An examination of switch cost and electrophysiological markers associated with attention switching

by

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Author's Declaration

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

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Abstract

In this age of advancing technology, people often perform multiple tasks at the same time, which actually requires either dividing or switching attention. The ability to switch attention between two tasks is used often in daily life and the timing of switching can be critical. When switching attention, there is a behavioural switch cost, measured as delays in reaction times. It is important to understand the mechanisms of the switch cost to better address age and disease related changes in attention switching. This thesis, comprised of two studies, investigated the behavioural and electrophysiological aspects of attention switching and the resulting switch cost in young healthy adults. Study 1 evaluated an approach to measure switch cost with temporal precision when switching attention between tasks of two modalities and determined the relationship between task challenge and switch cost. This approach involved a background auditory choice reaction time task and switching to a visual reaction time task at an unpredictable time point. Results revealed, in contrast to the hypothesis, that as the task difficulty increased, the switch cost decreased. Study 2 used electroencephalography to examine differences in an event-related potential, the P3, when switching attention to probe the underlying neurophysiology of the switch cost. When comparing switch and non-switch trials, P3 latency was longer in switch trials, but there was no difference in P3 amplitude. This indicates that when switching, there are other possible processes that are associated with the delay in the P3, such as disengagement, which could involve the updating of the mental representation of the task in working memory and this is revealed in the switch cost. Future work could investigate task switching performance using this paradigm in other populations such as older adults and those with certain neurological disorders as well as investigating switch cost components (eg disengagement) in more detail.

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List of Abbreviations

ANOVA	Analysis of variance
CNS	Central nervous system
DLPFC	Dorsal lateral prefrontal cortex
EMG	Electromyography
ERP	Event-related potential
EEG	Electroencephalography
EOG	Electrooculography
fMRI	Functional magnetic resonance imaging
LRP	Lateralized readiness potential
PFC	Prefrontal cortex

Chapter 1: Introduction

1.1 Background

In this age of advancing technology, people are increasingly trying to perform multi-tasking (eg walking and talking on a cell-phone). The act of multitasking can be viewed as being achieved in two ways: 1) dividing resources between two tasks (divided attention) and/or 2) switching resources back and forth between two tasks (attention switching) (Pashler, 2000). While both may well play a role, there is a view that attention switching is particularly important (Monsell, 2003). Attention switching, the ability to disengage from one task and engage in another, is an executive function that allows for cognitive flexibility in an environment that is constantly changing (Klanker et al., 2013). This permits individuals to disengage and engage attention elsewhere when required, in order to adapt to the dynamic environment in the world around us (Pesce and Audiffren, 2011). This ability is not only important for specific groups of people, like elite athletes, but also in the everyday lives of normal individuals and the speed at which attention switching is performed can be critical. It may not be critical in certain situations like switching between watching television and writing a grocery list; however in other situations, where timing of responses is important, like texting and driving which could result in a car accident, this capacity for attention switching is critical. The speed at which people switch attention declines with age (Kray and Lindenberger, 2000), as well as in certain diseases, like Parkinson’s disease (Cameron et al., 2010). As a result advancing our understanding of the processes that underpin the ability to attention switching are important for understanding the determinants of performance and age and disease related changes.

One experimental measure of attention switching is behavioural switch cost. It is measured as the difference in reaction times between trials involving switching between two tasks and non-switch trials (Wylie and Allport, 2000). As attention switching is related to the speed of information processing in the central nervous system (CNS), this switch cost is associated with speed of processing of a certain stage or multiple stages of information processing. There are discrepancies in the literature as to whether such switch cost involves the response selection stage or more perceptual stages (Hsieh, 2006). Furthermore, investigating electrophysiological correlates of attention switching can provide further insight into the underlying mechanisms or factors contributing to the switch cost, allowing for stages of information processing to be examined.

In the present study, young healthy adults were recruited to examine behavioural and electrophysiological aspects of attention switching. The main objectives of this thesis were to evaluate an approach to precisely measure switch cost with temporal precision when switching attention between tasks involving different modalities and to examine changes in cortical activity and electrophysiological markers associated with transient moments of attention switching. Electrophysiological correlates, with a focus on the P3, were examined in switch and non-switch trials to investigate differences in various stages of information processing. This research leads to a greater understanding of the switch cost and underlying mechanisms, which could indicate ways in which to improve poor performance in attention switching in our everyday lives as well as in the growing aging population and in certain disease states.

