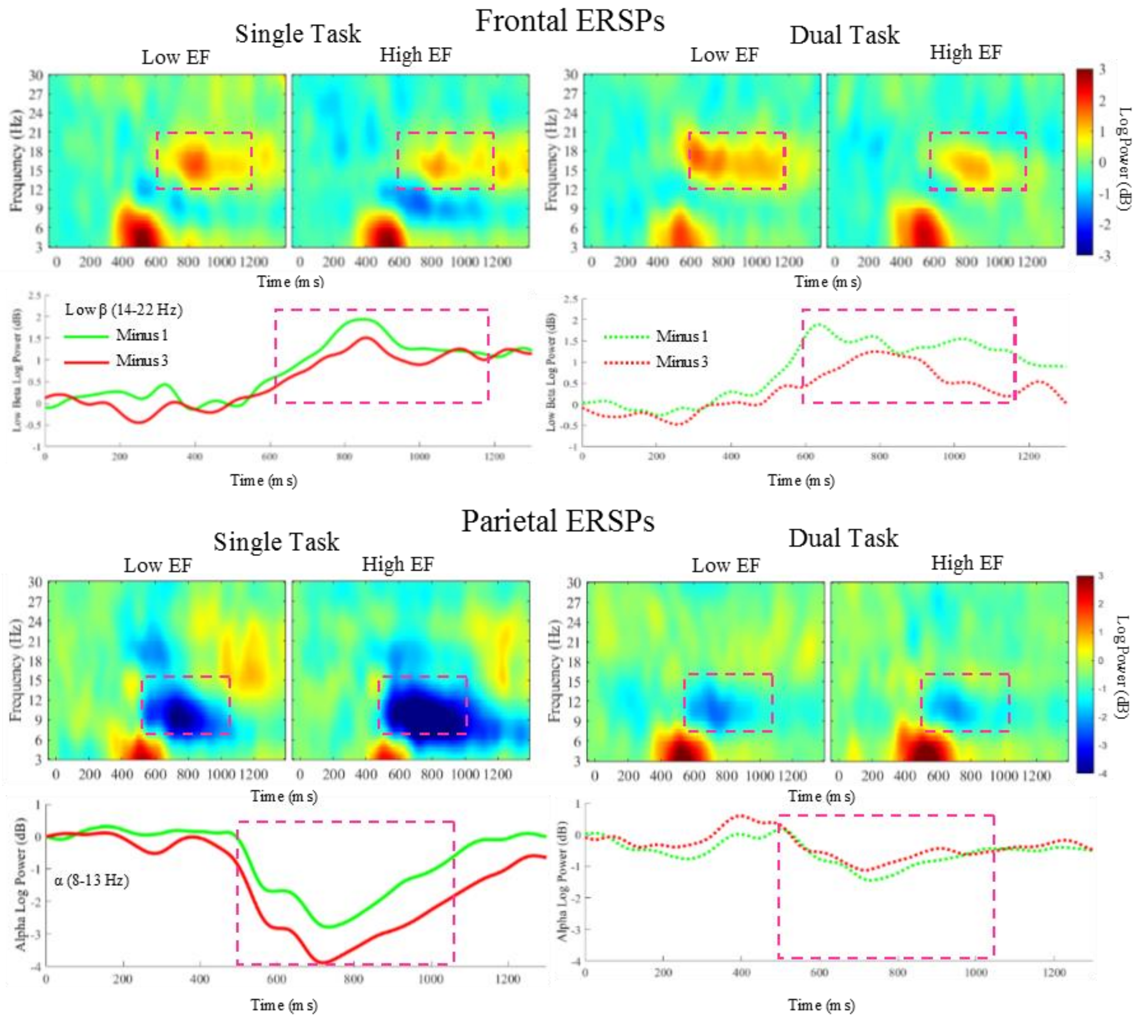

Figure 4.5. *Grand average time-frequency plots and low beta time series derived from frontal midline electrode C21 (top) and alpha band time series from parietal midline electrode A19 (bottom) for target stimuli in single and dual task conditions (left and right, respectively) under low (tally task: Minus 1) and high (tally task: Minus 3) EF loads relative to pre-stimulus baseline. The dashed squares show the correspondence between time-frequency plot features and the derived time series. For frontal alpha/low-beta, a reduction in power was observed during dual-tasking (relative to the single task) at 750 ms post stimulus onset. Higher EF load also reduced frontal alpha/low-beta power relative to the low EF load. In the case of parietal alpha, dual-tasking reduced alpha ERD, while higher EF load increased ERD. Under high EF load, parietal alpha power was significantly lower (i.e., desynchronization was greater) for target than standard stimuli during the single task.*

Parietal Alpha Band Power

The main effect of task was significant [*F*(1,23) = 4.35, *p*<.05, η_G^2 = .02; parietal alpha-band desynchronization was reduced during dual tasking]. The main effect of stimulus was significant [*F*(1,23) = 10.35, *p*<.01, η_G^2 = .02; parietal alpha desynchronization was greater for the target stimulus]. The main effect of EF load was also significant [*F*(1,23) = 6.98, *p*<.05, η_G^2 = .002; parietal desynchronization was greater during higher EF load].

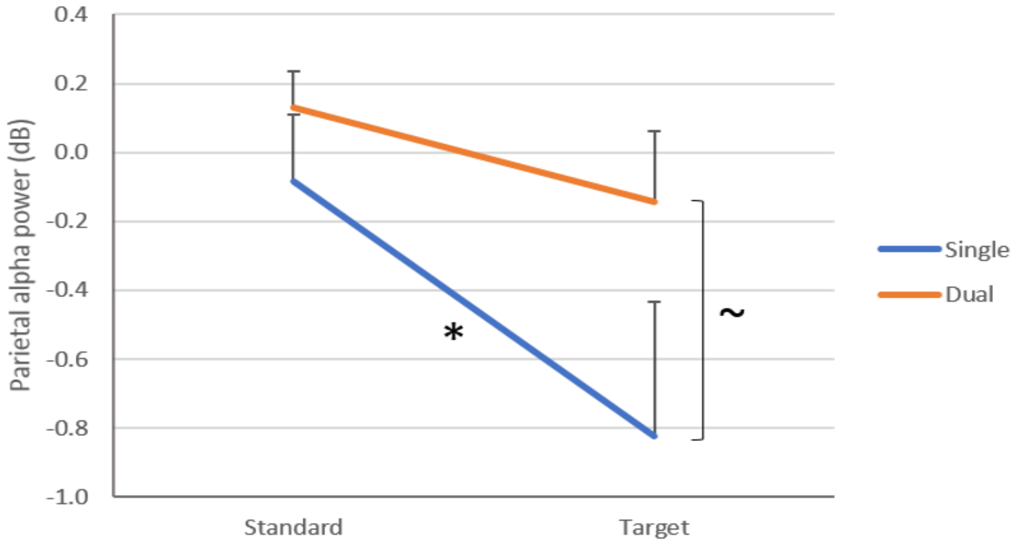

Figure 4.6. Grand average parietal alpha power means for standard and target stimuli under single and dual task conditions. Parietal alpha ERD was greater (i.e., power was lower) for target than standard stimuli in the single task condition. Dual-tasking reduced the alpha ERD difference between standard and target stimuli. Error bars show standard error.

The task x stimulus interaction was significant [*F*(1,23) = 4.68, *p*<.05, η_G^2 = .05; parietal alpha desynchronisation was greater (i.e., power was lower) for the target stimulus during single tasking but this difference was not significant during dual tasking (Fig. 4.6)].

The stimulus x time interaction was significant [*F*(19,437) = 12.48, *p*<.001, η_G^2 = .03; parietal alpha desynchronization was greater for the target stimulus in the 500-700 ms post-stimulus onset period (Fig. 4.7)].

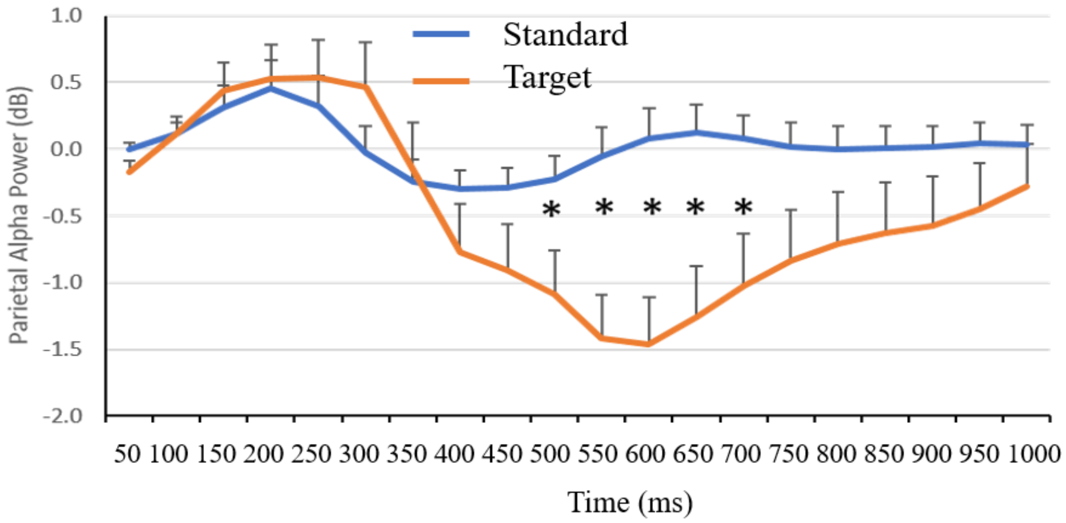

Figure 4.7. Parietal alpha power time series for standard and target stimuli.. Target stimuli generated greater desynchronization than standard stimuli between 500 and 700 ms post stimulus onset. Error bars show standard error.

The interaction between task, stimulus type and EF load approached significance [$F(1,23) = 3.93$, $p=.06$, $\eta_G^2 = .02$]. Post-hoc analysis showed that, under high EF load, parietal alpha power was significantly lower (i.e., desynchronization was greater) for target than standard stimuli during the single task. The implication is that the reduction in desynchronization from single to dual tasking was more prominent under high EF load (Fig. 4.8)].

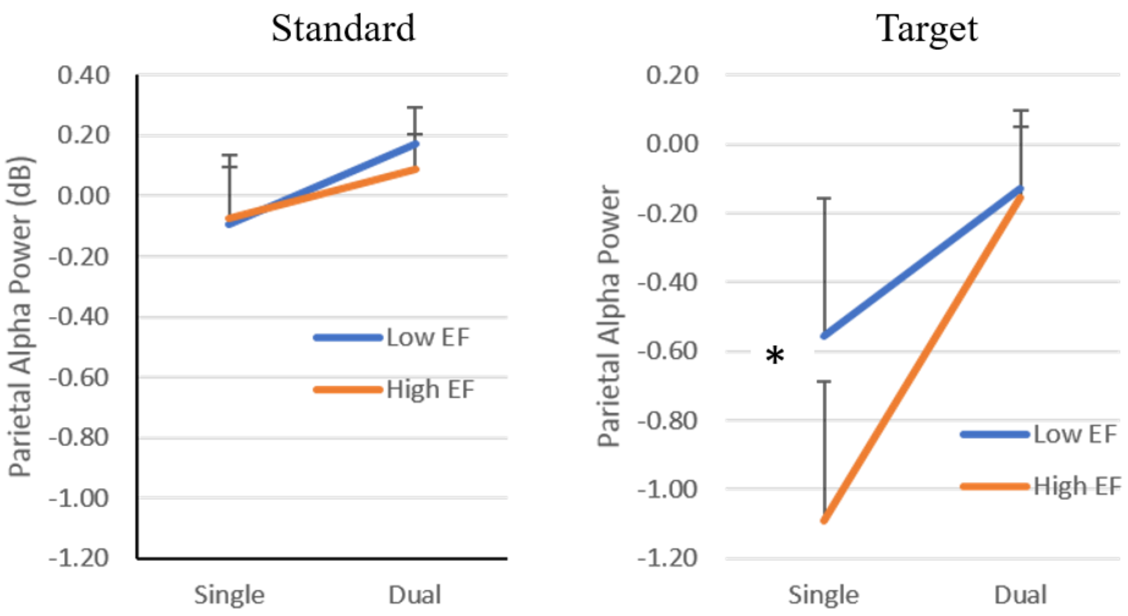

Figure 4.8. Grand average parietal alpha power for standard and target stimuli in single and dual-task conditions under high and low EF load. Under high EF load, parietal alpha power was significantly lower (i.e., desynchronization was greater) for target than standard stimuli during the single task. Dual-tasking reduced desynchronization more under high EF than low EF such that the difference between EF loads that was seen in the single task disappeared. Error bars show standard error.

Frontal Alpha/Beta Band Power

The main effect of time was significant [$F(9,207) = 6.33$, $p<.01$, $\eta_G^2 = .01$; Frontal alpha/low beta power peaked at 750 ms post-stimulus onset]. The main effect of stimulus type was also significant [$F(1,23) = 8.96$, $p<.01$, $\eta_G^2 = .002$; frontal alpha/low beta power was greater for the target stimulus. The interaction of time with task [$F(9,207) = 4.61$, $p<.01$, $\eta_G^2 = .03$] showed that frontal power was lower during dual-tasking, significantly so at 750 ms post-stimulus, when it peaked during the single task (Fig. 4.9, left). The interaction of time and stimulus was also significant [$F(9,207) = 3.78$, $p<.05$, $\eta_G^2 = .003$], which showed that frontal power was greater when the stimulus was a target. This difference was greatest (and significant) between 750-900 ms post stimulus-onset (Fig. 4.9, right).

Notably, the main effect of EF load was significant [$F(1,23) = 5.78$, $p<.05$, $\eta_G^2 = .009$; frontal alpha/ low beta power was lower when EF load was high, suggesting that WM resourcing was compromised in the high EF condition. The interaction between EF load and time was not significant, however.

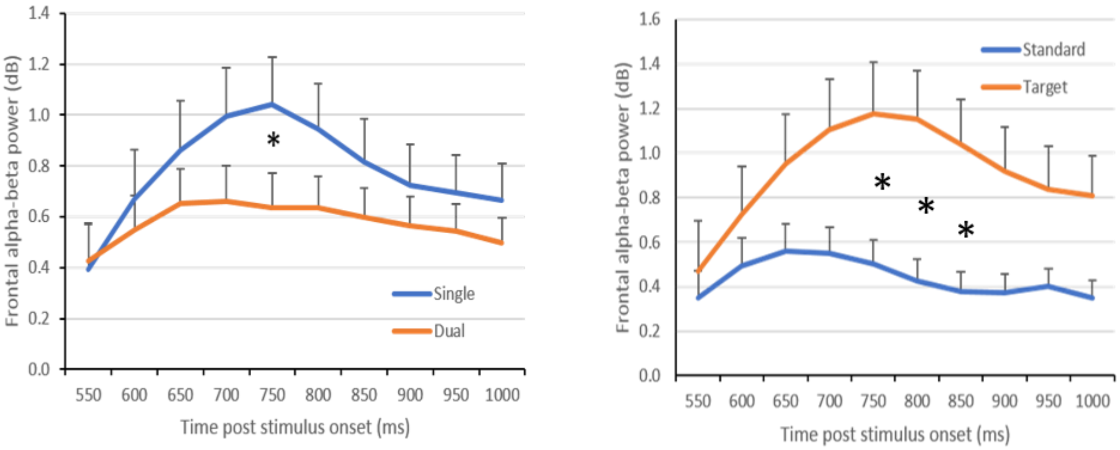

Figure 4.9. Frontal alpha/low-beta power over time. Left panel: Frontal power was lower in the dual-task condition (significant difference occurred at 750 ms post stimulus onset). Right panel: Frontal power was greater for the target than standard stimuli (significant differences occurred at 750, 800, and 850 ms post stimulus onset). Error bars show standard error.

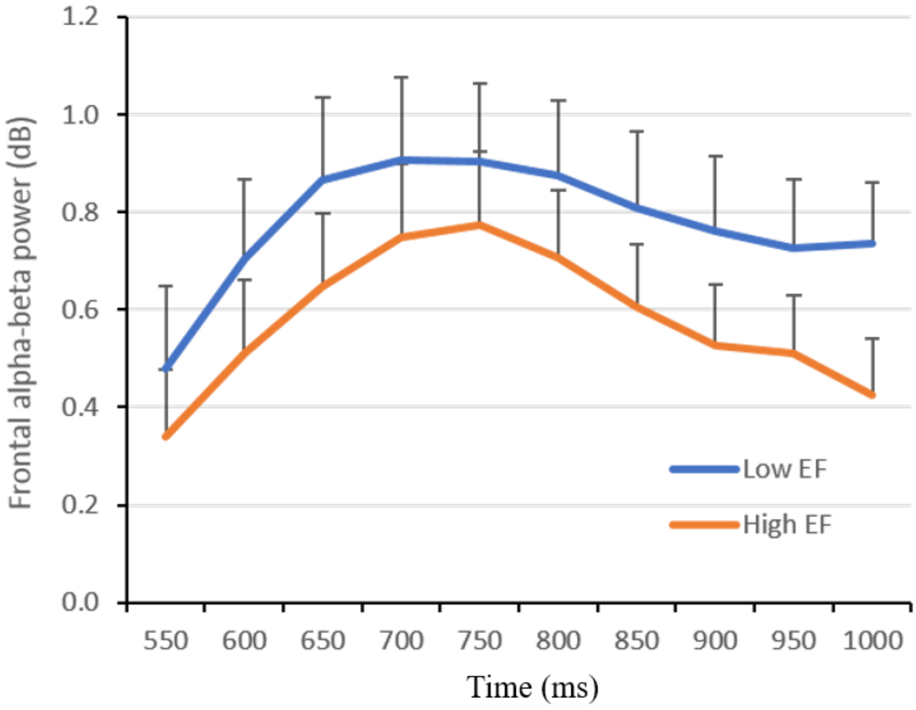

Figure 4.10. Frontal alpha/low-beta power for both low and high EF load conditions. Overall, frontal alpha/low-beta was reduced in the high EF load condition, but the pairwise differences per time point were not significant. Error bars show standard error.

Fronto-parietal Alpha Band Coherence

Magnitude Coherence: The main effect of task was significant [$F(1,23) = 26.73$, $p<.001$, $\eta_G^2 = .005$; magnitude coherence was reduced during dual tasking]. The task x stimulus [$F(1,23) = 10.86$, $p<.01$, $\eta_G^2 = .003$] was significant, but post-hoc mean comparisons only confirmed that coherence was reduced during dual tasking for both stimulus types (Fig. 4.11, left). The task x time interaction was also significant [$F(19,437) = 3.16$, $p<.01$, $\eta_G^2 = .005$]. Magnitude coherence was lower during dual tasking throughout the epoch, but the reduction seen in the single task case around 500-600 ms did not occur during dual tasking (Fig. 4.11, right). There were no significant effects involving EF load.

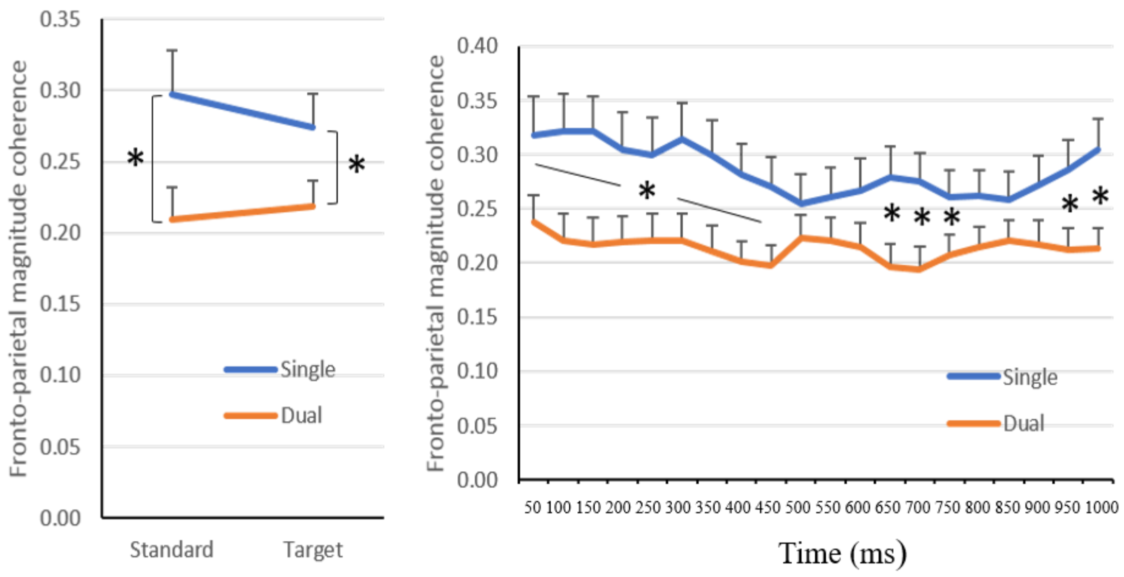

Figure 4.11. Fronto-parietal alpha-band magnitude coherence during single and dual tasks. Left panel: Magnitude coherence was reduced by dual-tasking. Right panel: Significant differences between task conditions occurred at all time points up to 450 ms post stimulus onset, and then at 650-750 ms, and 950-1000 ms post stimulus onset. Error bars show standard error.

Phase Coherence: The main effect of time was significant [F(19,437) = 3.16, p<.01, η_G^2 = .007; phase coherence varied over the epoch]. The main effects of task [F(1,23) = 24.66, p<.001, η_G^2 = .003; phase coherence was reduced during dual tasking] and stimulus [F(1,23) = 19.13, p<.001, η_G^2 = .009; phase coherence was greater for the target stimulus] were also significant. The task x stimulus interaction was also significant [F(1,23) = 9.65, p<.01, η_G^2 = .001; the increase in phase coherence for the target stimulus (over the standard) was greater during dual tasking (Fig. 4.12)].

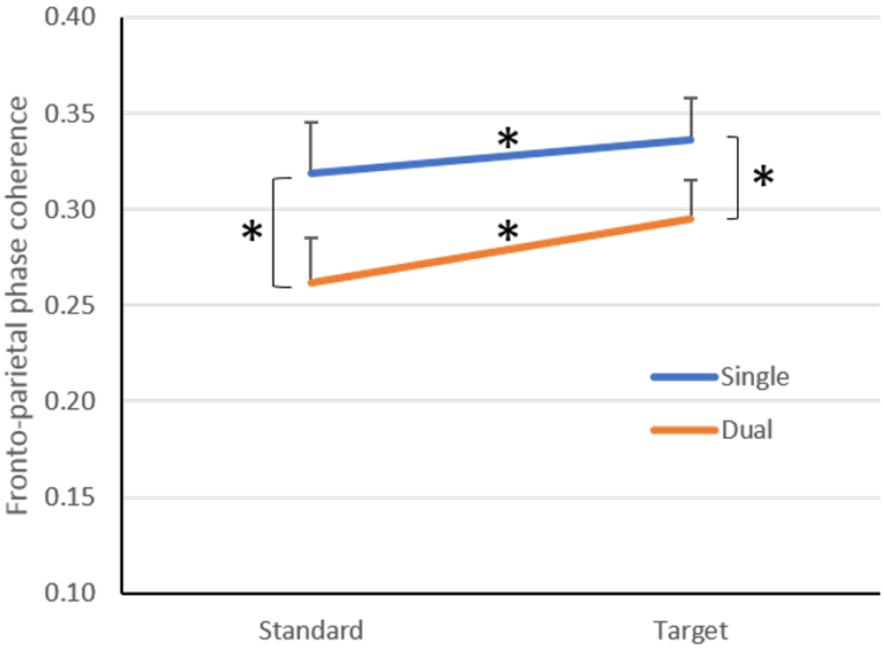

Figure 4.12. Fronto-parietal alpha phase coherence for standard and target stimuli in single and dual task conditions. Phase coherence was higher for target stimuli in both single and dual-task conditions. Dual-tasking reduced phase coherence for both standard and target stimuli. Error bars show standard error.

Visuomanual Tracking Deviation

In Chapter 2, the effects of dual-tasking on tracking deviation occurred in the time period following the P3b peak, and only in the case of target stimuli. The level of deviation was also uncorrelated with P3b amplitude. These findings suggested that the observed tracking deviation was due to interference from the executive function of tallying the oddball targets that followed the identification of the stimulus as a target. As the present experiment manipulated the EF load associated with the target-tallying element of the oddball task, the first analysis of tracking deviation was carried out on theta and rho time series that were baseline corrected at the average P3b peak (Fig. 4.13). This analysis would clarify how tracking deviation in the post P3b period was affected by the EF load manipulation.

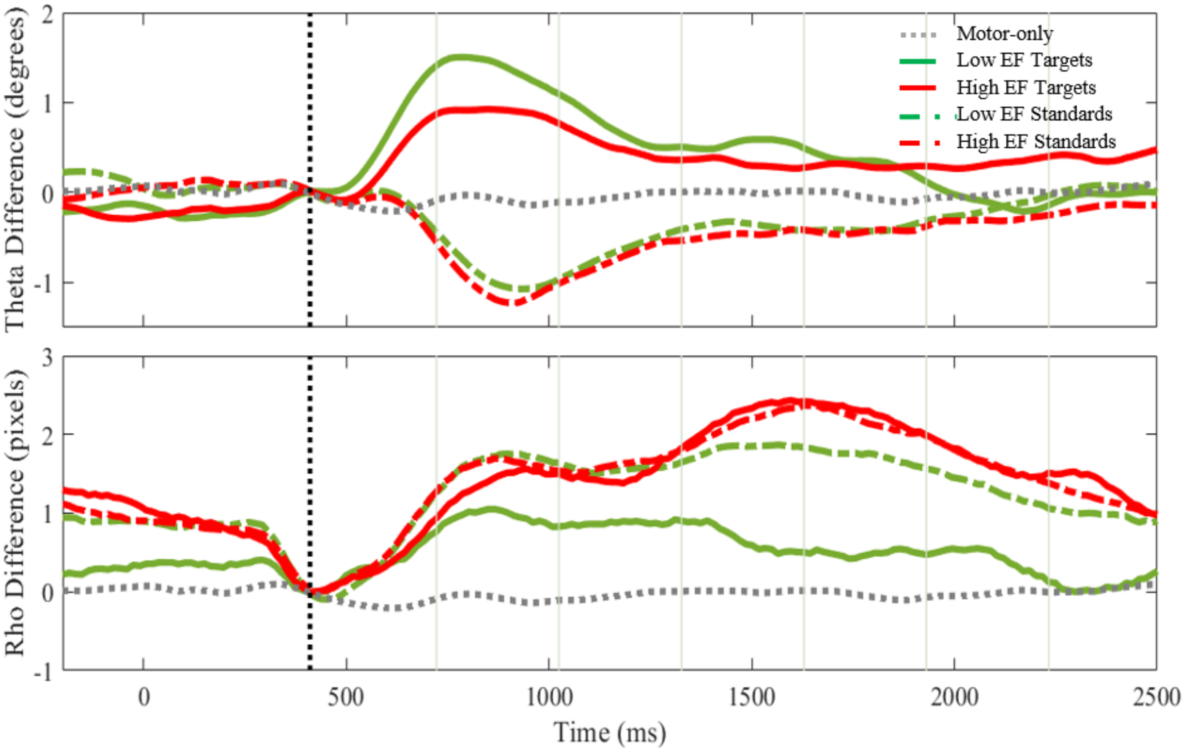

Figure 4.13. Rho/theta deviation over time (P3b baseline corrected). Rho/Theta deviation time series for standard and target stimuli in the dual-task condition for low and high EF loads. Also shown is the motor-only task time series (no oddball task). The dotted vertical line at ~420 ms shows the latency of peak P3b.

A 2 (Task: motor-only, dual task) x 2 (Stimulus: standard, target) x 2 (EF load: low EF load, high EF load) x 5 (Time since P3b peak: 300, 600, 900, 1200, 1500 ms) repeated measures ANOVA was conducted. For theta, the main effect of task was significant [$F(2,46) = 3.93$, $p<.05$, $\eta_G^2 = .05$], as was the interaction between task and time [$F(8, 184) = 4.08$, $p<.001$, $\eta_G^2 = .02$; theta deviation for target stimuli was positive, i.e., an angular lead at 300 ms post P3b peak, relative to the deviation for the standard stimuli at 300 and 600 ms after the average P3b peak at 420 ms (Fig. 4.14)]. There was no effect of EF load on theta. For rho, The main effect of EF load was marginally significant [*F*(1,23) = 4.16, *p*=.05, η_G^2 = .007; Rho deviation was higher in the high EF load condition (Fig. 4.15)]. The main effect of task was also significant [*F*(2,46) = 7.89, *p*<.01, η_G^2 = .09; Rho deviation in both dual-task conditions was positive, i.e., participants tracked outside the lead dot's circular trajectory].

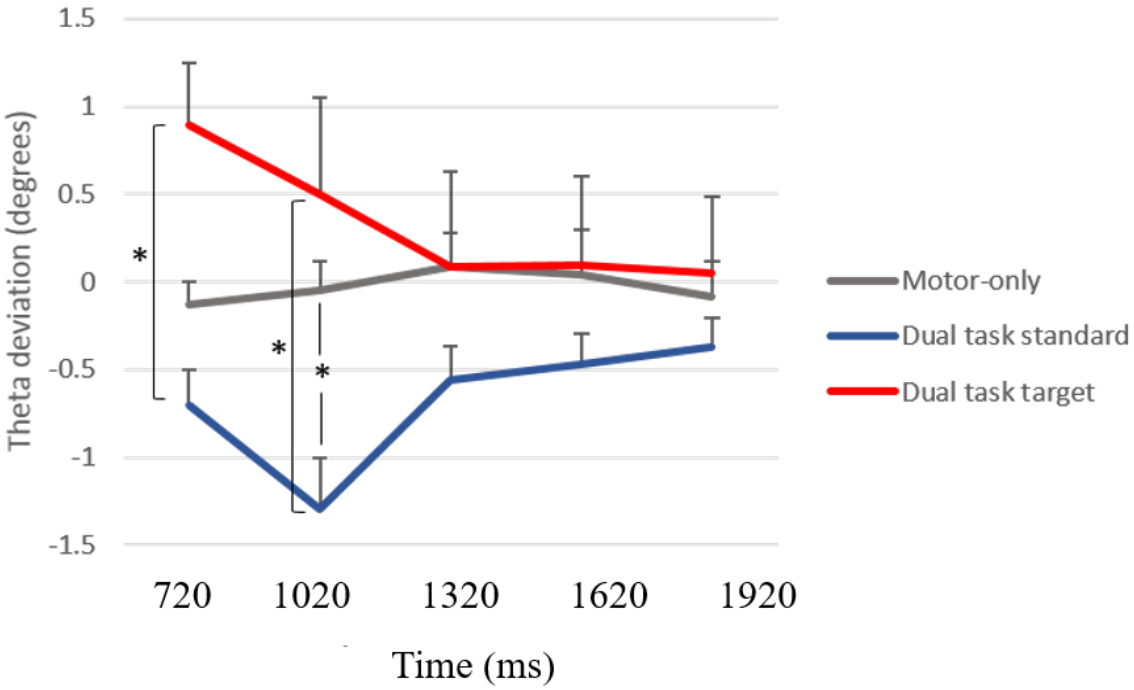

Figure 4.14. Grand average theta deviations over time (P3b baseline corrected). Theta deviation from 720 ms to 1920 ms post stimulus onset for motor-only and dual task standard and target trials, zero normalized using the values at the timing of the P3b peak (420 ms). Error bars show standard error.

The above analysis considered tracking deviations in the time period following the P3b peak. The data were therefore baselined at the average P3b peak latency (420 ms). The EF load manipulation in this experiment was intended to affect the cognitive operations that occurred after the P3b, and only when the stimulus was identified as a target. However, the EF load manipulation appeared to have also impacted some cognitive processes before the P3b peak (see the effect of EF load on P3b amplitude in Fig. 4.4). Given this observation, it was considered that there may have been tracking deviations that occurred prior to the P3b that could have been affected by the EF load manipulation. To investigate this possibility, a second analysis on rho and theta was conducted with the deviation time series baseline corrected by calculating the mean of the deviation values in the pre-stimulus window for each condition and removing this mean from each sample throughout the relevant epoch (Fig. 4.16). These time series were divided into 100 ms bins, from time zero (stimulus onset) to 500 ms, and the means calculated within each bin, for each condition/stimulus. A 3 (stimulus: motor-only, dual task standard, dual task target) x 2 (EF load: low, high) x 5 (time window: 0-100, 100-200, 200-300, 300-400, 400-500) repeated measures ANOVA was then carried out.

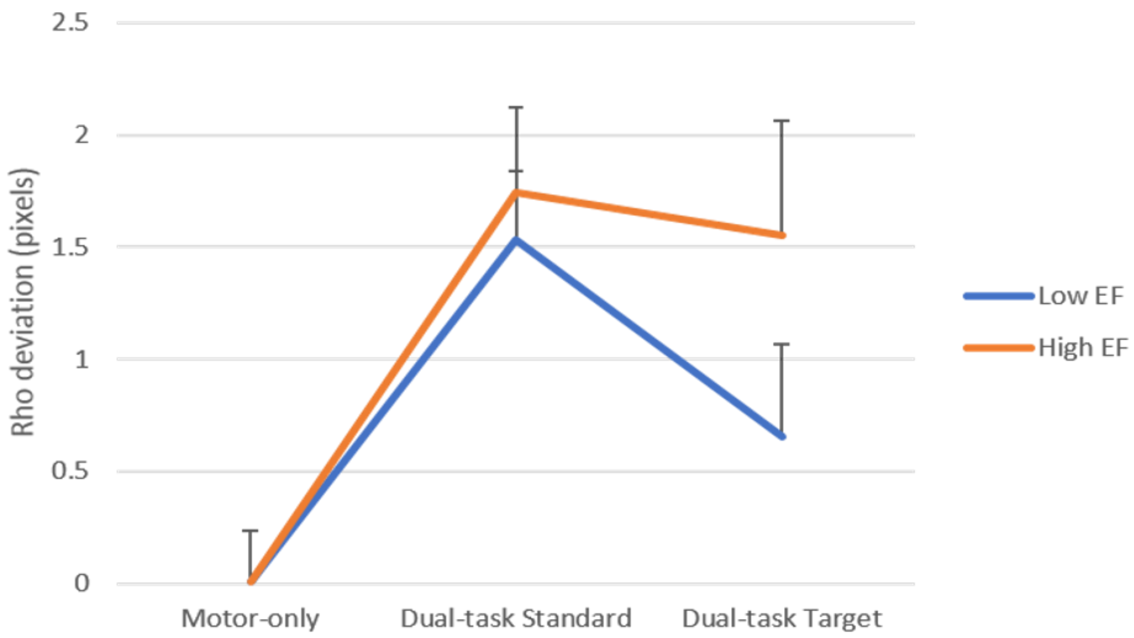

Figure 4.15. *Mean rho deviations for motor-only, dual-task standard and target trials for low and high EF load conditions. Rho deviated positively for both dual-task stimuli (relative to no deviation in the motor-only trials). Overall, rho deviation was greater under high EF load. Error bars show standard error.*

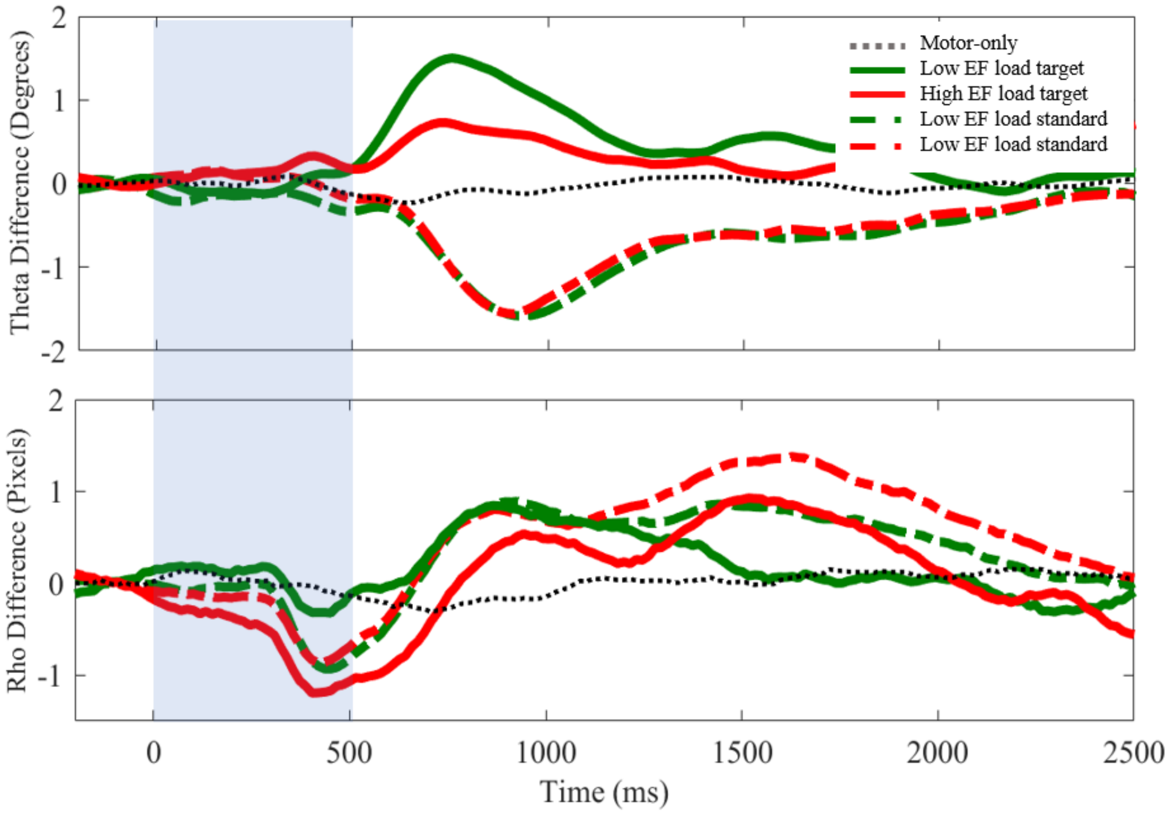

Figure 4.16. Rho/theta deviation time series (pre-stimulus baseline-corrected). Blue-shaded area shows period of analysis (between 0 and 500 ms).

For theta, no significant effects were found. For rho, a significant main effect of time was found ($F(4,92) = 11.45$, p=.001, $\eta_G^2 = .03$); Rho values were more negative in the time periods 400 and 500 ms post stimulus onset than the preceding time periods (Fig. 4.17). The 400 and 500 ms periods also differed from each other but note that the interaction between stimulus and time was not significant.

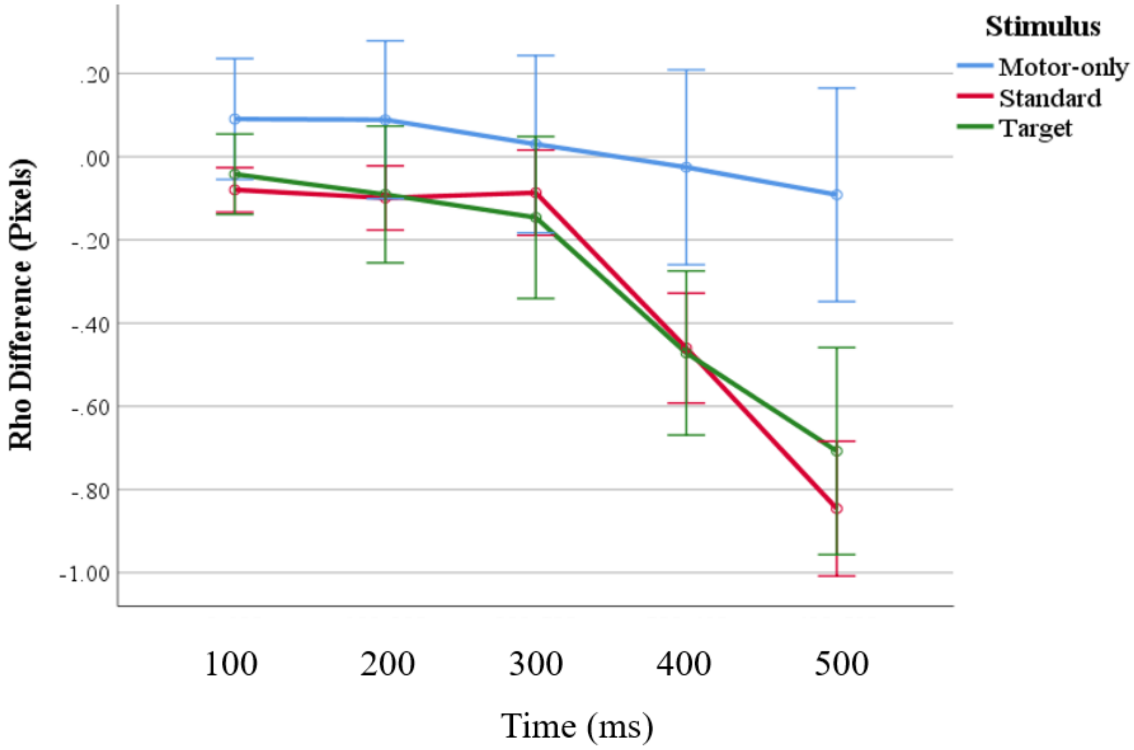

Figure 4.17. Rho deviations over time (pre-P3b period). Although there was no significant interaction between task and time, the main effect of time suggests an overall downward trend in rho in the 300-400 and 400-500 time periods.

Effects of Oddball Task Performance on Spectral Power over Primary Motor Cortex

To investigate the effects of oddball task processing on the spectral dynamics of the motor system, separately for alpha and beta power bands, a 2 (hemisphere: LH, RH) x 9 (task: low EF load single-standard, low EF load single-target, low EF load dual-standard, low EF load dual-target, high EF load single-standard, high EF load single-target, high EF load dual-standard, high EF load dual-target, and motor-only) repeated measures ANOVA was conducted using absolute power as the dependent measure.

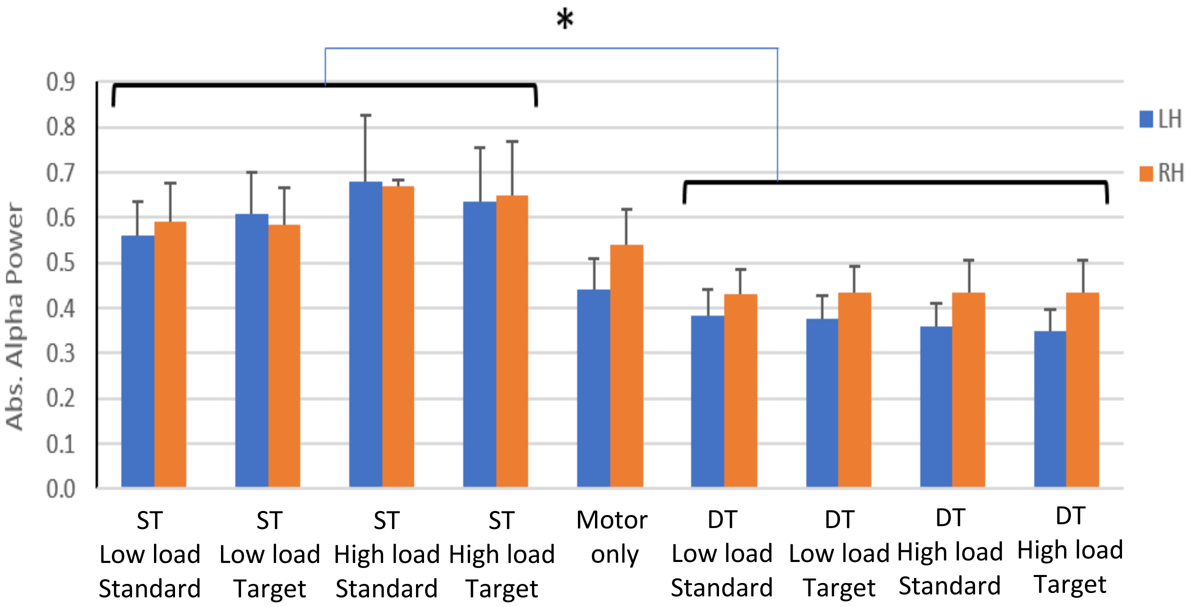

Figure 4.18. Alpha and beta-band power over left and right motor cortex during single-task (ST), dual-task (DT) and motor only conditions for standard and target stimuli. Power was reduced (indicating desynchronization) when the motor task was performed in the dual-task conditions. The numerical trend was for lower power (greater desynchronization) in the left motor cortex (the motor task was performed by the right hand.

The main effect of condition was significant [$F(8,184) = 8.92$, $p<.01$, $\eta_G^2 = .06$; alpha power was lower during the dual task conditions]. The main effect or interaction involving hemisphere was not significant, but Fig. 4.18 suggests a numerical trend of lower alpha power in the LH during dual tasking. The results were identical in the beta band. The main effect of condition was significant [$F(8,184) = 13.48$, $p<.001$, $\eta_G^2 = .11$; beta power was lower during the dual task conditions]. Again, the main effect or interaction involving hemisphere was not significant, but, as for the alpha-band, there was a numerical trend of lower beta power in the LH during dual tasking.

In case any power differences occurred over shorter durations and therefore could not be detected over the whole trial period, spectral power was also analysed over left primary motor cortex (contralateral to the moving hand) using a 5 (task: motor-only, low EF load dual-standard, low EF load dual-target, high EF load dual-standard, high EF load dual-target) x 6 (time: 0-200, 200-400, 400-600, 600-800, 800-1000, and 1000-200 ms) repeated measures ANOVA. The main effect of time was significant [*F*(5,115) = 5.38, $p<.01$, $\eta_G^2 = .03$]. The interaction between time and condition was also significant [*F*(20,460) = 4.25, $p<.001$, $\eta_G^2 = .04$; alpha power was lower during the dual task conditions]. Post-hoc analysis showed that alpha power dipped in the 400-600 ms post stimulus-onset time window for the target stimuli (Fig. 4.19).