Chapter 2: Literature Review

2.1 Cognition

2.1.1 Cognition and executive function

In general, cognition involves higher level information processing that allows for online perception of a stimulus and subsequent goal-driven response. Executive functions are required in order to regulate cognitive sub-processes during the completion of complex tasks (Audiffren et al., 2009). Executive functions include scheduling, mental-set shifting, planning, inhibition, working memory and the coordination of complex cognitive functions (Colcombe and Kramer, 2003; Hillman et al., 2008; Audiffren et al., 2009). These higher level conscious processes demand increased effort (Hillman et al., 2003) and are controlled mainly by the frontal lobe of the brain (Audiffren et al., 2009).

2.1.2 Attention

Attention allows for the processing of relevant sensory information, while ignoring or suppressing irrelevant distractor information. Attention can be automatic or voluntary and directed towards particular objects or spatial locations (Herrmann and Knight, 2001). There are two primary mechanisms by which attention is controlled and processed. Top-down processing is goal-driven, based on knowledge, expectation and experience. The second mechanism, bottom-up processing, is stimulus-driven, gathering information from sensory input to perception of a stimulus, recruiting higher brain areas, and subsequent motor response. The primary areas of the brain responsible for attention encompass the prefrontal and parietal cortices (Sarter et al., 2001; Corbetta and Shulman, 2002). Top-down control involves mainly the dorsal parietal cortex, specifically intraparietal sulcus and superior parietal lobule, as well as the dorsal frontal cortex alongside the precentral sulcus and near the frontal eye field. A ventral frontoparietal network is responsible for stimulus-driven control which includes temporoparietal junction cortex, middle frontal gyrus, inferior frontal gyrus, frontal operculum, and anterior insula (Corbetta et al., 2008). While there are multiple domains of attention, including selective, sustained, and divided attention (Sarter et al., 2001), this thesis will focus on switching attention, due to the temporal aspects and link to the speed of processing.

2.1.3 Attention switching and switch cost

Attention switching is an executive function involving the disengagement from one stimulus or task and engagement to another (Posner and Presti, 1987). In the literature, it is alternatively termed “task switching”, “shifting attention” or “attention shifting” (Wager et al., 2004). Some authors differentiate between different types of attention switching, including switching between locations, objects, object attributes, rules, and tasks, although they activate similar brain regions (Wager et al., 2004). In spite of the modality of the task conditions, the ability to switch attention rapidly is required in the midst of constantly changing environments.

When switching attention there is a resulting switch cost. This is the decreased level of performance, as reflected by errors and delays in timing, when switching between two tasks compared to performing a single repetitive task. The switch cost is measured as the difference in reaction times between switch trials and non-switch trials (Wylie and Allport, 2000). During switch trials, response times are approximately 200 ms longer than during non-switch trials (Monsell, 2003) and error rates increase (Gajewski and Falkenstein, 2011). This indicates the extra cost of the involved control processes necessary for setting new task parameters, ending previously bound task parameters and overcoming interference from previous tasks

(Vandierendonck et al., 2010). Reducing the switch cost may indicate an increase in the speed of processing, suggesting more efficient executive functioning (Monsell, 2003). For the purposes of this thesis, reaction time is defined as the time from stimulus onset to the initiation of the muscular response, as measured through the onset of electromyography. Movement time is from the onset of the muscular response to the completion of the response. Therefore, response time is the period from stimulus onset to the completion of the response, hence, the sum of reaction time and movement time (Chang et al., 2009).