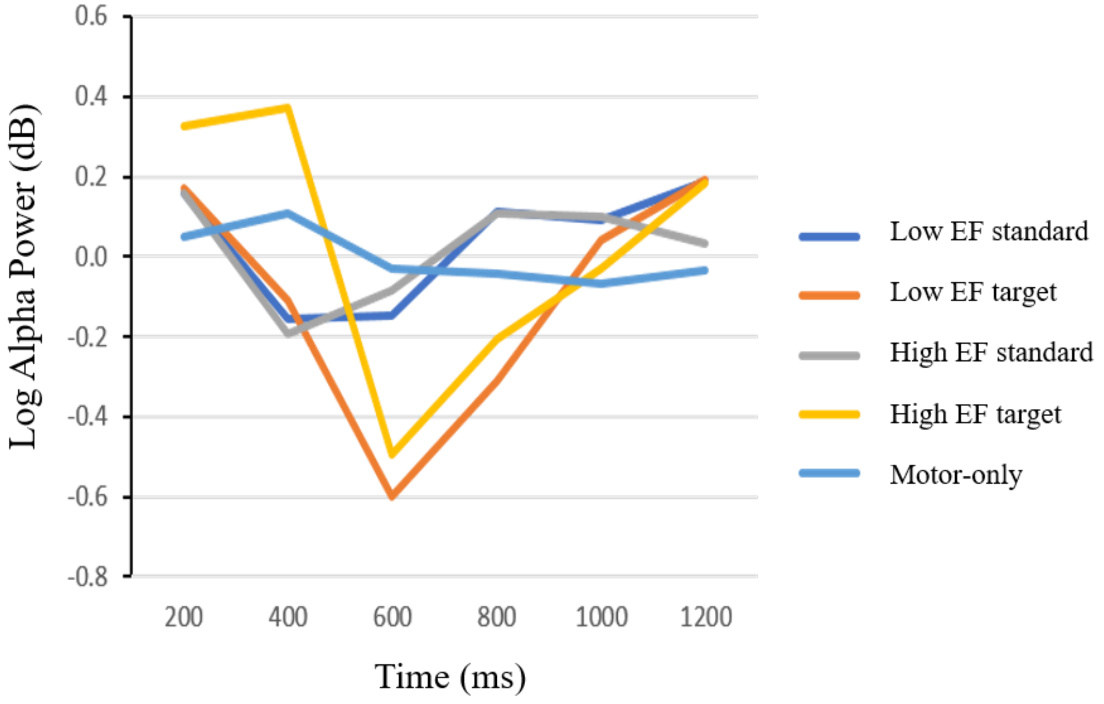

Figure 4.19. Alpha-band power over left motor cortex (electrode D19) for standard and target trials under low and high EF load across 6 time points following stimulus onset.

The results had a similar pattern in the beta band. The main effect of time was significant [*F*(5,115) = 6.21, $p<.001$, $\eta_G^2 = .01$]. The interaction between time and condition was also significant [*F*(20,460) = 1.68, $p<.05$, $\eta_G^2 = .009$]

Discussion

The main aim of the current experiment was to assess the impact of an increased tally-updating load and how, if at all, this modulated the CMi patterns observed in the first experiment. More specifically, the introduced load aimed to target the interference pattern in motor performance when participants were updating the target count.

The experiment reported in Chapter 3 showed that performing the tracking task concurrently reduced attentional resourcing of the oddball task but interference from the oddball task did not result in tracking deviations during the time period of the oddball task's attentional element. Rather, tracking deviation was prominent later in the oddball task's timeline when the target count was being tallied. This pattern of interference suggested that it was the EF load involved in oddball target tallying that disrupted the tracking task. The purpose of the present experiment was to manipulate the tallying task's EF load by making it an information reduction task of two different loads while keeping the load of the attentional element constant. Assuming the manipulation succeeded in selectively affecting EF load, the expectation was of greater tracking deviation at higher EF load, but no change in the unresponsiveness of tracking deviation to the attentional element occurring earlier in the trial. It was also considered possible that participants would strategically distribute the imposed EF load by pre-emptively reserving processing resources, or by not waiting until they detected a target to perform the subtraction task but beginning it earlier in anticipation of detecting a target. In this case, it was expected that effects of the EF load manipulation on the oddball task's earlier elements (e.g., in P2 or P3b amplitude) would be observed.

The results showed that the accuracy of target identification was unaffected by dual tasking or EF load. There was a numerical trend towards lower accuracy during dual tasking suggesting the expected pressure on processing resources due to dual tasking. The EF load manipulation did not affect the difficulty of identifying the target, but it did seek to manipulate the difficulty of accurately tallying and reporting the number of targets over the course of a block of trials. The result suggests that the EF load manipulation did not change the participants' accuracy in performing the tallying. This meant that there would need to be other indicators of the EF load manipulations having been effective. It also meant that other differences between the EF load conditions could not be attributed to differences in performing target detection and tallying tasks accurately.

On the ERP measures of oddball task-element resourcing, the early perceptual component P1 was only affected by the difference in contrast between the target and standard oddball stimuli. It was not expected to be affected by dual tasking (it was not in Chapter 3) or EF load, both of which taxed later processes. This supports the argument that P1 is primarily sensitive to the physical features of a task, and is usually not demonstrated to be modulated by attentional modulations introduced by dual-tasking (Capizzi et al., 2013; Gherri & Eimer, 2010). P2 amplitude indicated the resourcing of template-matching–it was reduced during dual tasking (as in Chapter 3). It was not affected by EF load. As the EF load manipulation targeted processes occurring after the P3b, the absence of any effects of it in the timeframe of P1 and P2 suggests that participants' resourcing of the oddball task's perceptual and template-matching elements were not subject to strategic resourcing adjustments in anticipation of a target being detected. However, higher EF load did reduce P3b amplitude to target stimuli, suggesting that loading up the task element following target detection reduced resourcing of the response-relevance acknowledgement process signified by P3b amplitude. The absence of such anticipatory effects on P1 and P2, but its presence on P3b suggests that participants did not engage in pre-calculating the updated tally throughout the trial timeline, but they may have engaged in some resource reservation from around the time of P3b peak in anticipation of the stimulus turning out to be a target (and requiring a higher EF load tally-updating process).

Time-frequency analyses of EEG data enabled studying the effects of dual tasking and EF load manipulation on the cognitive resourcing of target identification (parietal alpha-band desynchronization) and post-identification working memory load (frontal alpha-beta synchronisation). As in Chapter 3, dual tasking reduced parietal alpha desynchronization (i.e., power remained higher), particularly for the target stimulus. Additionally, there was an indication that higher EF load resulted in a greater loss of desynchronization due to dual tasking. In the case of frontal alpha/low-beta synchronisation, as in Chapter 3, power was greater for the target stimulus, indicating the engagement of frontal WM mechanisms involved in updating the target count. Unlike in Chapter 3, dual tasking attenuated frontal alpha-beta synchronisation. An increase in frontal alpha-beta power under dual tasking has been observed in imaging studies of cognitive-motor dual-task interference (Doi et al., 2013; Holtzer et al., 2011; Leone et al., 2017; Meester et al., 2014) as well as in Chapter 3. Here, the interaction between task and stimulus type was not significant, so it could not be claimed that the unexpected power attenuation due to dual tasking was reserved for target stimuli. It appears that the EF load manipulation changed the way participants allocated working memory resources in the post-P3b period. It is notable that the high EF load condition also attenuated frontal alpha-beta synchronisation and this reduction did not interact with time and stimulus type. Thus, one effect of introducing the EF load manipulation, which increased the importance of the arithmetic involved in updating the target tally, appears to have been to reduce working memory resource allocation in the post-P3b period.

Finally on time-frequency measures, the EF load manipulation in this experiment did not affect the strength of the fronto-parietal network, even as dual tasking attenuated both magnitude and phase coherence, as found in Chapter 3. This was as expected assuming that the fronto-parietal coherence measures relate more closely to the process of identifying the target than to the actions taken post-identification (Kwon et al., 2015). EF load was also found not to have affected the power over motor cortex, which suggests that the resourcing of motor processes was not modulated by changing the EF load of the target-tally updating process.

This leaves consideration of the effects of manipulating EF load on performance in the tracking task. Chapter 3 showed that it was the target-tally updating process, rather than the preceding perceptual and attentional elements, that coincided with deviations in the tracking trajectory. The large positive deviation in theta (indicating the controlled dot went ahead of the lead dot in terms of angular position) in the post-P3b period was again observed here, but its magnitude was not affected by changing concurrent EF load. The pattern of deviation in rho, on the other hand, did show sensitivity to changing the EF load, whereby the controlled dot radially extended beyond the lead dot’s circular trajectory by a greater amount under high EF load. There was also a general tendency for a negative rho deviation (falling inside the lead dot’s circular trajectory) around the time of the P3b peak, although this effect was not specific with respect to stimulus, task or EF load manipulations. The unresponsiveness of theta deviation to the EF load manipulation suggests that it may not be tied to specific operations involved in the EF task. It may be a more general phase advancing action to compensate for the resource draw of having to perform an EF task after identifying a target. The EF load-sensitive rho deviation is consistent with reduced direction change (centripetal acceleration) leading to straying outside the circle, and more so under high EF load. This does suggest that increasing the resources needed for the EF task reduces resourcing of the tracking task. In this respect, the indication provided by Chapter 3 is supported by this chapter's data.

Chapter 5: Experiment 3: The effects of increasing stimulus differentiation difficulty on concurrent sensorimotor coordination

Introduction

The experiments presented in Chapters 3 and 4 showed that performing the tracking task concurrently had a negative impact on the resourcing of the oddball task's attentional components in the 200-500 ms period post stimulus-onset. The impact of performing the oddball task on tracking deviation was evident later in the post P3b peak period (i.e., beyond 400 ms post stimulus-onset) when oddball task performance had moved out of the attentional phase of identifying the target and into the EF of updating the target tally. In both these demonstrations of temporally asymmetric interference, the target identification task remained the same. The standard and target stimuli were easily differentiated and the load associated with matching the current stimulus with the target held in WM was very low. How the observed interference pattern could be affected by a challenging target differentiation and template-matching load remained unclear.

The aim of the present experiment was to increase the load involved in target identification by increasing the physical similarity between the standard and target stimuli. When the standard and target stimuli are more similar, the target's features need to be held in WM in finer grained detail, and the process by which stimuli are differentiated becomes more resource-intensive (Fedota, 2012). If the tracking task competes for these resources, the harder discrimination task could negatively impact the tracking task during the template-matching and response-relevance judgment phases (~ 200-400 ms post stimulus-onset) of the oddball task.

In order to increase the standard-target discrimination difficulty, it was necessary to increase the complexity of the stimuli. To achieve this, gabor patches in which the spatial frequency differed between standard and target stimuli were used. The difference in spatial frequency was smaller in the high load condition. This change also increased the perceptual load of the oddball task compared to Chapters 3 and 4. As such, the implementation of gabor patches stressed both bottom-up processing (the stimuli are of a finer grained resolution), and top-down processes (the template matching process becomes more demanding). This increase in perceptual load also increased the possibility of earlier interference with the tracking task than was observed in Chapters 3 and 4.

The increase in similarity between the standard and target stimuli was expected to modulate the electrophysiological components associated with the oddball task. Though no differences were expected for P1 (given the high degree of physical similarity between stimuli), modulations of P2 and P3b were predicted. When the attentional resource demands of the task are increased, P3b amplitude decreases (Polich, 1987; 2007; Kok, 2001). P3b has also been found to be attenuated to target stimuli if they are more physically similar to standard stimuli (Fedota, 2012). If oddball task accuracy is found to be sensitive to the increase in difficulty (e.g. a decline in target count performance was observed), then any effects on either tracking or the cognitive task elements would be hard to interpret as modulations of electrophysiological components could be due to differences in the rate of target misidentification (either failing to detect a target or falsely identifying a standard as a target).

It was hypothesized that concurrent performance of the tracking task would attenuate P2, P3b, and parietal alpha desynchronization, and that this attenuation would be greater in the higher load condition, if the taxed resources are shared. It was unclear whether P1 would be modulated by dual tasking, but if this was observed, it would demonstrate that the perceptual process was also subject to resource-sharing with the tracking task. It was predicted that frontal alpha/low-beta synchronization would increase during dual tasking, but that this increase would not interact with the level of difficulty (as it occurs in the post-P3b time period, once a target has been identified). It was also hypothesized that coherence in the fronto-parietal network would be attenuated during dual-tasking, and that this attenuation would be greater in the high load condition.

On the effects of the oddball task on pursuit tracking measures, the key interest was in observing whether tracking deviations would appear during oddball task elements prior to target-count updating. Tracking deviations were still expected in the post target-identification tallying phase (beyond ~400 ms), but only in the case of target stimuli. Although the load manipulation was not intended to stress the target-count updating process, it remained to be seen whether changes to the difficulty in identifying targets modulated tracking deviation at a later time point.

Methods

The methods described here are specific to this chapter. For a detailed description of EEG and pursuit tracking data acquisition, dependent measures and analyses, and procedures, please refer to the general methods described in Chapter 2.

Participants

The participants were 22 self-reportedly right-handed adults (13 males; mean age = 24.6, SD=3.1, range 20-34), with normal or corrected to normal vision, no current prescribed medication, and no history of sensorimotor or cognitive deficits. They were recruited through a research participation scheme, and compensated with research credits. The participants gave informed consent before the session, and were fully debriefed following data collection. Ethical approval for the research reported in this paper was granted by the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee.

Tasks

The participants first completed the motor configuration task described in the general methods chapter. Following the selection of an appropriate tracking speed, participants then performed the visual oddball task (high and low discrimination load conditions blocked separately), the tracking task, and the dual task (high and low discrimination load blocked separately), in a counterbalanced order.

Pilot Experiment

Prior to data collection, a pilot study was conducted to determine the spatial frequencies of the standard and target stimuli to be used in the visual oddball task. Eight participants were asked to complete one block of trials containing either 8, 10, or 12 target stimuli, for five separate oddball tasks in which the spatial frequencies of the target stimuli differed across each task. Standard stimuli consistently had a spatial frequency of 10 cycles over a diameter of 200 pixels, whereas the target's spatial frequency changed in each task (11, 12, 13, 14 and 15 cycles). The task was to report the number of targets detected at the end of each block via a keypress. Accuracy was measured by considering the number of correct blocks across all participants for each target stimulus type. A block was recorded as correct if the number of targets presented within a block matched with the participant's response. Targets presenting spatial frequencies of 11 and 12 were disregarded, given a performance of near 100%, as these were considered too easy. It was concluded that target stimuli with spatial frequencies of 13 (25% accuracy) and 15 (75% accuracy), would serve as high and low discrimination load targets, respectively.

Oddball Task

The participants fixated at the centre of the screen while a sequence of circular gratings (r = 100 pixels, orientation = 330 degrees) with a Gaussian mask were presented, centred on the fixation cross. The oddball task presented two stimulus-discrimination load conditions. In the low load condition, the spatial frequencies of the presented standard and target gratings were more distinct, with standard stimuli having a spatial frequency of 10 cycles over the defined diameter, and target stimuli having a spatial frequency of 15 cycles over the diameter. In the high load condition, standard and target stimuli were more similar in spatial frequency, with standard stimuli having 10 cycles, and target stimuli having 13 cycles, over the defined diameter. These stimuli were presented for 200 ms, with an ISI of 2500 +/- 100 ms. The ratio of target to standard stimuli was 1:4, and there were at most 12 targets presented in each block (the number of trials per block varied between 40 and 60). There were 5 blocks of trials in both the low and high discrimination load conditions. At the end of each block, participants were asked to enter the number of targets detected via a keypress. This response was logged, as were their EEG data.

Dual Task

The participants performed the visual oddball task (both low and high discrimination-load variants) while also performing the tracking task. Five blocks of each variant were presented. Each block of trials started with the leading and controlled dots in an overlapping position. As the leading dot started moving, and the oddball task got under way, participants' task was to maintain the positional overlap between the dots while performing the oddball task. The coordinates of the controlled and leading dots, the reported target count and the EEG data were recorded.

Statistical Analysis

Statistical analysis for all measures were based on tests from the general liner model framework. Below I detail which tests were used for each measure in order to examine the effects of dual-tasking on single-task performance and the influence of the load of template matching.

Oddball target detection accuracy: In order to test the effects of dual-tasking and the loading of the updating operation on the oddball task on a behavioural level, a repeated measures ANOVA with task (single, dual) and load (low, high) as factors was used. If dual-tasking was to impede oddball task performance, then a reduction in accuracy would be observed. It was also possible that the higher load condition would reduce accuracy in the oddball task, as the differentiating of target and standard stimuli became much more demanding. It was possible that participants would misinterpret a stimulus and thus arrive at an incorrect count.

ERP components: P1, P2, and P3b ERP component amplitudes were compared using a repeated measures ANOVA with task (single, dual), stimulus (standard, target) and load (high, low) as factors. If P1 amplitude was to be reduced in dual-task conditions, then it would be inferred that pursuit tracking attenuated low level visual processing. It was also possible that the loading of the template matching process could modulate P1 amplitude, given that the stimuli present finer-grained physical properties. If P2 was to be reduced during dual-tasking, then it was inferred that attentional resources dedicated to categorising a stimulus was reduced. Again, it was possible that the updating load would modulate P2 as the introduced load was specifically introduced to target the template matching process. Finally, if P3b was to be attenuated, then it was inferred that attentional resources dedicated to response preparation was reduced. It was possible that the load manipulation introduced here could impact P3b amplitude, though the load was intended to stress processes that preceded P3b.

Regardless, the more difficult stimulus differentiation could influence later processes, including response preparation.

ERSP and fronto-parietal coherence: So as to test the effects of dual-tasking and template matching load on parietal alpha power, frontal alpha/low-beta power, and the coordination of the fronto-parietal network, a repeated measures ANOVA with condition (single task, dual-task), stimulus (standard, target), load (high, low) and time bin (0 to 1000 ms in 20 time bins) were considered as main factors. For parietal alpha, if the power that is typically reduced during target processing (alpha ERD) was attenuated, then dual-tasking would be shown to interfere with the processing of spatial representations in WM and the preparing of a suitable response. The introduced load could potentially modulate parietal alpha ERD, though as mentioned above, the load was introduced to stress preceding operations. As for frontal alpha/low-beta, if power was to be increased in the dual-task condition specifically after 500 ms following target onset, then the presence of pursuit tracking would be shown to increase the attentional demands associated with updating the target count. As for the effects of the introduced load, it was possible that the more difficult stimulus discrimination could result in ambiguity (confusion as to whether the stimulus was a target or not). As such, it was possible that the template matching load could impact WM operations. Finally, for fronto-parietal coherence, if dual-tasking was shown to reduce alpha coherence magnitude or phase, then the fronto-parietal network set up to maintain the performance of the oddball task would be hindered. It was also possible that the more demanding variant of the template matching operation could significantly modulate the behaviour of the fronto-parietal network, as successful performance in the oddball task becomes more difficult.

Pursuit-tracking: Pursuit tracking measures are reported in polar coordinates in two separate analyses. The first analysis baselines the tracking timeseries at the timing of the P3b peak, whereas the second analysis using a pre-stimulus baseline. A repeated measures ANOVA with task (single, dual, motor-only), load (high, low) and time bin (300, 600, 900, 1200, 1500 ms post P3b) were used in order to compare rho and theta tracking deviations in single task, dual-task, and motor-only conditions under different loads in the first analysis. For the second analysis, the factors remain the same, however with 5 time bins (from 0 to 500 ms in 100 ms bins). Rho and theta allow for the analysis of radial and angular deviations at specific time-points throughout the processing of oddball task stimuli. If theta was to assume a negative value at a certain time point, then the controlled dot could be considered to be lagging behind the leading dot, whereas a negative rho value would indicate that the controlled dot was positioned inside the trajectory set by the controlled dot. If values were to be positive in theta, then the controlled dot would be positioned further ahead than the leading dot, and a positive rho value would indicate that the controlled dot had extended beyond the boundary set by the leading dot. The timing of such deviations would be informative as to the contributing cognitive operation in the decline in motor performance. It was possible that the harder variant of the task (more similar standards and targets) would introduce greater tracking deficits, particularly around the timing of P2, when a presented stimulus is being compared to the representation of a target.

Modulations in motor cortex activity: It was expected that performing a motor task would reduce alpha and beta power over the left motor cortex (indicative of the involvement of the primary motor cortex in the coordination of positioning the controlled dot). A repeated measures ANOVA with hemisphere (left, right), load (high, low), and task (motor-only, single task standard and target, dual-task standard and target) as factors was used with alpha and beta power as the dependent measure (performed separately for each). If either alpha or beta ERD was to be reduced in the dual-task condition relative to the motor-only condition, then it would be demonstrated that the processes involved in the oddball task interfere with activations of the motor cortex. If alpha or beta ERD was to be modulated by the template matching load, then it would be demonstrated that motor cortex activation during pursuit tracking is hindered by the process of differentiating target from standard stimuli.

Results

Oddball Detection Accuracy

To test the effects of dual-tasking and stimulus discrimination load on target detection accuracy, a 2 (Task: single, dual) x 2 (discrimination load: high, low) repeated measures ANOVA was used. There was a significant main effect of task ($F(1, 22) = 12.18$, $p<.01$, $\eta_G^2 = .031$), in that performance was lower during dual-tasking.