2.1.3.1 Factors contributing to switch cost

There are two prominent views of the switch cost origin: 1) the interference view and 2) the reconfiguration view (Vandierendonck et al., 2010). The interference view presumes that residual parameters from a previous task may hinder or interfere with processing of novel parameters of another task during switching. This in turn produces a switch cost that is measured as the extra time required to overcome interference. The interference itself could be due to task-set inertia, which is the continued activation of task-set parameters from a previous task interfering with responding to a stimulus that has previously been processed for another task. A task-set is necessary to perform a task and encompasses the control settings or task parameters to carry out stimulus identification, response selection and execution (Vandierendonck et al., 2010). The task-set inertia hypothesis expects switch costs to be dependent on the original task an individual is switching from (Wylie and Allport, 2000). Besides task-set inertia, there are other factors that may contribute to task interference. When the stimulus is involved in both tasks, termed bivalent, switch costs are larger as there is more interference between the tasks (Kiesel et al., 2010). Task-rule congruency effects result in more interference for task-rule incongruent responses. This occurs when the required response to the stimulus varies between the two tasks. Therefore, the interference view attributes switch cost to the time required to resolve interference between task-sets (Vandierendonck et al., 2010).

The reconfiguration view proposes when switching tasks, extra time is required to reconfigure the task-set (Vandierendonck et al., 2010) including initiating the relevant stimulus-response rules (Yeung and Monsell, 2003). Reconfiguration is not necessary during non-switch trials as the task-set is already active from the previous trial. This view predicts that if adequate preparation time is given to switch tasks, the switch cost as measured by errors can be reduced. Increasing preparation time means there is more time to reconfigure the task-set before switching to the next task. The reaction time decreases for both switch and repetition trials, but for switch trials there is a greater reduction. The term residual switch cost describes the switch cost following a long preparation period (Vandierendonck et al., 2010).

There are other factors that contribute to switch cost which may or may not be present in certain paradigms. Depending on the tasks and stimuli involved, the processing of a new stimulus may be affected by task-set priming. If the task performed in the last few minutes had the same stimuli as the current task, this results in slower responses (Monsell, 2003). It is thought that stimuli, responses and task goals are bound together, where task-set priming is due to retrieval of these relationships when the stimulus is presented (Yeung and Monsell, 2003). Furthermore, some authors suggest that task-set inhibition takes place as a component of the reconfiguration process or to settle interference (Vandierendonck et al., 2010). When a new task-set becomes active, the irrelevant task-set is inhibited, and this inhibition could be carried over to subsequent trials. Yeung and Monsell (2003) proposed that during a switch trial, inhibition either results in lengthening the time for a certain control process or brings forth additional control processes necessary to overcome the inhibition. Switch costs are reduced when a cue is presented prior to switching to the new task (Kieffaber and Hetrick, 2005).

2.1.3.2 Task-switching paradigms

Several paradigms are used in task-switching literature, such as the list paradigm (Vandierendonck et al., 2010), alternating-runs paradigm, task-cueing paradigm, and intermittent-instruction paradigm (Monsell, 2003). The original protocol used to investigate task-switching was termed the list paradigm, in which two types of list conditions were employed. One list required the participant to perform a single task for all stimuli while the other list involved completing two tasks that alternated in order (Vandierendonck et al., 2010). The resulting switch cost was determined by taking the mean difference in time to complete the lists (Wylie and Allport, 2000). The alternating-runs paradigm involves switch and repetition trials within a single block, switching tasks after a predetermined number of trials (Rogers and Monsell, 1995). A pre-specified task sequence can also be given to the participant so they know when to switch tasks. Task-cueing paradigms are unpredictable, as a cue appears prior to or at stimulus presentation in order to indicate which task to complete. The intermittent-instruction paradigm is a form of task-cueing that involves occasional instructions to the participant as to which task to perform after the instruction (Monsell, 2003). The cueing protocol can be useful as the timing between the cue and stimulus, as well as between the response and next cue, can be manipulated to allow the switching to be less predictable. Differences in switch cost between different paradigms may be due to added control processes that are required in one but not the other (Vandierendonck et al., 2010).

2.1.3.3 Tasks used in task-switching paradigms

Just as there are different paradigms to study task-switching, there is a wide range of tasks included within these paradigms. Quite often, two tasks are completed that have different task-sets, of either varying stimuli or responses to the same stimuli (Kiesel et al., 2010). A common set of tasks involves determining if a number is odd or even, and then if a letter is a consonant or vowel. The computerized task, depicted in a two-by-two grid, switches every two trials dependent on the stimulus' position in the grid. Switch cost is determined through differences in response time when switching to the next task as opposed to the repetition of the same task (Rogers and Monsell, 1995; Coles and Tomporowski, 2008). Another specific example involves participants classifying faces as either male or female and switching to the categorization of words as having two syllables or not (Yeung et al., 2006). Other studies have used stimuli from the Stroop task and have switched between reading the word and then reading the colour of the word (Wylie and Allport, 2000). Some paradigms include tasks in various modalities, such as switching between a visual and auditory task in a study by Strobach and colleagues (2012). Participants were to respond to the spatial location of a circle on a computer screen for the visual task and then switch to discriminating between three tones of different frequencies for the auditory task (Strobach et al., 2012). The Madrid card sorting task, similar to the Wisconsin card sorting task, has been used in the study of task-switching, where cards are sorted based on certain attributes, like colour and shape, and the categorization of the cards is switched between certain trials (Barceló, 2003). All these studies employing the various tasks have found slower performance for switch trials as opposed to non-switch trials, demonstrating a behavioural switch cost.

Task-switching studies seem to mainly employ three different types of tasks: tasks like the Wisconsin card sorting task (Barceló, 2003; Buchsbaum et al., 2005), a computerized switching of rules like in the 2 by 2 grid (Rogers and Monsell, 1995; Coles and Tomporowski, 2008), and tasks involving switching between two modalities (Strobach et al., 2012). While the Wisconsin card sorting task is a simple task applicable as a clinical tool, it does not allow single trials to be examined in order to determine any trial effect. Furthermore, there is no direct measure of the processing time, as indicated through reaction time. In modified computerized versions, button presses indicate which sorting pile to put the choice card into and so response time can be measured (Barceló, 2003). However, again, there is no direct measure of the reaction time. The computerized rule switching tasks offer a method to quantify timing for individual trials. Responses are completed through a button press and although the contribution of movement time to the response time may be minimal, it is unknown and therefore, so is the reaction time. Furthermore, this task switching occurs between tasks that are dependent on the vision modality which may limit the potential to explore early stages of processing as performed in attention studies using electrophysiological markers of attention switching (Staines et al., 2014). Strobach et al. (2012) employ a task-switching paradigm involving switching between a visual and auditory task; however, the visual task involved determining the spatial location of a circle on the screen. With this type of task there would be increased eye movements, presenting a challenge to electroencephalographic recording, as well gaze time adds difficulty to the interpretation of reaction time processing.

2.2 Cognition and Electrophysiology

2.2.1 Attention

Electrophysiological and neuroimaging techniques have been used to examine cognitive function and associated changes in neural activity. Imaging techniques, such as functional magnetic resonance imaging (fMRI) and positron emission tomography, have great spatial resolution effectively defining specific active brain regions. Electroencephalography (EEG), with its millisecond scale temporal resolution, is employed to examine changes in electric potential that are time-locked to certain events, called event-related potentials (ERPs; Hillyard and Anllo-Vento, 1998). ERPs allow for the measurement of information processing under various task conditions (Barceló, 2003), so timing of cognitive processing can be characterized (Luck et al., 2000). These tools can be used to study cortical activity during attentional tasks.

Examining ERPs related to the attention of a stimulus have revealed three main components related to different phases of attentional processing: N1, P1 and P300 (P3) (Herrmann and Knight, 2001). The N1 and P1 component generators are centred within the auditory or visual cortices depending on the modality. These components are indicative of the first stages of attentional processing suggesting mainly exogenous contributions (Herrmann and Knight, 2001).

2.2.2 N1

The N1 is a negative component, influenced by attention (Luck, 2005), that indicates discriminative processing of stimulus attributes in early stages of information processing (Fonaryova Key et al., 2005). Differences exist in the N1 component between the vision and auditory modalities. The visual N1 component peaks approximately 150 to 200 ms after the presentation of the stimulus when examined posteriorly (Luck, 2005). The auditory N1 has a greater amplitude and shorter latency in comparison to the visual N1. The auditory N1 amplitude is greatest over frontocentral areas or the Cz electrode site while the visual N1 has peak amplitude in occipital areas (Fonaryova Key et al., 2005). The primary auditory cortex in the temporal lobe generates the auditory N1 while the visual N1 is generated in the extrastriate occipital cortex, as well as dorsal occipito-parietal and ventral occipito-temporal areas (Herrmann and Knight, 2001).