Event-related Potentials

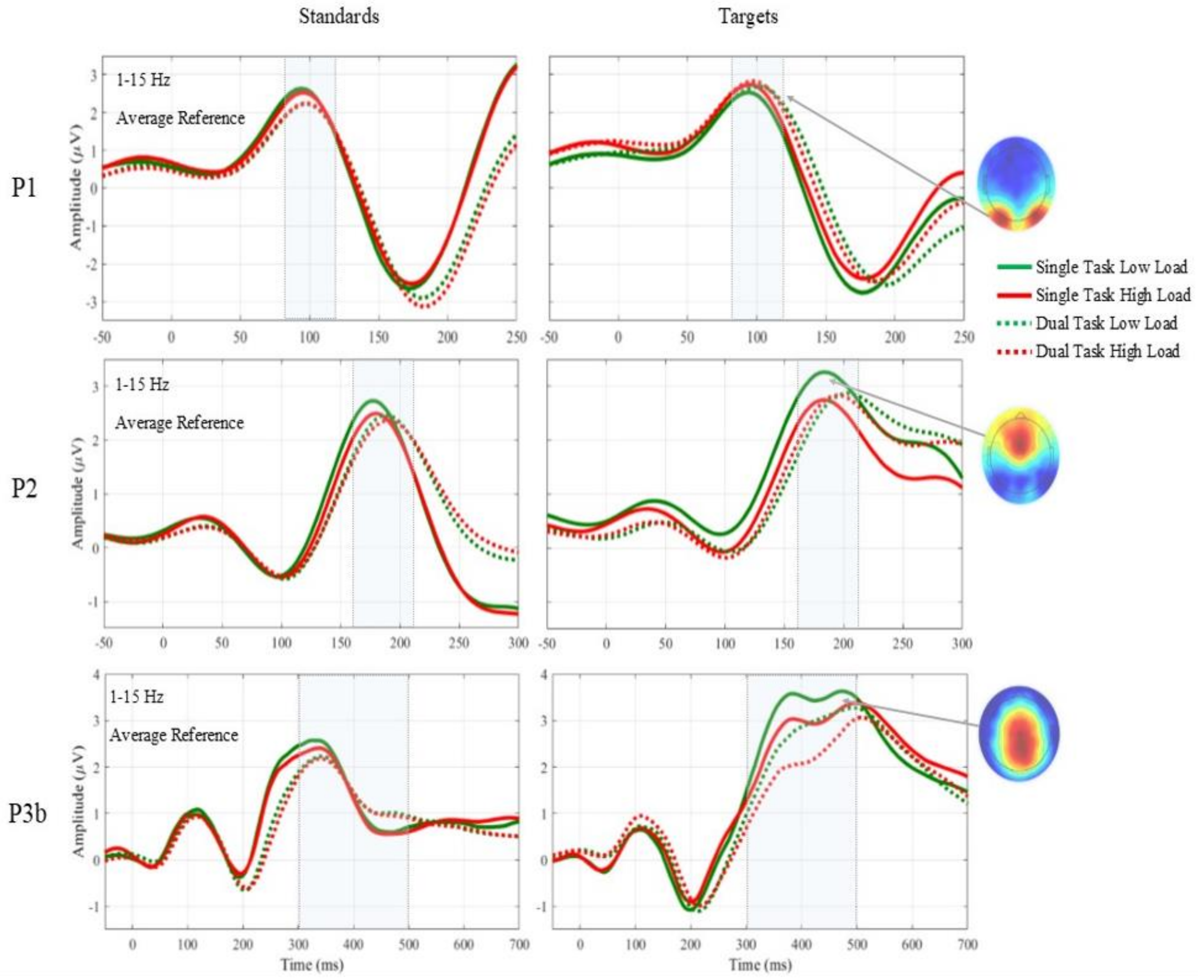

Figure 5.1. P1, P2 and P3b ERP component waveforms both standard (left) and target (right) stimuli in single and dual task under low and high discrimination load conditions. Waveforms are average referenced and show 1-15 Hz (for display purposes). Also shown are grand average scalp topographies for each ERP component. Dual-task effects were found for P1 (P1 amplitude for standard stimuli was lower than in the single task condition). P3b, but not P2, amplitude was lowered by dual-tasking. P2 and P3b for target stimuli were attenuated under high discrimination load.

The effects of dual-tasking and stimulus discrimination load on the amplitude of P1, P2 and P3b component waveforms were analysed using a 2 (Stimulus: standard, target) x 2 (Task: single, dual) x 2 (Discrimination load: high, low) repeated measures ANOVA.

P1: The main effect of stimulus was significant ($F(1,22) = 13.86$, $p<.01$, $\eta_G^2= .012$); P1 amplitude was higher for the target stimuli (there was more contrast alteration in the target Gabor patch), relative to the standard stimuli. The interaction between task and stimulus was also significant ($F(1,22) = 8.44$, $p<.01$, $\eta_G^2= .004$), where in the dual-task condition, P1 amplitude was lower for the standard stimuli relative to the single task condition.

P2: The main effect of stimulus ($F(1,22)=17.93$, $p<.01$, $\eta_G^2 = .02$) was significant, where target stimuli produced higher P2 amplitude than standard stimuli. There was also a significant main effect of discrimination load ($F(1,22) = 23.43$, $p<.05$, $\eta_G^2= .008$). There was also a significant discrimination load by stimulus interaction ($F(1,22) = 5.43$, $p<.05$, $\eta_G^2= .002$), in which P2 amplitude was attenuated for the target stimuli in the high discrimination load condition.

P3b: The main effects of task [($F(1,22) = 7.78$, $p<.05$, $\eta_G^2 = .02$); P3b was attenuated during dual-task trials)], discrimination load [($F(1,22) = 20.13$, $p<.05$, $\eta_G^2 = .007$); P3b was attenuated in the high load condition] and stimulus [($F(1,22) = 16.87$, $p<.01$, $\eta_G^2 = .08$); P3b was higher for target relative to standard stimuli] were significant. A significant task by stimulus interaction was also observed ($F(1,22) = 5.23$, $p<.05$, $\eta_G^2 = .004$). P3b amplitude increased less steeply from standard to target when performing the dual task. Finally, a stimulus by discrimination load interaction was observed ($F(1,22)=7.02$, $p<.05$, $\eta_G^2 = .002$), where P3b amplitude for target stimuli was attenuated in the high relative to the low load condition.

Event-related Spectral Perturbations and Fronto-parietal Coherence

Experimental effects on parietal and frontal alpha band power, and fronto-parietal alpha-band amplitude and phase coherence were analysed using a 2 (Task: single, dual) x 2 (Stimulus: standard, target) x 2 (Stimulus differentiation load: low, high) x 20 (time) repeated measures ANOVA. Time bins were of 50 ms duration and spanned 0-1000 ms post stimulus onset. Frontal alpha-band power was analysed over the 550-1000 ms time period, in 10 time bins.

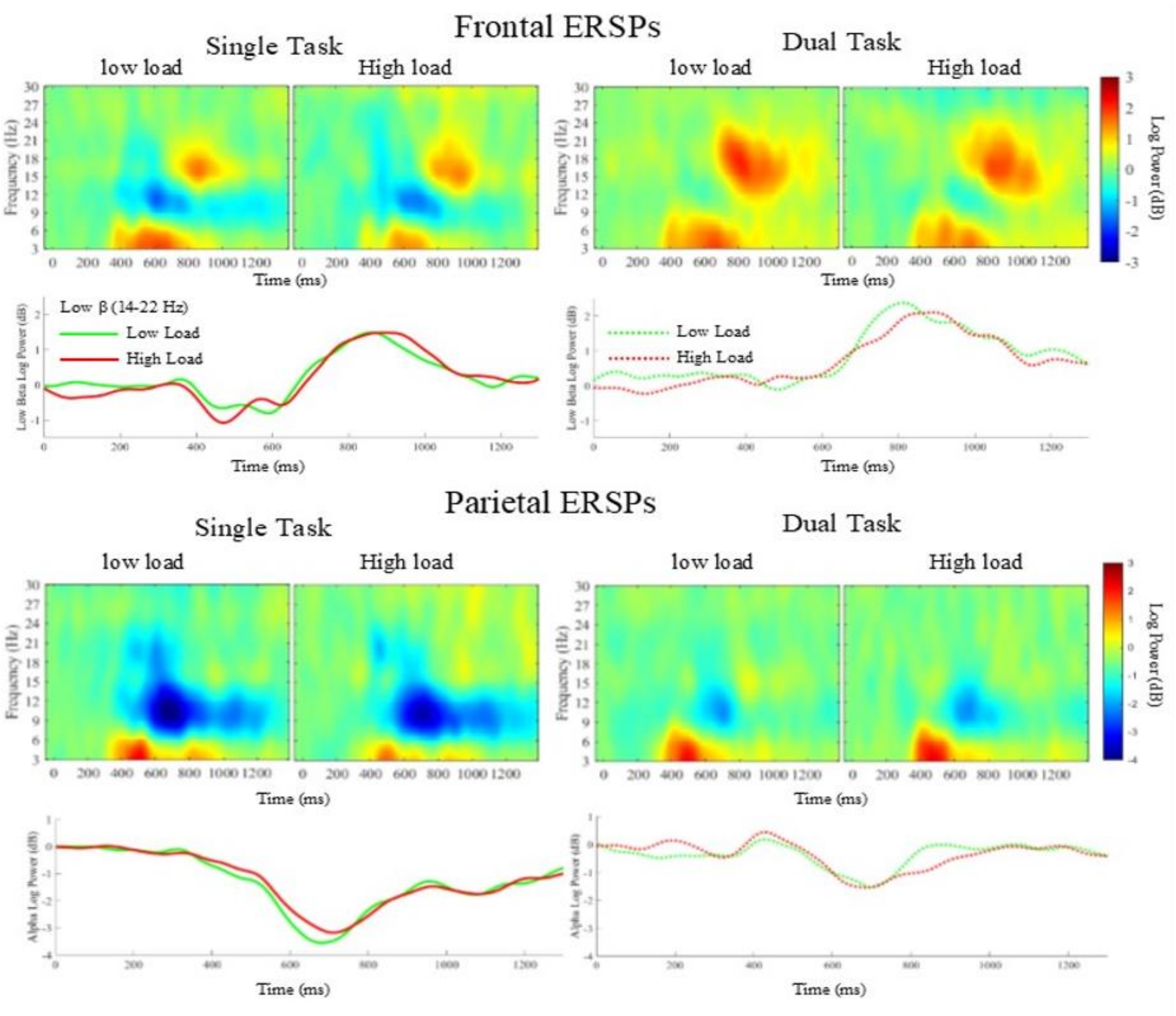

Figure 5.2. Time-frequency plots and derived low beta time series from frontal (top) and alpha band time series from parietal (bottom) for target stimuli in single (left) and dual (right) task conditions under low and high discrimination loads). Dual-tasking increased ERS for target stimuli. ERS was greater for the high discrimination load condition (high load) relative to the low load condition at 950 ms following stimulus onset. Target stimuli in the dual-tasking condition produced lower levels of parietal alpha ERD between 400 and 550 ms post stimulus onset.

Parietal Alpha Band Power

The main effect of time was significant ($F(19,418)=10.91$, $p<.001$, $\eta_G^2=.05$), as were the interactions task by time ($F(19,418)=4.05$, $p<.01$, $\eta_G^2=.008$), stimulus by time ($F(19,418)=22.06$, $p<.001$, $\eta_G^2=.03$), and the 3 way interaction between task, stimulus, and time ($F(19,418)=4.51$, $p<.001$, $\eta_G^2=.003$). Only for the target stimuli in the dual task, was there a reduction in alpha ERD. This was between 400 and 550 ms post stimulus onset. There were no effects of target discrimination load.

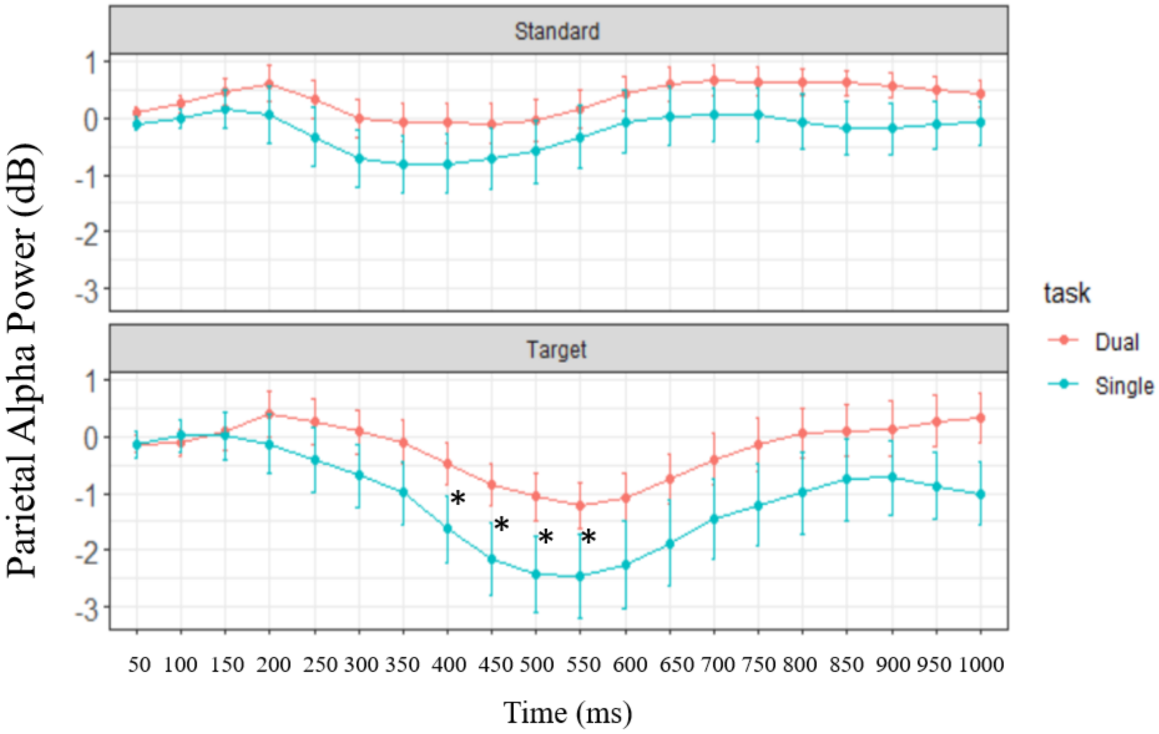

Figure 5.3. Parietal alpha band power showing ERD reduction due to dual-tasking between 400-550 ms post stimulus onset. Error bars show standard error.

Frontal Alpha/low-beta Band Power

The main effect of time was significant ($F(19,418)=10.92$, $p<.001$, $\eta_G^2=.02$), as was the main effect of task ($F(1,22)=6.59$, $p<.05$, $\eta_G^2=.03$) and stimulus ($F(1,22)=12.2$, $p<.001$, $\eta_G^2=001$). The significant interactions observed were stimulus by time ($F(9,198)=7.74$, $p<.001$, $\eta_G^2=.01$), and discrimination load by time ($F(9,198)=4.00$, $p<.005$, $\eta_G^2=.001$). In the stimulus by time interaction, significant differences between standard and target trials occurred between 550 and 700 ms post stimulus-onset, where frontal alpha power was greater for target trials than standard trials. An interaction between stimulus-discrimination load and time showed that frontal alpha/low-beta power was similar for both high and low load conditions, however stimuli in the high load condition displayed a slightly delayed response (peaked around 50 ms later than stimuli in the low load condition).

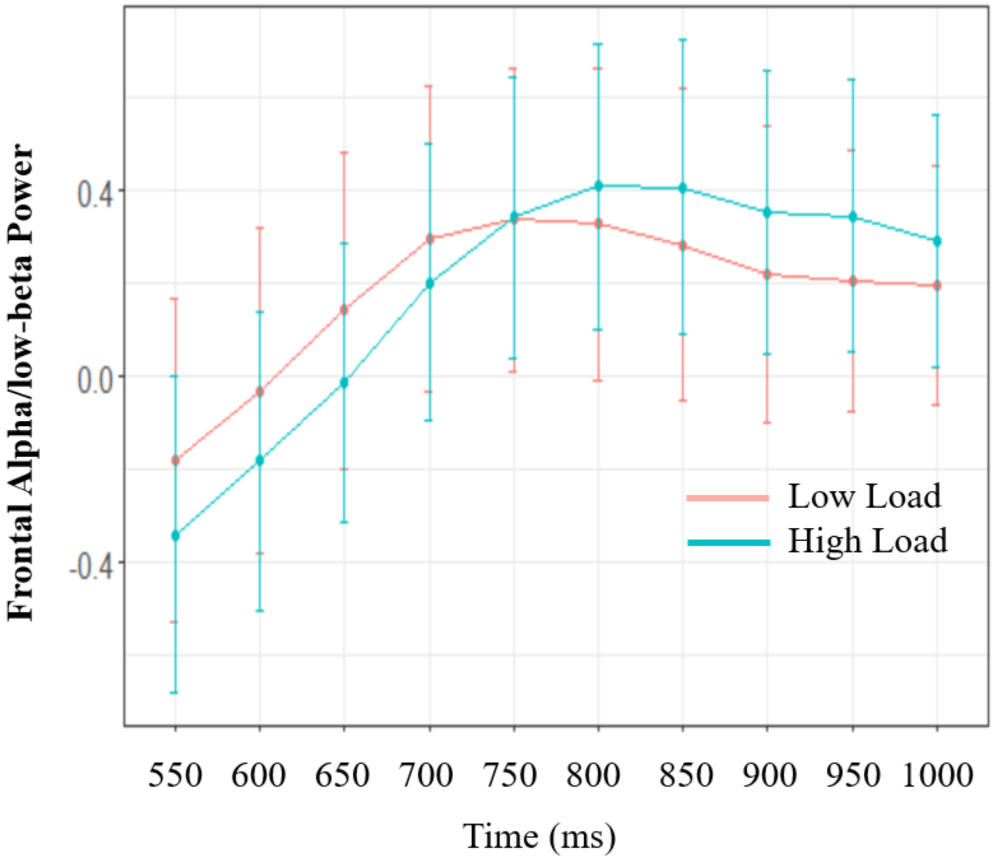

Figure 5.4. Frontal alpha/low-beta power for high and low discrimination load conditions between 550 - 1000 ms post stimulus onset. Both high and low loads present a similar pattern, with stimuli in the high load condition presenting a slightly delayed response. Error bars show standard error.

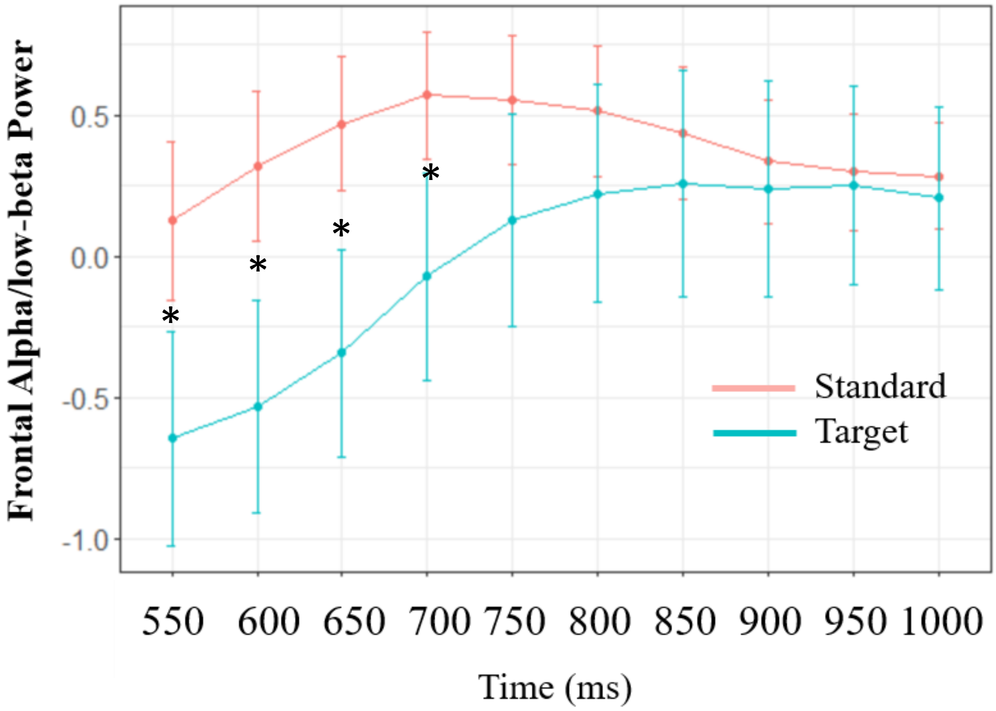

Figure 5.5. Frontal alpha/low-beta power for standard and target trials over time. Target stimuli generated lower ERS between 550-700 ms post stimulus onset. Error bars show standard error.

Fronto-parietal Alpha Band Coherence Magnitude Coherence:

The main effect of time was significant ($F(1,22)=4.58$, $p<.01$, $\eta_G^2 = .009$), as were the interactions task by time ($F(19,418)=3.56$, $p<.05$, $\eta_G^2 = .003$) and stimulus by time ($F(19,418)=3.84$, $p<.01$, $\eta_G^2 = .002$). Significant differences between single and dual task trials were observed in the time window 150-250 ms post stimulus onset, where fronto-parietal alpha magnitude coherence was reduced during dual-tasking. There were no differences related to stimulus-discrimination load.

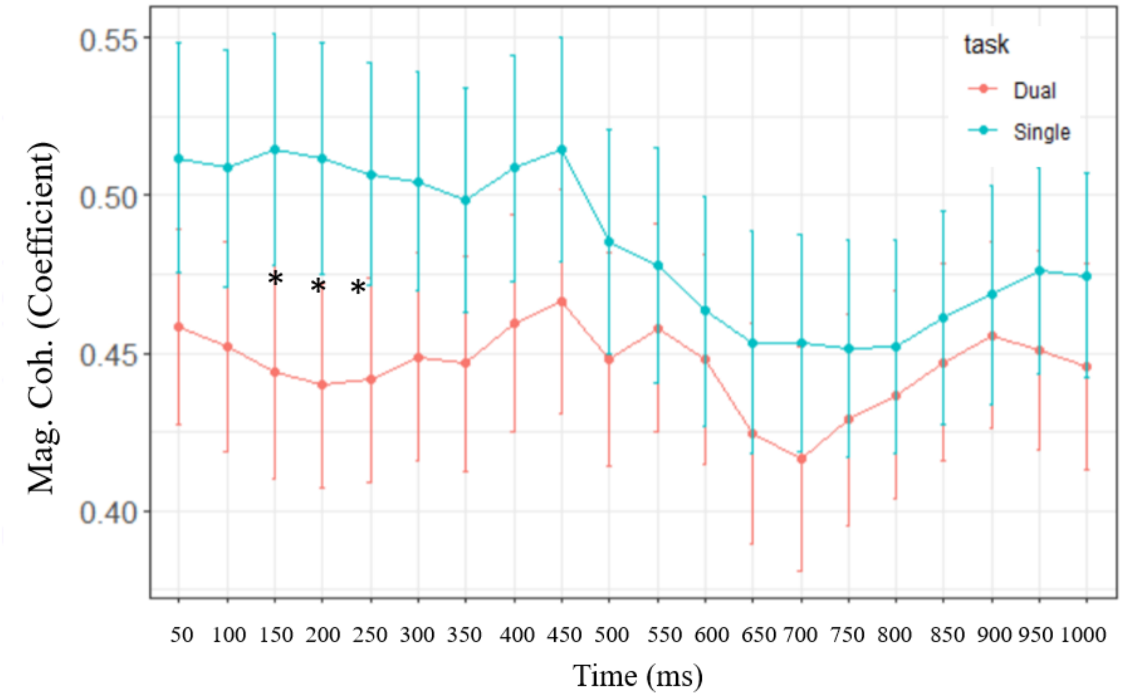

Figure 5.6. Fronto-parietal alpha-band magnitude coherence for single and dual task trials over time. Coherence in dual-task trials was significantly lower than single task trials in the 150-250 ms time window. Error bars show standard error.

Phase Coherence

The main effect of time was significant ($F(19,418)=3.66$, $p<.01$, $\eta_G^2 = .007$), as were the interactions task by time ($F(19,418)=3.51$, $p<.01$, $\eta_G^2 = .002$) and stimulus by time ($F(19,418)=2.45$, $p<.05$, $\eta_G^2 = .003$). Fronto-parietal alpha phase coherence was reduced during dual tasking during the150-200 ms window following stimulus onset. There were no effects of stimulus-discrimination load.