2.2.3 P3

The P3 is a positive component of the ERP peaking around 300 ms after the presentation of a stimulus; however, its latency can vary. The P3 is evoked when individuals attend to a stimulus and distinguish its characteristics (Herrmann and Knight, 2001). The P3 sometimes displays two distinct peaks, referred to as P3a and P3b. The presentation of a novel stimulus evokes an earlier positive peak (P3a) which is more frontally distributed. The later peak (P3b) displays more centro-parietal distributed topography (Herrmann and Knight, 2001) and is evoked at the presentation of the target stimulus (Sussman et al., 2003). Therefore, there are multiple brain regions involved in the generation of the P3 in response to a visual or auditory stimulus, including the thalamus, temporal lobe, hippocampus/parahippocampal areas and the insula. Specifically for the P3 elicited by a visual or auditory stimulus, activity has been found over the occipital cortex and temporal lobe, respectively (Herrmann and Knight, 2001).

Several theories exist in determining the underlying meaning of the P3. The context-updating theory describes the P3 as an indicator of the updating of a mental representation of an event in working memory. For example, if a new stimulus is presented, a P3 response will be observed, representing the attentional resources required to change the stimulus representation. Furthermore, it is also thought that the P3 represents the amount of attentional resources available for a specific task. Therefore, for an easy task, the P3 tends to be larger with a shorter latency as fewer resources are consumed by the task and are available (Polich, 2007). The P3 amplitude tends to be larger in parietal electrode sites compared to frontal sites

(Polich and Kok, 1995). Its amplitude is comparative to the amount of attentional resources allocated to a specific task, while the latency reflects the speed of processing and the time taken to evaluate a stimulus (Kamijo et al., 2007). Generally, P3 latencies are commonly shorter in duration in frontal areas and longer over parietal areas. Shorter latencies are correlated to better cognitive performance on tasks (Polich, 2007) and latencies increase when target discriminability becomes more difficult (Linden, 2005). Not only is the P3 elicited when attending to a stimulus but also when switching attention between different stimuli (Herrmann and Knight, 2001). The electrophysiological component of this thesis will focus on changes in N1 and P3 amplitude and latency when attention switching.

2.2.4 Attention switching

Particular brain regions are active during attention switching as revealed through neuroimaging studies. Studies employing fMRI have shown activations in the dorsal lateral prefrontal cortex (DLPFC; Brass and von Cramon, 2004; Hyafil et al., 2009) as well as the parietal cortex (Shomstein and Yantis, 2004; Yeung et al., 2006) with some suggestion of contribution from the cerebellum and other subcortical regions (Monsell, 2003; Krumbholz et al., 2009). The posterior parietal cortex is often associated with switches of attention within the visual domain, however recent research suggests that it has a similar role in the auditory modality (Shomstein and Yantis, 2004; Krumbholz et al., 2009; Lee et al., 2014). The temporal nature of how these generators contribute to overall attention switching is unclear, but some suggest that parietal cortical activity may precede frontal activity (Green and McDonald, 2008). According to the guided activation theory, the prefrontal cortex (PFC) directs task-relevant activity to other brain regions in order to perform the task (Miller and Cohen, 2001). Consistent with this theory, task-relevant regions of the PFC are more active when switching between two tasks (Yeung et al., 2006). Furthermore, Yeung et al. (2006) found increased activity in the anterior cingulate cortex and pre-supplementary motor area to be associated with a greater switch cost, indicating increased levels of interference. However, across individuals it appears that alternative strategies may be employed as increased activity to task relevant stimuli in these areas presents as improved performance in some and prolonged processing in others. Within a subject, fluctuations in attentional control and interference can occur across trials (Yeung et al., 2006). These changes in brain activity indicate regions that are active during attention switching and the study of the P3 can indicate further details regarding attentional processing during switching.