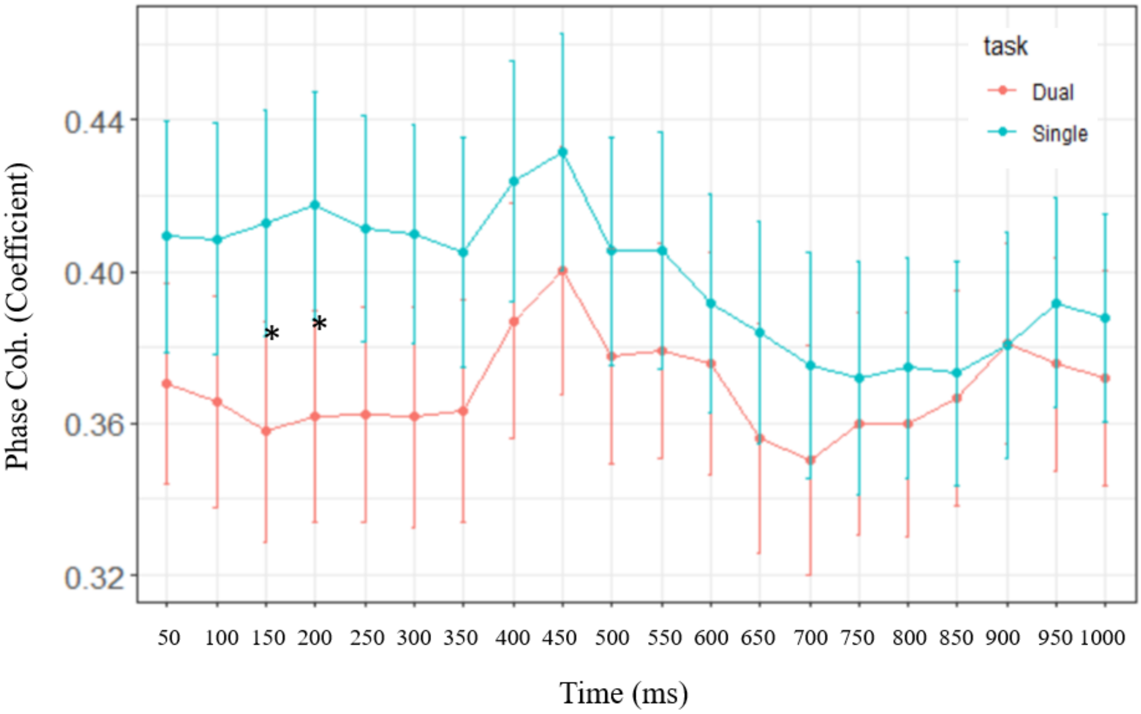

Figure 5.7. Fronto-parietal phase coherence over time. Fronto-parietal alpha phase coherence for single and dual-task trials over time. Phase coherence was significantly reduced during dual-task trials over 150-200 ms following stimulus onset. Error bars show standard error.

Visuomanual Tracking Deviations

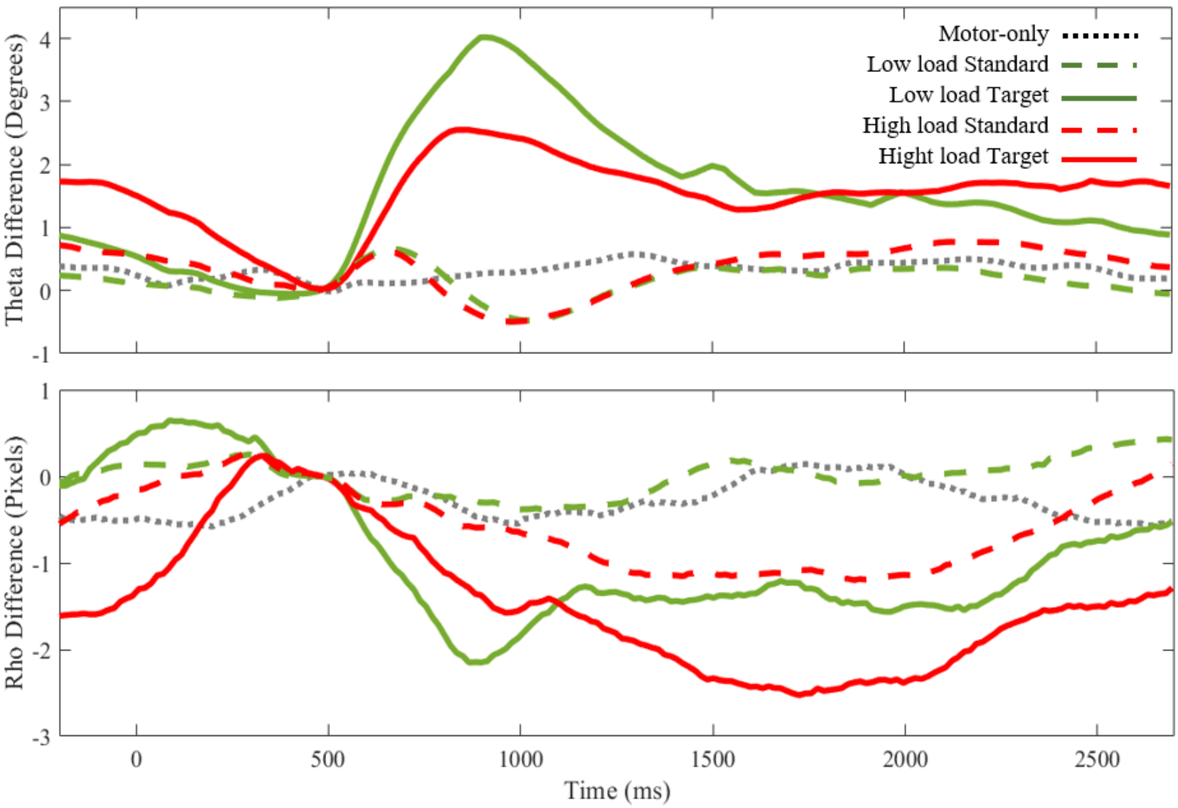

Figure 5.8. Rho/theta deviation time series for standard and target stimuli in the dual-task condition for low and high discrimination loads. Also shown is the motor-only task time series (in which no stimulus was presented). Time series are zero normalized to values at the average timing of the P3b peak (480 ms).

To examine the effects of task and stimulus differentiation load on both theta and rho deviations, a 3 (stimulus: motor-only (none), dual task standard, dual task target) x 2 (Difficulty: low similarity, high similarity) x 5 (Post P3b-delay: 300,600,900,1200,1500 ms) repeated measures ANOVA was used. As in Chapter 4, this analysis was done first with baseline correction applied at the average P3b peak (Fig. 5.8). This analysis highlighted tracking deviations in the post P3b period (as observed in Chapters 3 and 4). The manipulation in this experiment was of the attentional process preceding the P3b peak, but it is possible that differences in the loading of earlier processes would differentially impact tracking in this later time period.

For theta, a significant main effect of stimulus was found ($F(2,44)=9.80$, $p<.001$, $\eta_G^2 = .15$), whereby dual-task trials presented greater theta deviations than motor-only trials. A significant stimulus by time interaction ($F(8,176)=9.82$, $p<.001$, $\eta_G^2 = .03$) was observed, whereby target stimuli presented greater theta deviations than standard and motor-only trials over all time points (300–1500 ms post P3b time period). No effects of stimulus-discrimination load were observed for theta deviations.

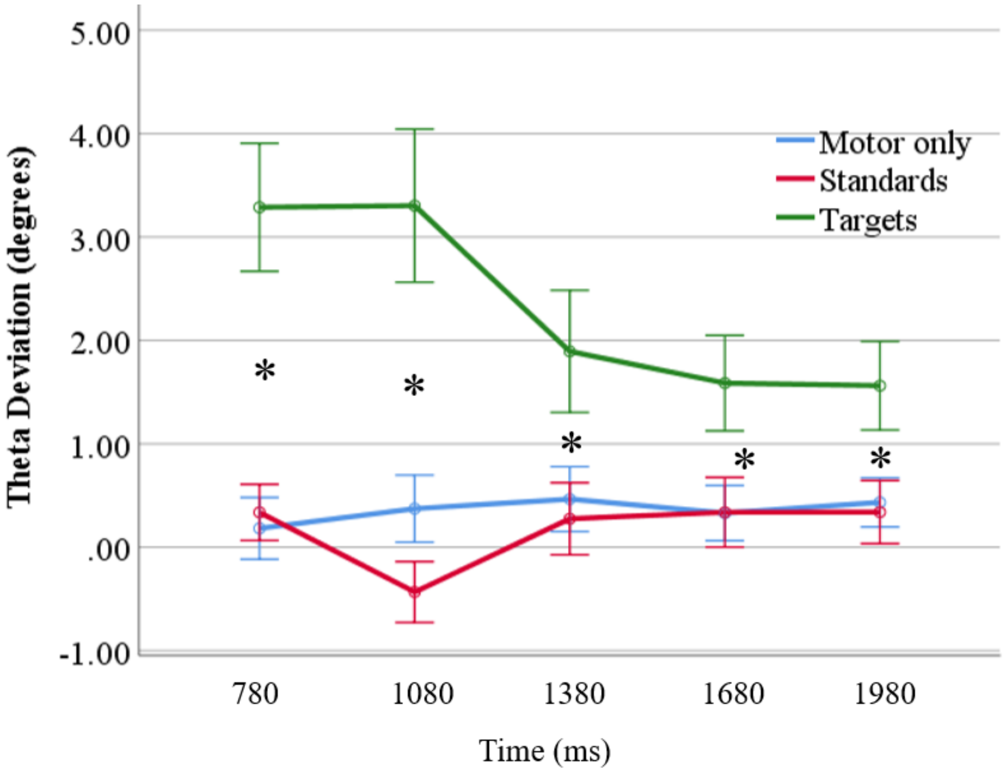

Figure 5.9. Theta deviation (P3b baseline corrected) for target and standard dual-task trials and for the motor-only task trials. Target stimuli generated greater (more positive) theta deviation in the 780-1980 ms post-stimulus onset period. Error bars show standard error.

For rho, the main effect of stimulus was significant ($F(2,44)=5.46$, $p<.05$, $\eta_G^2 = .05$); target trials showed greater rho deviation than standard and motor-only trials. No effects of stimulus discrimination load were observed for rho.

As in Chapter 4, the analysis of tracking deviation was also conducted with baseline correction applied in the pre-stimulus window. The load manipulation in this experiment affected the P3b period, so this analysis allowed the examination of any tracking deviations that may have preceded the P3b peak. For this analysis, the tracking time series were baseline corrected by calculating the mean of the deviation values in the pre-stimulus window for each condition, and removing this mean from each sample throughout the relevant epoch (Fig. 5.10). The time series were subsequently separated into 100 ms bins, from time zero (stimulus onset) to 500 ms, and the means calculated within each bin, for each condition/stimulus. A 3 (stimulus: motor-only, dual task standard, dual task target) x 2 (difficulty: low similarity, high similarity) x 5 (time window: 0-100, 100-200, 200-300, 300-400, 400-500) repeated measures ANOVA was used.

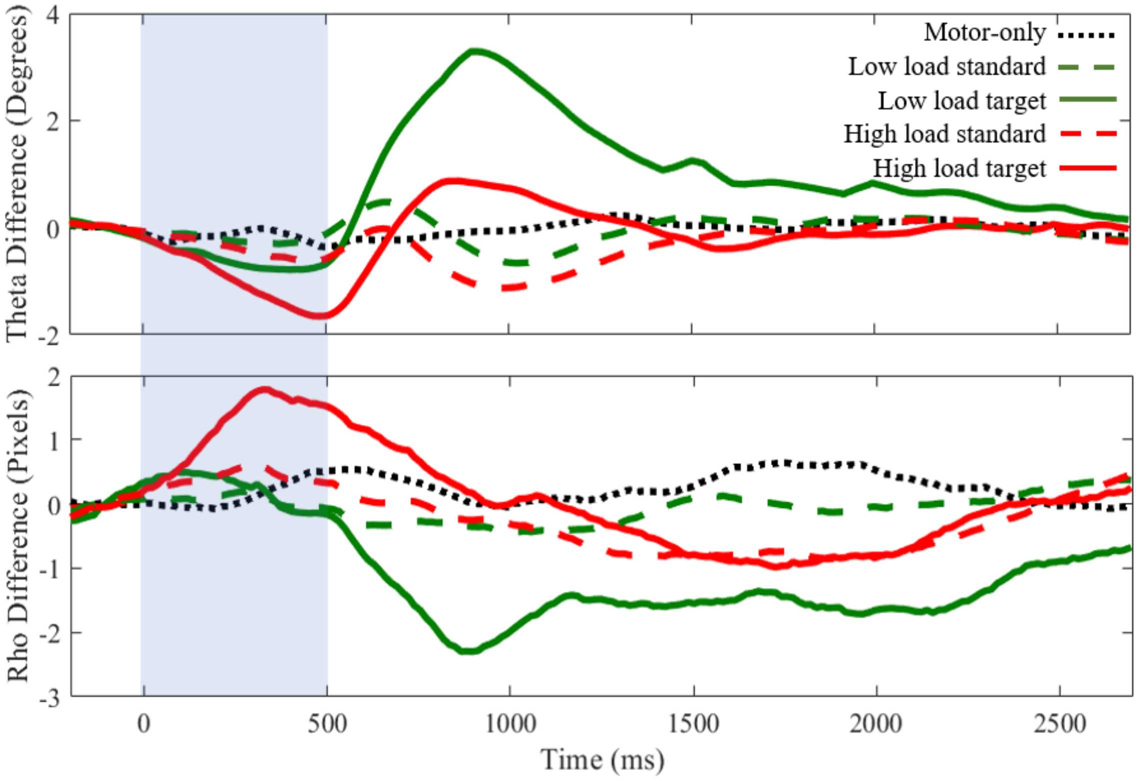

Figure 5.10. Rho/Theta deviation time series (pre-stimulus baseline-corrected). Blue square shows the period of analysis.

For theta, main effects of stimulus ($F(2,44)=5.09$, $p<.05$, $\eta_G^2 = .06$) and time ($F(4,88)=8.61$, $p<.001$, $\eta_G^2 = .02$) were observed. Target stimuli produced significantly greater theta deviation than both motor-only and standard stimuli. The interaction between stimulus and time was significant ($F(8,176)=4.78$, $p<.005$, $\eta_G^2 = .02$); target stimuli produced greater theta deviations than motor-only and standard stimuli from time period 3 onwards (i.e. 300 ms to 500 ms post stimulus onset) (Fig.

5.11). Finally, a stimulus-discrimination load by time interaction was ($F(4,88)=4.65$, $p<.005$, $\eta_G^2 = .005$), though following Bonferroni corrections, no pairwise differences remained significant. The numerical trend however, demonstrates that high load trials produced greater theta deviations (in the negative direction) than low load trials in the later periods of the analysis (Fig. 5.12).

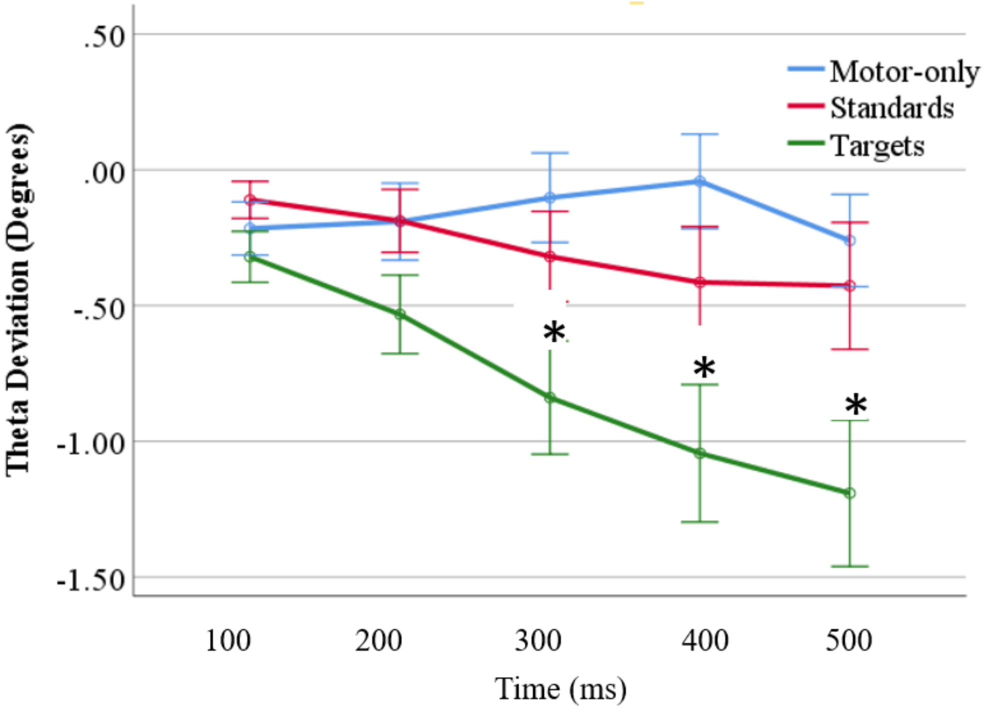

Figure 5.11 Theta deviations during the pre-P3b period. Target stimuli produced greater deviations (a slowing down) relative to standard and motor-only trials between 300 - 500 ms post stimulus-onset. Error bars show standard error.

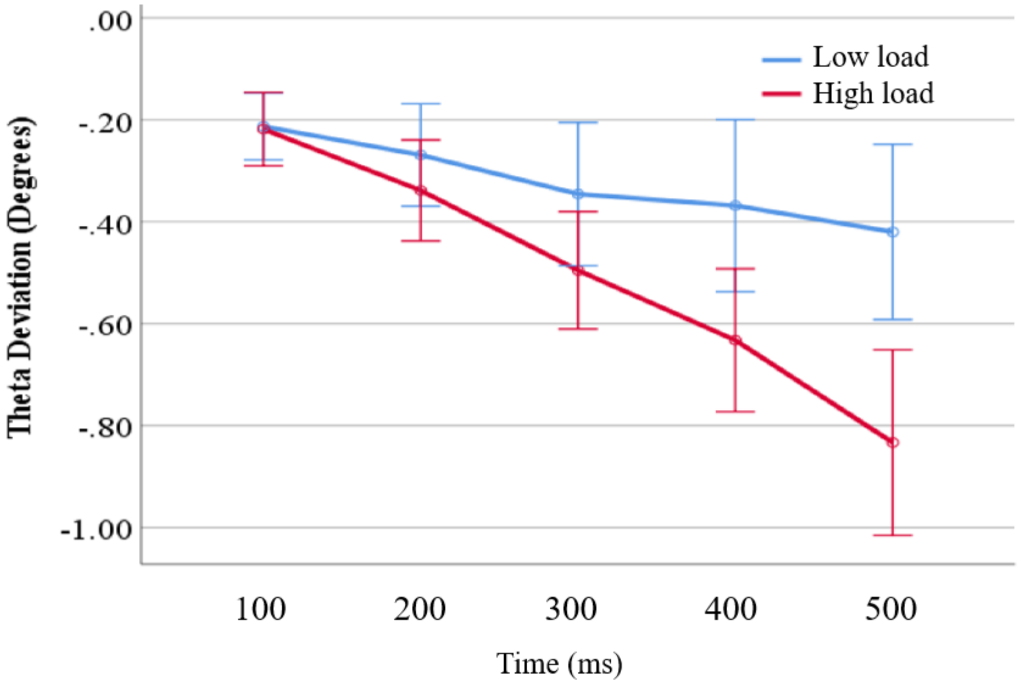

Figure 5.12. Theta deviation pattern in the pre-P3b period for high and low discrimination load trials. Error bars show standard error.

For rho, the interaction between stimulus, discrimination load, and time was significant (*F*(8,176)=4.44, *p*<.001, $\eta_G^2 = .01$). Target stimuli produced greater rho deviations than motor-only and standard stimuli when the difficulty was greater (Fig. 5.13). That is, the detection of target stimuli under more difficult conditions, forced the controlled dot beyond the boundary of the circle defined by the leading dot.

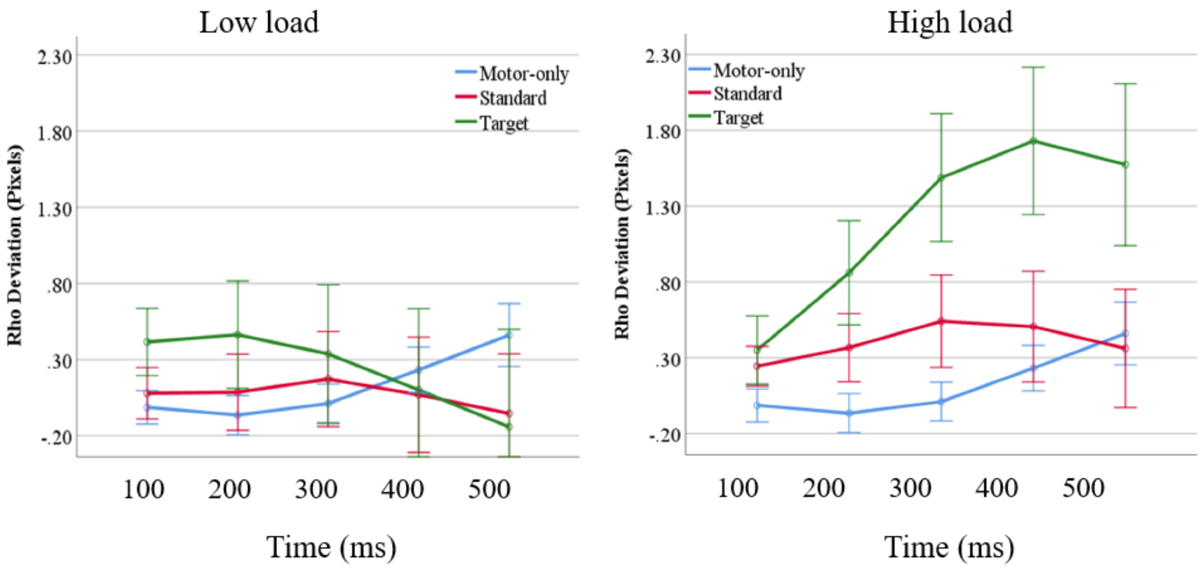

Figure 5.13 Stimulus discrimination load and rho deviations during the pre-P3b period. Error bars show standard error.

Effects of Oddball Task Performance on Spectral Power over Primary Motor Cortex

To observe the effects of oddball task processing on the spectral dynamics of the motor system, separately for alpha and beta power bands, a 2 (hemisphere: LH, RH) x 9 (task: low load single-standard, low load single-target, low load dual-standard, low load dual-target, high load single-standard, high load single-target, high load dual-standard, high load dual-target, and motor-only) repeated measures ANOVA was conducted using absolute power as the dependent measure. For the alpha band, a main effect of task was observed (*F*(8,168)=6.23, *p*<.005, η_G^2 = .05), where dual-task trials resulted in significantly less alpha power than single task trials (i.e., desynchronization was greater in the dual-task trials.

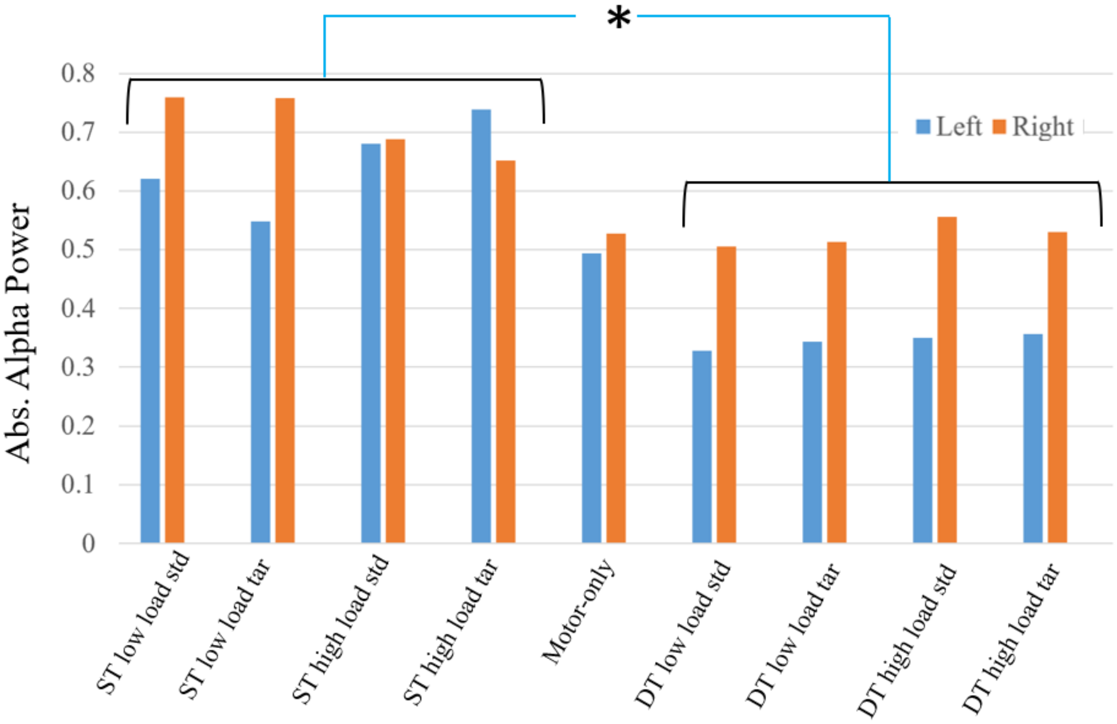

Figure 5.14. Alpha-band power over left (D19) and right (B22) motor cortex during all task conditions for standard and target stimuli. Dual-task conditions showed desynchronization (lower power). There was a numerical trend towards greater desynchronization in the left motor cortex in trials with the (right-handed) motor task.

In case any power differences occurred over shorter durations and therefore could not be detected over the whole trial period, spectral power over left primary motor cortex (contralateral to the moving hand) was analysed using a 5 (task: motor-only, low EF load dual-standard, low EF load dual-target, high EF load dual-standard, high EF load dual-target) x 6 (time: 0-200, 200-400, 400-600, 600-800, 800-1000, and 1000-1200 ms) repeated measures ANOVA. No significant effects or interactions were observed for alpha power. For beta power, a main effect of time was found ($F(5,110)=4.36$, $p=.005$, $\eta_G^2 = .02$). Stimulus discrimination load did not produce any significant differences in either alpha or beta power over left motor cortex.

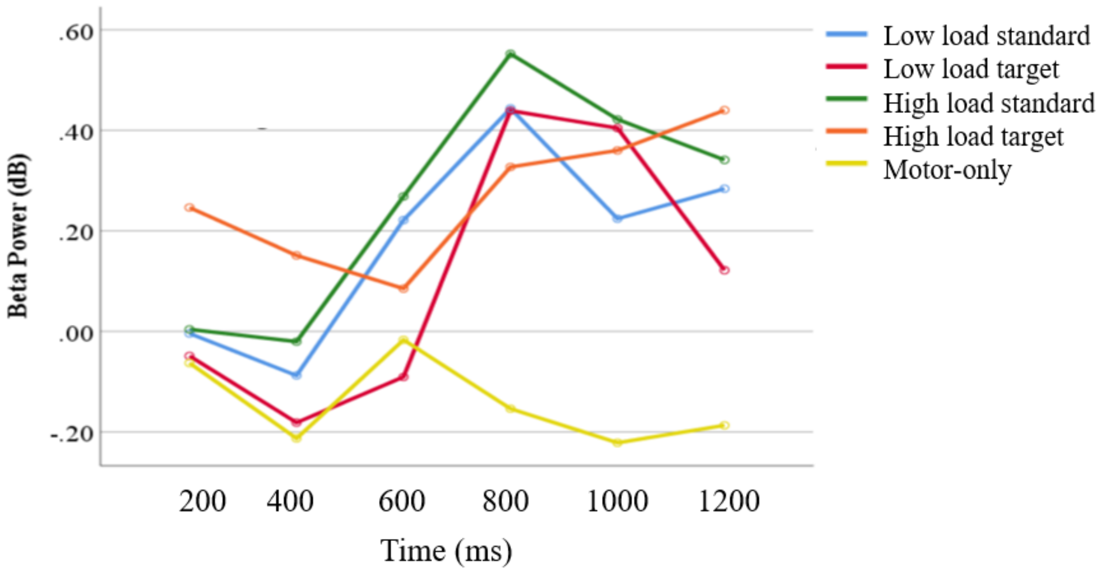

Figure 5.15. Beta-band power over left motor cortex for dual-task and motor-only conditions in the 0 - 1200 ms post stimulus-onset period. Although no significant interactions of task and time were found, there is a numerical indication of beta power modulation in the dual-task conditions beyond 400 ms post stimulus-onset.

Discussion

Experiment 3 explored the effects of manipulating the perceptual-attentional requirements of identifying oddball task targets on the electrophysiological indices of cognitive operations and on concurrent pursuit-tracking performance. This manipulation involved varying the degree of similarity between target and standard stimuli. Of primary interest was whether pursuit tracking deviations would manifest earlier than previously observed (i.e. before the time period in which the target count was updated).

Unlike in Experiment 2 (chapter 4), the accuracy of target identification was reduced during dual tasking, but it was unaffected by the stimulus discrimination load manipulation. The latter result meant that any other effects of the load manipulation could not be attributed to differences in accuracy between conditions. The lower accuracy under dual-task load suggests that the combination of increased stimulus complexity and lower standard-target discriminability led to a significant increase in overall workload when combined with the tracking task.

In Chapters 3 and 4, dual-task effects were confined to the attentional components P2 and P3b, and P1 remained unaffected by the simultaneous performance of pursuit tracking. In the present experiment, both perceptual and attentional loads were increased. Compared to the unfilled and filled circle stimuli in Chapters 3 and 4, the Gabor patches were harder to perceive as well as to discriminate. These additional loads appear to have been responsible for a dual-task effect on P1. A significant task by stimulus interaction was observed, where P1 amplitude was similar for single and dual-task targets, but lower for dual-task standards. This interaction requires further work to interpret unequivocally as it is not clear whether the dual-task standard or dual-task target data point is the anomaly. One possibility is that resourcing of the perceptual component suffered in the case of targets during the dual task. This could be due to the increased perceptual load presented by the target stimulus.

Both P2 and P3b ERP components exhibited the same dual-task effects as those observed in Chapter 3. The simultaneous performance of pursuit tracking attenuated both P2 and P3b amplitudes for target trials. Interestingly, an effect of stimulus-discrimination load was observed for both components. A significant load by stimulus interaction showed that P2 and P3b amplitudes to target stimuli were reduced in the high load condition. Higher discrimination load was expected to result in lower P3b amplitude if the manipulation succeeded in increasing the task’s attentional resource draw. The obtained load effect suggests this is what occurred, and corroborates findings from previous studies that increased the difficulty of stimulus differentiation (Comerchero & Polich, 1999; Fedota et al., 2012; Kok, 2001)

On the time-frequency measures, parietal alpha ERD for target stimuli during pursuit tracking was attenuated within the 400-500 ms post stimulus onset period, relative to single task targets. These findings present a similar picture to what was observed in Chapters 3 and 4, and in studies that demonstrate an increase in parietal alpha power (i.e. less alpha ERD) during higher mental workloads (Käthner et al., 2014; Krause et al., 2000). The degree of standard-target similarity resulted in no significant effects on parietal alpha ERD. For frontal alpha/low-beta ERS, a significant stimulus by time interaction demonstrated that frontal alpha/low-beta ERS was higher for standard stimuli in the 550-700 ms time period post stimulus onset. This is in contrast to the findings observed in

Experiments 1 (chapter 3) and 2 (chapter 4), where target stimuli elicited higher alpha/low-beta ERS than standard stimuli, presumably due to the additional operations required on the detection of a target. Here, it is possible that, given that the standard and target stimuli were physically similar (both in the low and high load conditions, relative to the simple circle stimuli used in Experiments 1 and 2), the difference was due to the difficult process of rejecting standard stimuli (i.e. inhibiting further processing) and may indicate increased distractor processing (Lavie, 2005). Figure 5.5 presents this interaction, and it can be seen that target stimuli display a somewhat lagged version of the standard stimulus. Frontal alpha/low-beta power does tend to become greater for target stimuli (relative to standard stimuli) later in the epoch, but this trend does not reach statistical significance.

A possible explanation for this is that the identification of a target stimulus took longer, which may have delayed subsequent processing. The discrimination load by time interaction was also significant and could also suggest a delayed identification of target stimuli in the high load condition, whereby both high and low discrimination load conditions presented a similar rise in frontal alpha/low-beta power from 550 ms post stimulus onset, however stimuli in the high load condition presented a delayed response (i.e. peaked 50 ms later).

The fronto-parietal network involved in perception, stimulus differentiation, target identification, and response preparation, was again shown to be prone to dual-task interference. Both alpha magnitude and phase coherence coefficients were reduced during dual-tasking in the 150-250 ms time period following stimulus onset. The performance of pursuit tracking reduced coherence in the attention phase of the oddball task, particularly in the stimulus discrimination phase. Modulations in fronto-parietal alpha coherence have also been previously demonstrated to be sensitive to the attentional demands of tasks (Kwon et al., 2015). No stimulus by time, or task by time interactions were observed, and so the dual-task effects demonstrated here did not discriminate between standard and target stimuli. The increased demand in stimulus discrimination therefore reduced the coupling of the fronto-parietal network during dual-tasking, regardless of the stimulus type.

Turning next to the effects of the oddball task on tracking performance, and considering the post P3b period first, both theta and rho deviation occurred for target stimuli (relative to standard and motor-only trials), but neither was affected by the stimulus-discrimination load manipulation. This suggests that the post-P3b tracking deviation pattern observed here (and in the previous experiments) was not connected to the oddball task's attentional load. Considering tracking deviation in the pre-P3b, however, target stimuli produced significant theta deviations (relative to standard and motor-only trials) from 300 ms post stimulus onset, and significant rho deviations during target trials when the stimulus discrimination load was increased. This is in contrast to Experiment 1 (chapter 3), where tracking deviations were not present until after P3b peak. Here, tracking deviations manifested during the stimulus differentiation stage (at 300 ms post stimulus onset). On the effects of stimulus-discrimination load, a significant interaction with time was found for theta, though this did not stand following Bonferroni correction. Figure 5.12 presents this interaction, and it can be seen that trials that are deemed more difficult, as they have a higher degree of stimulus similarity, present greater theta deviations than easier trials, and that this deviation is in the negative direction (i.e. trailing behind the leading dot). This finding coincides with significant deviations in rho during target trials in the higher load condition. That is, upon the detection of a difficult target stimulus, energy applied to controlling the dot is reduced. This is indicated by the reduced speed (decrease in theta), and the failure to contain the dot within the boundary defined by the leading dot (increase in rho). The reduction in applied energy results in the controlled dot 'swinging out' beyond the correct trajectory.

Given that the physical nature of the stimuli differs from those in the previous experiments, and that the identification of a target stimulus became more taxing, it was expected that the electrophysiological measures would present different patterns of interferences. A key challenge in introducing two levels of difficulty (low and high degrees of similarity), was the fact that making the task more neurophysiologically taxing, might have resulted in a reduction in the accuracy of target identification. If this had been observed, it would have been difficult to interpret patterns of tracking deviation. It would not have been possible to tell whether any average deviation differences between the levels of task difficulty were not due to more targets being missed in the higher similarity condition. Although target detection accuracy was reduced during dual-tasking (as observed in Experiment 1, and also as a numerical trend in Experiment 2), there were no differences in accuracy between the low and high stimulus-similarity conditions. This allows for the interpretation of dual-task interactions in all the measures concerned, without having to consider the effects of missed targets.

Finally, the effects of task dual-tasking and stimulus differentiation (stimulus similarity) load on motor-cortex activation was investigated. As with the previous experiments, a significant decrease (desynchronization) in alpha power was observed during both motor-only and dual-task trials, relative to oddball-only trials. This was predicted, as alpha/beta ERD over motor areas is indicative of activation of these areas (Pfurtscheller & Lopes da Silva, 1999), and these conditions involved the performance of the pursuit tracking task. Although no effect of stimulus-discrimination load was observed in alpha or beta power over the left motor cortex, a significant effect of time was found, whereby beta power significantly differed over time. Figure 5.15 shows beta power over time, and it can be seen that for all trials that contain a stimulus (i.e. all but motor-only trials), a ‘releasing’ of motor cortex engagement can be seen from 200-400 ms post stimulus onset (i.e. beta power increases). Though this was not found to be significant, a common pattern can be seen. Interestingly, this coincides with the theta deviations observed for target trials. Motor cortex engagement reduces, followed by an increase in theta deviation in the negative direction and rho deviation in the positive direction. Therefore, as the invested energy in the motor task is reduced (as indicated by an increase in beta activity), the controlled dot falls behind and extends beyond the lead dot’s trajectory.

Chapter 6: General Discussion

Dual-tasking is a ubiquitous component of everyday life. The dynamic and flexible nature of human cognition allows for successful performance on multiple simultaneous tasks, with little to no performance detriment in many cases. This success, however, depends on the types of tasks being performed, the commonalities between them, and the sensory domain in which they are placed (Halvorson & Hazeltine, 2019; Katus & Eimer, 2019; Pashler, 1994). Though the interactions between pairs of cognitive tasks allow for a detailed understanding of the dynamic attentional systems that govern dual-task performance, it is interactions between cognitive and motor tasks that merit thorough examination due to the potential risk to body safety. An abundance of studies have highlighted the susceptibilities of motor performance during non-motor cognitive processing, in healthy young adult populations (Al-Yahya et al., 2011, Matthews et al., 2006), aging populations (Hausdorff et al., 2008; Holtzer et al., 2012) and clinical populations (Bloem et al., 2001; Leone et al,. 2015; 2020, Manckoundia et al., 2006). Though modulations in motor performance due to the presence of a cognitive task may present minimal risk to the performer in many circumstances (e.g. reading while reclining a chair), there exist a number of motor-cognitive task combinations that involve safety risks if motor performance is jeopardised (e.g. driving while reading a road sign). Understanding how behavioural deficits manifest under the demands of processing cognitive task information while performing a continuous motor task, could allow for better designed environments that reduce the risk to both clinical populations, and healthy populations, when such dual task interference occurs.

As described above, motor-cognitive interferences can pose serious consequences for the human body. One must process incoming information and make judgements and decisions, all while operating the machinery of the body. If the ability to control the body becomes perturbed, then it could be argued that this would present greater risks to body safety than interruptions to cognitive performance. That is, the destabilisation of posture would present greater risks to body safety than the incorrect comprehension of a sentence while walking. In light of this, it might be expected that motor tasks (such as posture control) would be prioritised over any simultaneous non-motor cognitive operations. This is supported by the 'posture first' principle, whereby older populations demonstrate a prioritisation of motor performance, at the expense of cognitive task performance (Lacour et al., 2008; Lion et al., 2014). As for other populations, there are contradictory findings, whereby 'posture first' and 'cognitive first' prioritisation have been demonstrated for healthy young adults (Berger & Bernard-Demanze, 2011; Bloem et al., 2006; Jacob et al., 2011). The exact patterns of interferences are seemingly dependent on the complexity of the tasks, and the associated risks to body safety (Fraizer & Mitra, 2008).

The exact reasons as to why motor and cognitive tasks interact with each other are not yet fully understood. As described in the introduction, there exists three influential theories that address the dual-task interference patterns observed in the literature. The first describes performance deficits due to a limited central attentional capacity, which all simultaneous tasks 'tap' into (Kahneman, 1973). This theory suggests that interference patterns could manifest due to costs in attentional resource allocations. That is, in order to manage an increase in the demands of a task, additional resourcing would be required. If additional resources are not available (i.e. being utilised across other simultaneous tasks), then resources could be redirected from other tasks to cope with the additional demands, potentially resulting in performance deficits. This theory suggests a non-domain specific attentional resource pool, and that performance on any combination of tasks, would be dependent on the distribution of this pool. This theory could support the observations of motor-cognitive interference patterns during tasks that conceptually share little commonalities, as in the current set of experiments. Navon & Gopher (1979) present a similar theory, though argue that multiple resource pools exist, to manage separate types of task. This however would suggest that tasks which do not share the same resource pool, would not compete for the same resources, resulting in no change in performance on either task. However, task combinations that involve seemingly separate resource pools, for example, driving and talking (Beede & Kass, 2006), have been demonstrated to produce performance deficits, challenging this theory.

An additional explanation of observed interference suggests a limitation for some cognitive operations to be run in parallel. This 'processing bottleneck' approach (Ruthruff et al., 2001) suggests that the performance of a dual-task would be hindered, given the presence of a central, single channel that directs attention to relevant processes necessary to perform a task. Interference occurs when two tasks require access to this single channel at the same time. This model need not suggest a single bottleneck, the presence of multiple bottlenecks that are associated with different types of cognitive functions could also explain interference patterns.

In order to ascertain which theory best describes motor-cognitive interference, it is important to understand the exact measures, and their sensitivities to interferences. Many real-world scenarios, and indeed experiments, present an environment in which subtle interferences can be masked. That is, any disturbances to behaviour are contained within a tolerance level, and do not present measurable, or consequential deficits in task performance. Take for example the task of maintaining lane position whilst driving a car. Performance on this task only becomes problematic if the car is positioned outside of the lane. Given that the width of the car is smaller than the width of the lane, the car can deviate from a central position by some degree, without being considered a performance deficit. As with maintaining a stable posture; one can deviate from one's centre of pressure to some degree, without falling over. These examples show that one can maintain performance on a task without displaying performance deficits, by means of a flexible adaptation of the task(s), so that performance persists within a given acceptable tolerance.

The experiments described in the current thesis were designed to avoid performance deficits being masked. The pursuit tracking task exposed any observable change in motor performance due to the presence of cognitive load-bearing events. That is, slight deviations from baseline motor performance were detectable. It is also important to consider the exact cognitive components required for the performance of a cognitive task. If a cognitive task requires a complex synergy of high-level cognitive operations, then it is difficult to ascertain which specific operation poses a risk to motor control. By using a well understood, multi-component cognitive task (like the visual oddball task used in the current set of experiments), time-locked perturbations in motor performance could be observed alongside electrophysiological markers of specific cognitive operations and their sensitivities to concurrent motor demands, displaying the temporal dynamics, and the directionality of interference patterns. Also, by loading specific elements of the oddball task (i.e. by making it more ‘resource demanding’), it could be ascertained as to whether the pattern of interferences was either static or were dynamically modulated under different, more taxing conditions.

The design of the collective set of experiments, and the sensitivity of the measures presented in this thesis, were able to establish whether interference patterns were bidirectional or unidirectional, whether any interferences occurred at the same time within both tasks, or whether interferences present an asymmetric pattern. The manipulation of the loading of specific elements of the oddball task allowed for the understanding of whether stressing the system at different points throughout the task would modulate any observed interference patterns.

The presented series of experiments demonstrates the intricate patterns of motor-cognitive interference between the processing of task-relevant stimulation and the performance of a pursuit tracking task. The utilization of the well-studied visual oddball task allowed for the analysis of constituent cognitive operations across the time course of stimulus processing, while the use of a continuous pursuit tracking task allowed for the observation of instantaneous tracking deviations alongside the cognitive operations. Identifying the timing and shape of tracking perturbations in the context of the electrophysiological measures associated with the oddball task’s cognitive processes made it possible to identify which cognitive task elements contributed to performance deficits in CSC. It was also possible to identify which cognitive task element was affected by the addition of tracking in the dual-task setting. The first experiment highlighted detailed interference patterns in a basic motor-cognitive dual-task set. The observed patterns shaped the design of the subsequent experiments where experimental manipulations stressed specific elements of the cognitive task to further clarify the nature of dual-task interference patterns.

The visual oddball task can be considered to have four task elements (Figure 6.1). The first task element is the detection of a stimulus. Then, in the second element, the stimulus’ features are evaluated and compared to the target features held in working memory. The third element is the acknowledgement of the stimulus as a target (i.e., response relevance) and the preparation to respond. The final task element is updating of the target count, which is a manipulation of information held in working memory.

This discussion will summarise the dual-task interference patterns observed in the project's three experiments and consider the broader implications of the obtained results.

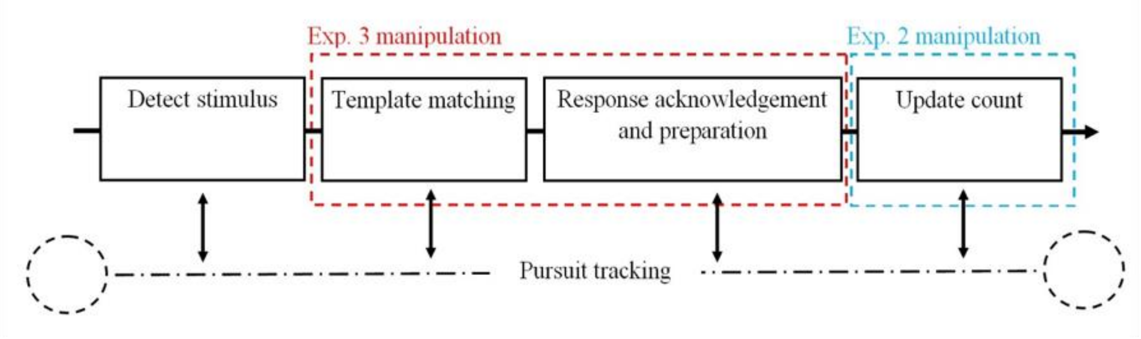

Figure 6.1. Schematic representation of four elements of the visual oddball task during motor-cognitive dual-tasking. The double-ended arrows show the periods in which interference patterns were analysed for both the oddball and pursuit-tracking tasks. The coloured dashed boxes indicate the task elements that were manipulated in Experiments 2 and 3.

Summary of findings

This section of the discussion will first detail the specific tasks used across the three experiments, followed by a discussion of the dual-task interference effects observed across each of the cognitive task elements.

Experiment 1: Understanding the fundamental interference patterns

The first experiment served as the basis for both Experiments 2 and 3 (chapters 4 and 5, respectively). Here, participants were presented with three tasks given in a counterbalanced order. In the oddball single task, participants were asked to mentally count the number of targets (filled green circles) amongst a continuous stream of target and standard stimuli (unfilled circles). The number of targets detected was reported at the end of each block of trials via a keypress. In the motor-only task, participants performed a pursuit tracking task in which the requirement was to continuously match the velocity and position of a small leading dot, by controlling a cyan coloured dot with a stylus on a digital graphics tablet. The leading dot rotated around a fixation cross in the clockwise direction at a comfortable velocity defined by a motor configuration task performed before any of the experimental tasks. In the dual-task condition, pursuit tracking and the visual oddball task were performed concurrently.

Experiment 2: Increasing the Executive Function load

The findings of Experiment 1 indicated an asymmetric interference pattern between the oddball and pursuit tracking tasks. Though adding the tracking task modulated the neural resourcing of cognitive task components as early as the second task element (template matching), pursuit tracking was not shown to be susceptible to interference until the final task element (the EF function of updating the target count). The second experiment was designed to manipulate the load of the updating element to further test the susceptibility of tracking performance to interference from the oddball task's final EF element.

Participants performed five tasks in a counterbalanced order; the motor-only task, in which participants pursued the leading dot rotating clockwise about the central fixation cross, and high and low EF load variants of both the single oddball task, and the dual task. In the low load variant of the oddball single task and dual-task, participants were started off with a random integer between 65 and 95 at the beginning of each block. On the detection of a target stimulus (green filled circle as in Experiment 1), participants were required to deduct 1 from the initially presented integer, and were required to continue to deduct 1 each time a target was detected. In the high EF load variant of the single oddball task and dual-task, a random integer was again presented at the beginning of each block, but the participants were required to deduct three each time a target stimulus was detected. Participants were instructed to refrain from computing the anticipated result before a target was presented/detected so as keep the EF load confined to the post target-detection period.

Experiment 3: Increasing the Perceptual-Attention load

The previous two experiments identified that the period in which CSC was susceptible to the simultaneous processing of cognitive load-bearing events, was constrained to the 4th and final element of the task. That is, during the executive function of updating the target count. Given that the stimuli used in the previous experiments were easily differentiated (filled green circles vs unfilled circles), it was of interest as to whether increasing the load of the perceptual and template matching element of the task (and in turn, the response acknowledgement element), would produce performance deficits in the pursuit tracking task, at the time of template matching or the acknowledging of the need to respond. In order to achieve this, the degree of physical similarity between standard and target stimuli was manipulated.

Purposefully, the simple stimuli used in the previous two experiments were replaced with grating stimuli. The difficulty modulation involved two types of target, presented in separate tasks. Targets in the low load condition differed to standard stimuli by a larger degree than in the low load condition. That is, the spatial frequency of the standard and target stimuli differed to a greater extent than in the high load condition. Participants completed five separate tasks; the motor-only task in which participants were required to pursue a leading dot rotating about a central fixation cross, and two levels of difficulty (low and high load) for the single oddball task and dual-task. These tasks were presented in a counterbalanced order. On all tasks with the exception of the motor-only task, participants were required to simply add one to a continuous count, starting at zero, on the detection of a target stimulus. On using this method, the EF loading of the task is matched with that of Experiment 1, and only the perceptual-attentional systems involved in elements 2 and 3 of the task are subject to the introduced load.

Each of the cognitive task elements will be discussed below in relation to the findings across the three presented experiments.

Element 1: Detection of a Stimulus

At around 100 ms following the presentation of a visual stimulus, the visual system generates an electrophysiological signature (P1), indicating successful detection of the stimulus. In chapters 3 and 4, where the oddball task presented basic filled and unfilled circles, target stimuli presented greater contrast than standard stimuli, resulting in a larger response of the visual cortex in both the oddball only task and in the dual-task. When comparing the response to target stimuli in single and dual-task conditions, no differences were observed. This demonstrated that the simultaneous performance of pursuit tracking did not interfere with the initial element of the oddball task when stimuli were easily detected and differentiated. Tracking deviations during the same time scale were non-existent, indicating that the processes involved in the successful detection of a stimulus did not produce measurable deviations in tracking performance. Given these findings, motor-cognitive interference was not observed during the first element of the oddball task when the oddball task stimuli are easily differentiated.

Only when increasing the perceptual-attention load do interferences manifest. The load introduced in Experiment 3 was intended to stress both perceptual and attentional processes utilized in the oddball task. That is, the stimuli used were more complex than those used in Experiments 1 and 2, and so the perceiving of a more feature-rich stimulus, relative to basic filled and unfilled circles, would require a more rigorous untangling of the information presented to the visual cortex. Given that both standard and target stimuli were designed to be similar in their physical features, it was predicted that their perception would demonstrate no differences in magnitude in the early response of the visual cortex (as indicated by P1). This was indeed the case, P1 amplitude did not differ for standard and target stimuli during single task conditions. However, when considering the impact of the pursuit tracking task on the perception of the stimuli, the response of the visual cortex was attenuated on the perception of standard stimuli, relative to the target stimulus. These findings are not easy to interpret without further work. For example, one could implement an additional (third) stimulus type, such as a distractor stimulus, so as to explore whether the reduction in P1 is specific to standard stimuli, or whether it is also observed for ‘target-like’ distractors. Regardless, the addition of pursuit tracking modulated the activity of early stage perceptual processes involved in element 1 of the task when the perceptual-attention load is greater. This modulation is the first instance of the effects of CSC on early stage visual processing throughout the set of experiments, and is likely due to the increase in the complexity of the stimuli presented. The increased loading of the systems used to detect basic physical features of visual stimulation, leads to the susceptibility of said systems to interference from CSC.

Given that the loading introduced in Experiment 3 was during the early stages of stimulus processing, it was of interest as to whether deficits in pursuit tracking performance would manifest at an early stage. Therefore, deviation analyses in polar space were carried out in the pre-P3b period, whereby deviation time series were baseline normalised using the pre-stimulus period, rather than using the value at the timing of the P3b peak. In doing this, any tracking deviations would be quantifiable, from the onset of the stimulus. These analyses demonstrated no such deviations in tracking performance during the first element of the task. Therefore, though CSC impacts early visual processes involved in perceiving the relatively feature-rich stimuli, CSC remains unhindered during this period.

Consequently, when the perceptual-attention load of the oddball task is low (i.e. stimuli are basic and easily differentiated), both CSC and visual processing remain unscathed. In the case of an increase in the loading of perceptual-attention mechanisms, CSC performance remains unhindered, at a cost to a modulation of low-level visual processing.

Element 2: Template Matching

At around 200 ms following the presentation of a stimulus, the detected stimulus is analysed for target features. This is achieved by a process of template matching, whereby the detected stimulus is compared to a representation of the target held in WM. When this template is successfully matched, the P2 ERP component is observed over fronto-central electrodes. When stimuli are easily differentiated (as in Experiments 1 and 2), during the performance of the dual-task, P2 for target stimuli was smaller than targets in the single task condition. This attenuation during dual-tasking demonstrated that the tracking task modulated template matching. The reduction in P2 amplitude suggests that attentional resourcing of template matching was reduced when the tracking task was added. The attenuation in P2 during dual-tasking is consistent with the reduced target detection accuracy observed during dual-tasking under basic task conditions.

Interestingly, when the EF load of the task was increased, this reduction in resourcing of the template matching process during dual-tasking, did not reduce the accuracy of target detection. It is important to acknowledge that this behavioural measure is not only sensitive to the successful detection of a target stimulus, but also the arithmetic involved in updating the count held in WM. Given this, it was expected that poorer performance in the target count measure would be observed in the high EF load variant of the oddball task and dual-tasks, as errors accumulated in the arithmetic operations would result in incorrect block totals. This however was not the case; the EF load manipulation did not reduce accuracy.

Within the same time scale, no significant tracking deviation patterns were observed when the perceptual-attention load was minimal (as in Experiments 1 and 2). Though pursuit tracking was shown to impede the cognitive task, the process of template matching did not introduce any concurrent performance deficits in tracking performance. It could be that attentional resourcing withdrawn from the template matching process are deployed in the performance of pursuit tracking so as to avoid performance deficits in CSC.

In the case where the perceptual-attention load is increased, the process by which a perceived stimulus is matched for target features held in WM becomes more demanding in the current experiment. Participants must maintain target features in a finer grained resolution than in both previous experiments. Given this, it could be expected that target stimuli are miss-identified, resulting in a detriment in performance on target counting. Were this to be the case, then any interactions observed would be difficult to interpret, given that any differences in the electrophysiological measures or pursuit tracking deviation patterns could be attributable to missed or false hit targets. Target count accuracy was not found to exhibit differences between hard and easy variants of the task. That is, participants were able to successfully identify targets and update the count, regardless of the loading of the template matching process. This success, however, became compromised during simultaneous CSC performance (as observed in Experiment 1). Target detection performance was found to be lower during dual-tasking for both easy and hard variants of the task.

Interestingly, though target identification and the proceeding count updating was not found to be compromised under higher loads (relative to lower loads), differences in P2 amplitude were found between the low and high load variants of the task. As with both previous Experiments, P2 amplitude was higher for target stimuli relative to standard stimuli, indicating the successful identification of a target stimulus. This amplitude was reduced, however, during the more demanding variant (higher load) of the task, where the standard and target stimuli were more similar. Therefore, the reduction of P2 amplitude likely reflects the increase in demands in the template matching process, in that the successful detection of a target stimulus does not produce as big a volley in the signal, given that the targets are not as obvious.

On the effects of CSC on template matching under more challenging stimulus differentiation conditions, no significant differences were found. This is in contrast to Experiments 1 and 2, in which the addition of pursuit tracking dampened the P2 response to target stimuli. Here, the template matching operation is demanding, and the attentional resourcing dedicated to such an operation might not allow for dilution. Therefore the introduction of the pursuit tracking task might not further dampen the P2 response, given it is already stressed by the increased load. In fact, during the current element of the task, significant theta and rho deviations in the pursuit tracking task were observed. Target stimuli produced greater theta deviations in the negative direction (trailed behind the leading dot) and greater rho deviations in the positive direction (extended beyond the trajectory defined by the leading dot) relative to standard stimuli and no stimuli (motor-only). This is the first instance of tracking deviations being observed throughout the performance of the task, and could explain the lack of effect of CSC on the already stressed template matching process. In other words, tracking performance is compromised, given that the template matching procedure is already operating at full capacity, and cannot further reduce its resourcing to compensate for performance of CSC, without compromising target count accuracy. When considering interactions between stimulus differentiation load and pursuit tracking, it can be seen that upon visual inspection of the theta deviation time series (see fig. 5.12), stimuli in the high load condition produced greater theta deviations in the negative direction, than those in the low load condition, and that this slowing down of the controlled dot in the high load condition became exaggerated from around 300 ms. In addition, target stimuli in the high load condition presented significantly larger rho deviations in the positive direction (extended beyond the trajectory of the circle defined by the leading dot. Therefore, towards the latter stages of the second element in the task, stimuli in the high load condition exhibited a more positive rho deviation than those in the low load condition. In combination with the decrease in theta, it appears that upon the detection of a target stimulus when differentiation is difficult, the controlled dot slows down, which causes the radial position of the controlled dot to extend beyond the circle boundary.

The fronto-parietal network utilized during the oddball task displays sensitivity to concurrent CSC in the current element, when the perceptual-attention load is manipulated. Both alpha magnitude and phase coherence were shown to be attenuated during dual-tasking. The maintenance of a demanding fronto-parietal network, particularly in the template matching phase of the task, is therefore shown to be compromised. Given that no stimulus interactions were observed, it appears that this attenuation is present for both standard and target stimuli. Though this network is demonstrated to be degraded during dual-tasking, participants are still able to maintain a high degree of accuracy when detecting targets and performing the associated arithmetic.

Therefore, under basic task conditions where stimuli are easily differentiated, template matching is modulated by the simultaneous performance of CSC, while CSC performance presents no deficits in accuracy. It is possible that the relatively untaxing template matching procedure, receives diluted resourcing in favour of the tracking task, which as a consequence, reduces oddball task accuracy. It is only when the perceptual-attention load becomes challenging, that no such apparent resource dilution is present, and as such, performance deficits manifest in the tracking task as a slowing down of the controlled dot, relative to the leading dot.

Element 3: Response Acknowledgement and Preparation

Once a target is identified, acknowledgement of the need to take further action is electrophysiologically manifested as a P3b ERP component, observed over parietal cortex. This top-down, attention-driven component exists alongside a number of other electrophysiological indices of target processing; a decrease in the power of on-going alpha oscillations (ERD), also observed over parietal cortex, a spike in alpha phase coherence between parietal and frontal sites observed at around 400 ms post target onset, and an event-related decrease in fronto-parietal alpha magnitude coherence.

Response acknowledgement and preparation was observed to be attenuated under dual-task conditions throughout all three of the presented experiments, as indicated by P3b. That is, regardless of the difficulty of the task, a dilution to P3b was observed during the performance of pursuit tracking. Again, when the perceptual-attention load of the task was untaxing (as in Experiments 1 and 2), no CSC performance deficits occur within the same period, indicating a potential redirecting of attentional resources to the performance of the pursuit tracking task, again resulting in performance deficits on the oddball task. Under more challenging conditions in which the perceptual-attention components are stressed, CSC performance deficits are present during the current task element, possibly indicating a continuation of the deficits introduced in the template matching element.

Interestingly, under higher perceptual-attention loads, P3b was attenuated during dual-tasking (in contrast to P2, where no such attenuation due to CSC was observed). P3b displayed the same pattern of attenuation to that of the index of template matching (P2) due to the introduced perceptual-attentional load. That is, targets in the higher load condition displayed a dampening of P3b, relative to the low load condition. Given the coincidence of significant theta deviations during this time, it is possible that CSC becomes susceptible to the loading of the template matching process, and thus the proceeding response preparation process. Therefore, though template matching could spare no resourcing to the simultaneous CSC task, response acknowledgement does demonstrate a dilution. This observed dilution, however, is not shown to correct the tracking deviations observed in element 2 (template matching). The sapping of resourcing of the processes involved in response acknowledgement, do not appear to get redirected to tracking performance, given the theta deviations observed during this time period. As with element 2, theta deviations during element 3 of the task continue to display greater (more negative) deviations in response to high load stimuli.

The increasing of the EF load associated with the oddball task modulated response acknowledgement processing, even though the introduced load was presented in element 4 of the task, in which EF operations were active. The effects of stressing the updating operation was therefore not limited to the processing involved in updating, rather, they were apparent in the preceding process of acknowledging the need to respond. This EF load-induced modulation was manifested as a reduction in P3b amplitude to target stimuli in the high EF load condition, relative to the low EF load condition. Given that this reduction in P3b amplitude is indicative of a reduced resourcing of the response-relevance acknowledgement process (Polich, 1987), it is possible that resourcing is reserved in anticipation of a more difficult EF operation, or that participants are performing the EF operation at this time.

In basic task conditions (as in Experiment 2), along with P3b, parietal alpha ERD and fronto-parietal alpha coherence were attenuated during dual tasking. Dual-tasking was found to impede the connectivity of the fronto-parietal network involved in the processing of target stimuli during the task (as indicated by a reduction in alpha magnitude coherence), both before and after element 3 of the task. The reason for the absence of statistical differences between single and dual task targets in fronto-parietal alpha magnitude coherence in element 3, is likely to be that for single task targets, coherence magnitude drops for a brief period of time, whereas this drop is not observed for dual-task targets, and the general level for alpha magnitude coherence is lower during dual-tasking. Coherence values, therefore, become similar (low) for single and dual-task targets during element 3.

It is worth noting that parietal alpha ERD was also modulated by EF load manipulations. Parietal alpha ERD was attenuated for targets during dual-tasking, relative to single task targets, and this attenuation compliments the pattern observed in P3b. During higher EF load conditions, this attenuation was exacerbated. This indicates that while participants anticipate a more difficult calculation, the pull on attentional resources as a consequence of simultaneous pursuit tracking is greater.

The behaviour of the fronto-parietal network underlying the oddball task under more difficult tally updating requirements, quantified using alpha magnitude and phase coherence measures, showed the same pattern observed in chapter 3. Dual-tasking reduced coherence measures, indicating that the inclusion of tracking task compromised the fronto-parietal network organised for the oddball task. Under more difficult stimulus differentiation conditions (as in Experiment 3), though alpha ERD was attenuated during dual-tasking, no effects of stimulus similarity (load) was found. Given the functional associations between P3b and parietal alpha ERD, it is surprising that this desynchronising is not sensitive to the load manipulation. Though, taken with the findings from chapter 4, this demonstrates a dissociation of P3b and parietal alpha ERD, suggesting that they may reflect the workings of separate cognitive operations.

Therefore, response acknowledgement processes were demonstrated to be sensitive to both the performance of CSC, and the introduction of a higher EF load. While perceptual-attentional demands are low, no performance deficits were observed in pursuit tracking. It is only when said demands are increased, that pursuit tracking deficits were observed, possibly an overflow from the deficits introduced in the template matching element.

Element 4: Updating the count

After identifying a target, participants were required to update the target count held in WM. This operation, the EF of updating, was associated with modulations in frontal alpha/low-beta power (ERS), beginning at around 600 ms post target onset, and remaining for a further 400 ms. During the basic addition of one to the target count (as in Experiments 1 and 3), it was found that the simultaneous performance of pursuit tracking increased alpha/low-beta ERS, relative to single task target condition. This suggests that the overall WM load involved in target count updating increased while dual-tasking. When the EF load of the task is increased, frontal alpha/low-beta ERS presents a different, more complex picture. Here, frontal alpha/low-beta ERS was attenuated during dual-tasking, which suggests that the addition of pursuit tracking compromised WM mechanisms involved in the updating of the target count. It appears that the EF load manipulation changed the way participants allocated working memory resources in the post-P3b period. It is notable that the high EF load condition also attenuated frontal alpha-beta synchronisation and this reduction did not interact with time and stimulus type. Thus, one effect of introducing the EF load manipulation, which increased the importance of the arithmetic involved in updating the target tally, appears to have been to reduce working memory resource allocation in the post-P3b period.

When increasing the perceptual-attentional load, the electrophysiological index of updating the target count did not present any differences between the high and low load conditions at any particular time point, though stimuli in the high load condition seemed to present a slightly delayed response relative to stimuli in the low load condition. This was expected, as the updating of the target count is performed following the successful identification of a target. Therefore whether a target is in the low or the high load condition, once it is considered a target, the updating operation is the same. The introduction of pursuit tracking was shown to increase alpha/low-beta ERS, as was observed in Experiment 1. This demonstrates the impact of CSC on the overall WM demands of the task.

Interestingly, a significant stimulus by time interaction showed that standard stimuli elicited greater alpha/low-beta ERS than target stimuli. This is in contrast to Experiment 1, where target stimuli (which encourage the updating operation) present greater alpha/low-beta ERS. These findings suggest that, if the increase in alpha/low-beta ERS is indicative of WM demands, then standard stimuli prove more demanding for the system, when they are physically similar to the target stimuli. That is, the inhibiting of responding to standard stimuli manifested as an increase in WM load.

The most salient feature of the observations in this final element is the presence of tracking deviations during target trials. When analysed in polar coordinates, it was clear that target stimuli (i.e. trials in which the EF function of updating was present) produced greater angular deviations in the positive direction (a phase advance of the controlled dot relative to the leading dot) than both motor-only (no stimulus) and standard stimuli, at around 700-1000 ms post stimulus onset. That is, participants ‘speeded up’ and extended beyond the position of the leading dot, whilst updating the target count.

When the EF load of the oddball task was increased, it was expected that both tracking performance and the mechanisms involved in the target count updating would be affected. This was confirmed in the tracking deviation analyses. High EF load trials resulted in a greater radial deviation than lower EF load trials. In the post P3b period, the controlled dot extended beyond the boundary defined by the leading dot to a greater extent during the higher EF load condition. Though no EF load effects were observed for angular deviation, greater angular deviation were found for target trials relative to standard and motor-only (no stimulus) trials, in that the controlled dot displayed a phase advance of the leading dot, from 700 ms to 1000 ms following target onset. In addition to these observed angular deviations, the time-course of left motor cortex activity was analysed. This showed a significant dip in both alpha and beta power (indicating increased activation of the motor cortex) between 400 and 600 ms post target onset. The rho and theta deviations observed here could present the behavioural consequence of this increase in motor cortex activation.

It was unclear as to whether the perceptual-attention load manipulation introduced in Experiment 3 would modulate the previously observed deviation patterns shown in the final element of the task, in Experiments 1 and 2. If the loading was to introduce tracking deviations prior to element 4, as was the case, then these earlier deviations could modulate the shape of the later deviations. The tracking deviation analyses revealed that, as in Experiments 1 and 2, target stimuli produced greater theta deviations. It was predicted that if the load manipulation was to modulate the tracking deviations in this element of the task, then targets in the high load condition would display greater deficits, given the greater difficulty in identifying them. Though this was not the case, it is useful to observe the effects of the load manipulation on the previous 2 elements of the task. Theta deviations become more negative during the preceding elements, thus the positive theta 'bounce' that is observed in the previous experiments in the current element, starts at a lower (more negative) level for the targets in the higher load condition. Therefore, targets in the higher load condition do not reach the same values (as high) as targets in the low load condition, which start from a more positive theta deviation value at the start of the current task element.

Therefore, CSC performance is demonstrated to be susceptible to interference during the EF function of updating, and this interference is modulated by the difficulty of the updating modulation. When the load is high, the controlled dot extends beyond the trajectory of the path defined by the controlled dot, more so than in the low load condition. The angular deviations present no such sensitivity to EF load, suggesting a general speeding up of tracking performance due to the EF operation, and not its difficulty. The activations of WM operations also appear to be sensitive to the nature of the updating operation. While increasing a target count by 1 is shown to increase activations, the information-reduction involved in subtracting from the target count, attenuated WM processing.

Synthesis

In all, the collective findings present a dynamic picture of interference patterns between continuous CSC performance and the processing of multi-element cognitive tasks such as oddball detection. The observed motor-cognitive interferences display an asymmetric, bidirectional pattern, whereby the cognitive task element that is susceptible to interference from the CSC task, does not necessarily introduce reciprocal interference within the CSC task during the same period. The presence, and even the direction, of interference patterns appears to be load-dependant. That is, the nature of the interference patterns (such as the timing and the direction), are shown to change as a function of task demands. The load-sensitive motor-cognitive inference patterns observed throughout the set of experiments, present an intricate dance of attentional resourcing to both cognitive task components and CSC task performance, throughout the different task elements.

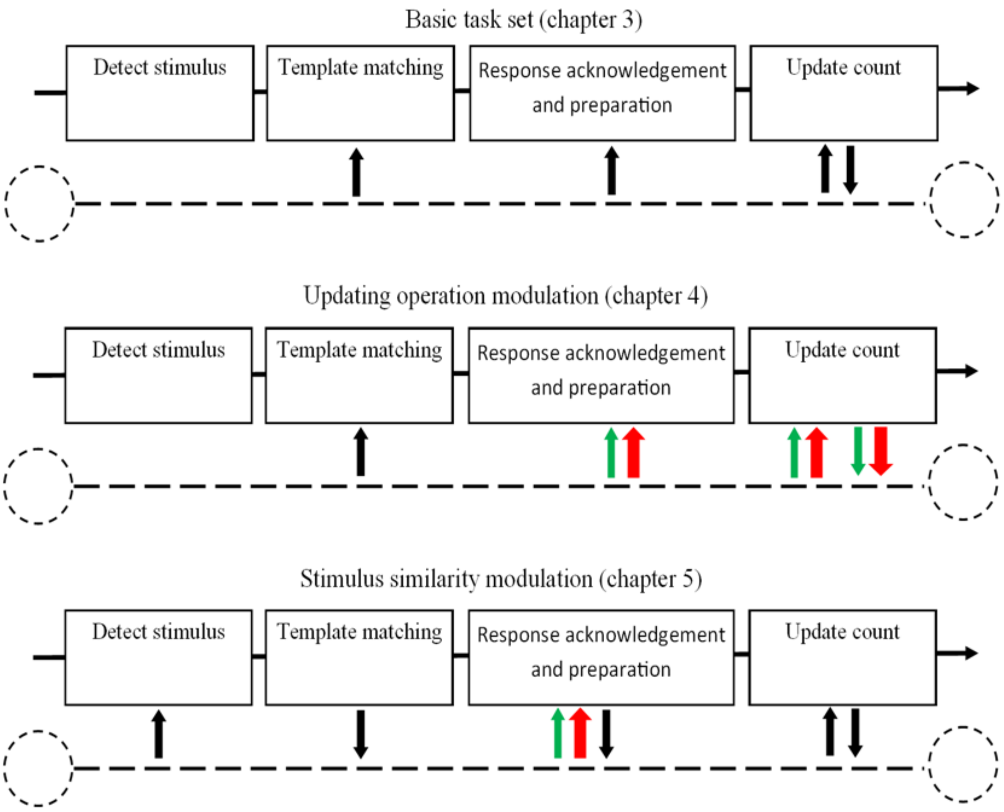

Figure 6.2. Summary of the observed dual-task interference effects and their direction. For each experiment, the cognitive task elements are shown above the continuous pursuit-tracking task. Green arrows indicate interference observed under the low load conditions (EF or stimulus-discrimination) and red arrows indicate the high load conditions. The width of the arrows indicate the relative magnitude of the interference. Black arrows indicate interference where no effects of task load were found.

The processes involved in detecting visual stimulation was only found to be compromised during simultaneous CSC, when the stimuli contained richer features and were harder to discriminate. That is, when oddball stimuli were simple and were easily identifiable (as in Experiments 1 and 2), visual processing remained unaffected by pursuit tracking. Though in the case where CSC did introduced interferences in the detecting of visual stimuli, no reciprocal interferences were observed in CSC performance. This unidirectional effect suggests a prioritization of motor performance over cognitive performance, and alongside similar findings for the attentional components of the task (see below), results in oddball performance deficits.

The demonstrated sensitivity of the attentional components of the task (template matching and response acknowledgement) to CSC appear to be modulated by both the increase in EF load and perceptual-attentional loads. Under basic dual-task conditions (Experiment 1), in which stimuli were easily differentiated, and the response requirements to target stimuli were to simply add one to a continuous count, CSC performance is maintained during the attentional components of the task. During this period of successful tracking performance, however, a reduction of resourcing to template matching and response acknowledgement processes takes place (possibly re-directed to the tracking task in order to maintain accuracy), which as a consequence, produces inaccuracies when detecting and counting task relevant stimuli, as indicated by oddball task performance.

When the load of the EF updating operation was increased (as in Experiment 2), template matching again proves sensitive to simultaneous CSC without simultaneous detriment to CSC performance, while response acknowledgement processes demonstrate a susceptibility to EF load and CSC. That is, when participants were required to minus 3 from the continuous count held in WM, the effect of CSC on response acknowledgement and preparation processes were exacerbated, again in the absence of deficits to CSC performance. This again demonstrates a prioritization of the motor task over the cognitive task during this period. This ‘motor first’ strategy is often demonstrated in the dual-task gait literature, whereby older populations demonstrate a prioritisation of motor performance, at the expense of cognitive task performance (Lacour et al., 2008; Lion et al., 2014). As for other populations, there are contradictory findings, whereby ‘posture/motor first’ and ‘cognitive first’ prioritisation have been demonstrated for healthy young adults (Berger & Bernard-Demanze, 2011; Bloem et al., 2006; Jacob et al., 2011).

When the perceptual-attentional load of the task is increased (as in Experiment 3), the direction of the interference during the attentional elements of the task is modulated, and the previously observed motor-task prioritization is no longer evident. Tracking deviations were present during the process of template matching, where targets in the more difficult (higher load) condition, tended to present more ‘lagging’ of the controlled dot, relative to the lower load condition. Interestingly, the template matching process was shown to be reduced during higher loads, but demonstrated no sensitivity to CSC performance under either low or high loads. Therefore, when stimulus differentiation is demanding, attentional resources cannot be diluted and redirected to the performance of the simultaneous pursuit tracking task, if performance on the cognitive task is to be without deficit. In contrast to template matching, response acknowledgment processes were attenuated by simultaneous CSC, and this was further exacerbated in the high load condition. The introduced tracking performance deficits during template matching continued throughout the response acknowledgement element, though this was not found to be sensitive to perceptual-attentional load.

Across all presented experiments, the EF function of updating the target count introduced performance deficits in CSC. The shape of the perturbation observed in CSC performance presented a ‘speeding up’ of the controlled dot at around 700 ms following the presentation of a target (i.e. when the count was being updated). That is, the ability to tightly constrain the velocity of the controlled dot was compromised, resulting in a phase advance of the controlled dot relative to the leading dot. When the EF updating operation was more difficult (as in Experiment 2), tracking deviations were more prominent, whereby participants extended beyond the trajectory of the leading dot more so than in the lower load condition. These findings suggest a specific susceptibility of CSC during the EF function of updating, which is evident across all variations of the task.

The effects of CSC on the mechanisms involved in the updating operation are shown to be dependent on the type of task, though in all cases, the performance of CSC modulates frontal WM mechanisms involved in the target count. In Experiments 1 and 3, where the response requirements are to simply add one to the target count, considered measures suggest an overall increase in WM demands, during the updating operation while performing CSC. This increase coincides with significant tracking deviations, suggesting a redirection of resourcing from the pursuit tracking task to the updating operation. When the EF load is increased, and the response requirements are to subtract from a continuous count (as in Experiment 2), the pattern of interferences during the updating operation become more complex. The mechanisms associated with target updating appear to demonstrate the opposite effect of those observed in Experiments 1 and 3, whereby an attenuation of frontal WM mechanisms is observed during pursuit tracking, rather than an indication of increased engagement. The change in nature of the updating operation was shown to modulate the impact of CSC on WM mechanisms. Though it cannot be claimed that the higher level of difficulty specifically compromised WM operations, it was demonstrated that the deducting of an integer from the continuous count, in combination with CSC performance, reduced resourcing to WM operations, whereas the addition of CSC performance whilst simply adding one, enhances resourcing. This demonstrates that the impact of CSC on cognitive operations required for updating a count, is dependent on the nature of the updating operation.

Interestingly, the increase in the loading of the updating element of the task, impeded prior response acknowledgement operations (as indicated by an attenuation of P3b), but did not introduce tracking deviations during the same period. This observation presents a dilution to resourcing of P3b, possibly due to the anticipation of a difficult arithmetic operation (manifesting as a reservation of resources), or due to participants performing the arithmetic before arriving at the decision that the stimulus is a target. Given that pursuit tracking performance is unhindered during this period, it is possible that P3b resourcing is redirected to maintain tracking performance and to concurrent arithmetic performance if performed prior to target acknowledgment.

The pattern of tracking deviations across the presented experiments suggests CSC susceptibilities to WM and EF mechanisms, and that the impact of such mechanisms presents different patterns of interference. When a stimulus is compared to that of a representation of a target stimulus in WM (when template matching is difficult), a slowing down of CSC is observed, whereas the EF updating operations presents a speeding up of CSC.

Measure	Experiment 1 (Chapter 3)	Experiment 2 (Chapter 4)	Experiment 3 (Chapter 5)
Oddball Accuracy	DT reduced accuracy	No effect of DT or EF load. Trend towards lower accuracy during DT.	DT reduced accuracy. No effect of load
P1	Targets produced larger P1 amplitude.	Targets produced larger P1 amplitude.	Targets produced larger P1 amplitude. Amplitude is reduced for standard stimuli during DT
P2	Targets produced larger P2 amplitude. Target amplitude reduced during DT.	Targets produced larger P2 amplitude. Target amplitude reduced during DT.	Targets produced larger P2 amplitude. No reduction during DT. Reduced amplitude to targets under higher load.
P3b	Targets produced larger P3b amplitude. Target amplitude reduced during DT.	Targets produced larger P3b. Target amplitude reduced during DT. Higher EF load reduced target amplitude.	Targets produced larger P3b. Target amplitude reduced during DT. Higher load reduced target amplitude.
Parietal Alpha ERD	Reduction of ERD to targets during DT in the 450-650 ms post stimulus period.	Reduction of ERD to targets during DT, which was exacerbated under higher EF load. ERD was greater under higher EF load.	DT reduces alpha ERD to target stimuli between 400 and 550 ms post stimulus onset.
Frontal alpha/low-beta ERS	Targets produced greater ERS during DT between 650-750 ms post stimulus period.	Targets produced greater ERS, which was reduced during DT. ERS reduced during higher EF load.	Targets produced greater ERS. ERS was increased during DT. ERS was greater under higher load at 950 ms post stimulus onset.
Fronto-parietal Alpha Mag. Coh.	Reduced during DT across the epoch. Negative dip seen for single task not present during DT.	Reduced during DT from 500-600 ms post stimulus onset	Reduced during DT from 150-250 ms post stimulus onset.
Fronto-parietal Alpha Phase. Coh.	Reduced during DT around 450 ms post stimulus onset.	Reduced during DT.	Reduced during DT from 150-200 ms post stimulus onset.
Theta	Targets induced positive deviations between 700 to 1000 ms post stimulus period.	Targets induced positive deviations at 720 ms post stimulus onset.	Targets produced negative deviations in the 300-500 ms post stimulus period. Tendency for higher load to produce greater deviation. Targets produced positive deviations in the 780-1980 ms post stimulus onset.
Rho	Rho deviation were greater at 500 ms post stimulus onset relative to any other period. Though the difference is on the order of sub-pixels.	Tendency for negative dip between 400-500 ms post stimulus onset. Greater (positive) deviations under higher EF load, for both standards and targets after P3b peak.	Targets produced greater (positive) deviations under higher load in the time period preceding P3b.
Spectral Power over Motor Cortex	Reduced during DT (indicative of motor task).	Reduced during DT (indicative of motor task). Targets presented greater activation of left motor cortex between 400-600 ms post stimulus onset.	Reduced during DT (indicative of motor task). The time-course of beta activation over left motor cortex differed across the epoch.

Table 6.1. Modulations of measures across the experiments. A brief description of the modulations of each of the measures across all experiments

Findings within the framework of theories of attention and potential patterns of interference. Within the introduction, I described dual-task interference within the framework of three theories of attention. That is, capacity sharing models, bottleneck models, and cross-talk models. Though the motivation of the current set of experiments was not to provide evidence for or against any particular theory of attention, the presented findings could offer insights as to which model best explains dual-task costs. The data derived from the present set of experiments suggest an intricate dance of attentional resourcing to simultaneous processes associated with both of the single tasks that is dependent on the loading of particular components of the oddball task. This could be indicative of a capacity-sharing account of attention. That is, attentional resourcing is dynamically modulated in order to accommodate successful dual-task performance. The attenuation of ERP components at specific time points and it's sensitivity to load manipulations suggests this to be the case. Time-locked perturbations to motor performance may also demonstrate a shift in attentional resourcing. For example, in chapter 5 (stimulus-differentiation manipulation), P2 amplitude which was usually diluted to accommodate successful tracking performance, was no longer reduced when template matching became more difficult. Successful performance in the oddball task became so demanding that a strategic adjustment of resources was not possible. As a consequence, tracking performance was impeded. These findings could also be explained by the attentional blink (Shapiro, 1977), whereby attention to the behaviour of the leading dot could not be deployed, given the unresolved processing of the difficult-to-identify target stimulus.

As for the bottleneck account of attention, these data do not suggest a single channel for information processing demands. The specific parametric impact of the introduced load manipulations suggest a more complex and dynamic picture of attention, unless the proposed theoretical bottleneck(s) allow for a modulation in their capacity to process more than one operation simultaneously. As for cross-talk models of attention, the current set of experiments do not offer enough variety in task or response types to afford any specific insight.

Also detailed in the introduction is a classification system to describe 9 possible interference patterns that can manifest in cognitive-motor dual-tasks (Plummer et al. (2013). It is evident that a number of interference patterns were present in the current set of experiments which occurred at different time points throughout the processing of oddball task stimuli. Specifically, motor-related cognitive inference (performance in the motor task remained stable, however cognitive task performance was degraded) was observed. Pursuit tracking remained stable while attentional ERP component amplitudes were reduced, resulting in a reduction in oddball task performance. Cognitive-related motor interference (whereby performance in the cognitive task remained stable, however motor-task performance was degraded) was also observed. Participants failed to control the tangential energy input required to manoeuvrer the controlled dot whilst performing the arithmetic necessary on the detection of target stimulus and whilst performing a difficult target-standard differentiation. No facilitation effects were observed. When considering behavioural measures across the tasks, a mutual interference (both tasks suffered as a function of dual-tasking) was observed. That is, pursuit tracking impeded oddball task performance, whereas counting the target stimuli impeded tracking performance. In sum, it is evident that a variety of interference patterns can occur within a dual-task set at different time points throughout dual-task execution. Only by using a multi-component task such as the visual oddball task, and examining both neural signatures of cognitive operations alongside a continuous measure of motor performance, can such intricate interference patterns be studied.

Limitations and Future Research

Though the design of the tasks used throughout this thesis was able to disentangle interferences between motor coordination and the processing of task-relevant stimuli, it is in question as to whether the findings are representative of real-world dual-task settings. It must be acknowledged that most real-world dual-task scenarios exhibit a complex multitude of ever changing stimulation and motor requirements that require intricate synergies between multiple low and high level cognitive operations and the motor system. It is this level of complexity that proves challenging for the understanding and accurate measurement of such interferences in more ecologically valid settings. Though the tasks were designed to capture the specific mechanisms involved in everyday CSC (i.e., used as a proxy for tasks that require a continuous adaptation of motor behaviour due to changes in the visual environment, such as driving), and the detection, judgement, and response to task-related events, it cannot be claimed that the interference patterns presented in this thesis would mirror those in real-world settings.

For example, CSC is usually performed in dynamic physical environments, which present variations in the level of difficulty for the motor system in maintaining stable performance, such as a change in road surface while driving. The pursuit tracking task used here, presented no variations in the velocity or the trajectory of the leading dot. That is, all load manipulations were placed on the cognitive task, and the motor task was performed in a predictable, unchanging fashion, throughout each of the experiments. It is of interest as to how attentional mechanisms distributed between cognitive operations and motor control would be modulated by perturbations to the pursuit tracking task, though the practicalities of designing a task in which perturbations to the pursuit tracking task coincide with specific cognitive operations are challenging. Firstly, individual differences in the latencies of cognitive operations would specify variable periods in which the effects of motor perturbations can be measured. That is, though perturbations can be delivered at a specified time following stimulus onset, it cannot be claimed to target specific task elements for all participants. Secondly, the analysis of tracking deviations due to the impact of cognitive operations becomes harder to interpret when adaptations to motor behaviour are required due to perturbations to the motor task. In order to negate the first issue, one could first present a dual-task set in which no perturbations to the motor task occur, and the latencies for each cognitive component for each participant could be noted. The timings of said latencies for a particular participant could then infer the timings of perturbations to the motor task, for that participant. Alternatively, though technically demanding, one could utilize online EEG in order to deliver perturbations upon the detection of an ERP component in real-time, though such an algorithm would be noise-sensitive, and may deliver perturbations upon the false detection of said ERPs. Also, the delivery of a motor perturbation following the detection of an ERP, would necessarily mean that the perturbation is delivered after the cognitive operation, and would therefore not specifically target the operation itself. As for negating the second challenge, one could deliver perturbations to the motor task pseudo-randomly, in that they occur outside of the window of processing of the oddball stimuli. Though this would not allow for the observation of interferences between motor perturbations and specific cognitive components in time-locked juxtaposition, it would be possible to explore the impact of anticipated motor perturbations on the resourcing of oddball task components.

The reduction in oddball task performance during dual-tasking that was highlighted in the current set of experiments cannot be attributed specifically to either the misidentification of a target or inaccuracies in the target count updating. That is, the behavioural measure is a function of both. On requiring a physical response (e.g. a keypress) on the detection of a stimulus, additional motor demands are introduced alongside the pursuit tracking demands, and this would necessarily blur the interpretation of the effects of cognitive processing on pursuit tracking performance. In order to differentiate the sensitivities of the cognitive elements that contribute to oddball task performance, it would be necessary to ascertain whether a participant successfully detects each target stimulus. In doing so, discrepancies between reported detections and the final target count would highlight the susceptible task element. In order to achieve this, participants could produce an audible signal (e.g., a short hum) on the detection of a target stimulus that could be recorded throughout a block. Though the production of such a sound would necessarily involve the motor system, the noise introduced to the signal would be negligible, relative to the production of a word. Regardless of noise considerations, the introduction of a motor response to target stimuli would fundamentally change the nature of the task, and interference patterns would need to be considered with this in mind.

Throughout the set of experiments, participants were asked not to perform any tally updating prior to the detection of a target stimulus. This was implemented in order to isolate the WM demands associated with updating the target count, and so as not to merge said demands with the preceding task operations. It cannot be determined whether this instruction was successful, though a modulation in the design of the oddball task, such as varying the exact calculation needed on the detection of a target throughout the experimental blocks, could prevent individuals from pre-calculating.

The electrophysiological measures considered throughout the thesis were selected based on their association with cognitive processes that comprise typical daily cognitive tasks. That is, the detection of a stimulus in the environment (P1), the determining of the relevance of a detected stimulus (P2), the preparation of a response (P3b, parietal alpha ERD), and the updating of a representation of the external world (frontal alpha/low-beta ERS). The timing of the onset of these components (latency) was not considered in the current set of experiments, as it was the magnitude of activation within specific component-windows that was of interest, allowing for the quantification of attentional resourcing. It should be noted however, that there is also value in examining the variability of the onsets of such cognitive processes. A modulation in the latency of a component can reveal processing delays that could occur due to dual-tasking (De Sanctis et al, 2014), and could provide richer insights into how the CNS manages cognitive-motor dual-task situations. Future work should therefore consider the impact of pursuit tracking on the temporal variability of ERP components associated with the oddball task, in order to further understand the interference patterns that are observed in the current set of studies.

It should also be noted that there exists a wealth of other electrophysiological measures associated with relevant cognitive operations that should be examined under dual-task conditions. Although the current set of experiments consider only positive deflections in the EEG, there is also value in exploring negative deflections. For example, the visual N1 ERP is a component considered to reflect an early sensory gating mechanism for visual stimulation (Eimer, 1993). On utilizing a Filtering paradigm, one could assess the impact of pursuit tracking on low-level attention allocation to target stimuli presented in attended and non-attended spatial locations. Though this would offer further insight into attention modulation during dual-tasking, the current pursuit tracking task would require major modifications, as it requires attention to be allocated to the centre of the display at all times.

An additional negative ERP, the conflict N2 (Warren et al., 2011), is an anterior component considered to reflect the processing of the inhibition of motor responses, the detection of mismatch, and cognitive control (Folstein & Petten, 2008). Modulations in N2 have previously been demonstrated in cognitive-motor tasks (Gherri & Eimer, 2010), and is typically measured during the Eriksen flanker task or go/no-go paradigms. The impeding of an appropriate response selection (e.g. deciding to apply the brakes to a car at an unsuitable time) could have severe consequences. Accordingly, dual-task effects on such cognitive processes should also be thoroughly investigated.

The oddball task presented here did not require a physical action in response to target stimuli, and so inappropriate button presses (responding to non-target stimuli) were not recorded. An adaption to the current experimental setup, such as the requirement of a physical response to stimuli, would allow for the investigation of the effects of pursuit tracking on the conflict N2 component.

The current set of experiments examined ERP components in sensor space. That is, voltage fluctuations observed at the surface of the scalp that contain the contributions of many underlying sources. Though ICA was used as a means of identifying non-brain related sources, such a dimension reduction technique can also be used to analyses ERP components in source space. Source space analyses provide a means of analysing components in isolation from other components and sources of noise. With the additional of anatomical scans, source-space analyses can offer higher resolution source localisation, and can offer richer insights into distributed cortical networks. ICA could also discriminate sources contributing to the components considered in the current set of experiments. P3b, for example, has been shown to have frontal and temporal generators (Volpe et al, 2007). On utilizing source-space analyses, one could investigate the effects of pursuit tracking on the sub-components of ERPs in order to achieve a broader understanding of the interferences in motor-cognitive dual-tasking.

The dual-task effects observed throughout the thesis were measured by means of comparing amplitude and power values in single and dual-task conditions. Performance changes in dual-task paradigms are often conceptualised as dual-task costs, and represent a percentage change in performance for a given measure from single to dual-task conditions (Friedman et al., 1982). As such, future work that utilizes the paradigms presented here should express CMi as a percentage change, aligning the measures with those presented in other works.

Also of interest, is the impact of healthy aging on the distribution and allocation of attention across the oddball and pursuit tracking task. The comparison between healthy young and older adults in the patterns of interferences could identify the mechanisms by which aging brings about a decline in motor performance during cognitive operations.

Concluding remarks

In conclusion, the collective set of experiments present an intricate pattern of interferences that manifest during CSC and the detection and further processing of task-relevant events. Such interferences appear asymmetrical, in that the cognitive process that impedes CSC performance does not necessarily demonstrate reciprocal deficits. The presence and pattern of interferences is demonstrated to be sensitive to the level of task difficulty, specifically introduced by EF load manipulations, and perceptual-attention manipulations. That is, the difficulty of the cognitive operation required upon the detection of a task-relevant stimulus, and the difficulty in the ability to differentiate between a task-relevant, and task-irrelevant stimuli. When considering the findings from all of the experiments, it is demonstrated that a ‘motor first’ strategy is used in the presented set of experiments. That is, CSC performance is largely maintained at the detriment to performance on the cognitive task. When CSC is perturbed, it is the activation of WM mechanisms (both the retrieval of target-relevant features, and the updating of a continuous count) that are found to be the contributing factor.

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