The P3 component of an ERP can be utilized to examine attentional processing during switching between two tasks, in terms of its amplitude and latency. In task-switching literature, the P3 is often examined time-locked to the presentation of a cue, target stimulus, or response analyzing the preparation, implementation and execution of a task-set. The cue-locked P3, which tends to have a greater amplitude in switch trials, can be interpreted as the reconfiguration of stimulus and response sets (Gajewski and Falkenstein, 2011). With a cue, switching between tasks evokes a clear P3a over fronto-central electrodes, and a P3b-like component later over parieto-occipital electrodes (Kieffaber and Hetrick, 2005). The amplitude of a stimulus-locked parietal P3 is lower in switch trials compared to non-switch trials (Gajewski and Falkenstein, 2011). This indicates that there is greater demand for attentional resources and when switching to the other task, there is interference as well as resources being taken up resulting in a decreased amplitude (Polich, 2007). It has also been suggested that the lower amplitude is due to the complex cognitive nature of task switching yielding more variable data. The greater amount of variability in the P3 leads to a smaller average waveform

(Gajewski and Falkenstein, 2011). Furthermore, Gajewski and Falkenstein (2011) indicated that the attenuated P3 amplitude may be due to a more enhanced N2 component during switching. It is assumed that tasks that have greater response selection demands and are more difficult elicit a greater N2 amplitude, reducing the P3 amplitude (Gajewski and Falkenstein, 2011). An increase in N2 amplitude during switch trials has also been interpreted as suppression of a habitual response (Gajewski et al., 2010). The response-locked P3 has been less extensively studied with varying results of either no difference between switch and repetitive trials or a decreased amplitude for switching (Gajewski and Falkenstein, 2011).

This thesis will focus on the stimulus-locked P3 during switch and non-switch trials. Following switching, there is an associated P3-like ERP with decreased amplitude, but similar latency, compared to non-switch trials (Kieffaber and Hetrick, 2005). When switching attention, a P3a is evoked in frontal regions and a P3b in parietal regions. It is debatable which part of the process is demonstrated by the P3a; it may indicate the disengagement phase or the entire attention switching process. The parietal P3b elicited during task switching has been suggested to signify the activation of the relevant task set (Hölig and Berti, 2010). Depending on the specific task conditions, some studies have found difficulty distinguishing between the P3a and P3b sub-components (Hölig and Berti, 2010). Hsieh (2006) found similar P3 peak latencies between switch and non-switch trials in a paradigm involving switching task-sets. This research provides an indication of the electrophysiological correlates time-locked to stimulus presentation in attention switching paradigms.

2.3 Reaction Time

2.3.1 Reaction time determinants

In this thesis, reaction time is the primary behavioural measurement used in order to compute switch cost and is an index of speed of processing. As previously stated, reaction time is defined as the time from the presentation of the stimulus to the onset of muscular activity, as measured through electromyography (Chang et al., 2009). Reaction time has been studied for the past five decades, with many experiments being developed from the work by Donders on the speed of mental processes (Donders, 1969). The development of electrophysiological techniques has allowed for a greater understanding of the processes involved in reaction time (Falkenstein et al., 1993). Throughout the vast amount of research, numerous determinants of reaction time have been discovered.

An extensive amount of factors can modulate reaction time including: age (Verbrugge et al., 1996), gender (Adam et al., 1999), practice (Klapp, 1995), handedness (Dane and Erzurumluoglu, 2003), physical fitness (Spirduso, 1980), exercise (Audiffren et al., 2008), fatigue (Langner et al., 2010) and arousal (Eason et al., 1969). In addition, the use of a cue or warning signal prior to stimulus presentation provides an indication that the stimulus is approaching, allowing for preparation. However, the length of time between the cue and stimulus, the foreperiod, can be varied, introducing a dimension of uncertainty. When the foreperiod is varied and the stimulus timing is unpredictable, reaction times are longer compared to reaction times using constant foreperiods. Generally, as foreperiod length increases, reaction time is slower due to the increased time uncertainty of when the stimulus will appear (Niemi and Näätänen, 1981).

Additionally, several stimulus characteristics can impact reaction time, including intensity and modality. As the intensity of the stimulus increases, the reaction time decreases up to a certain level (Pins and Bonnet, 1996). In terms of stimulus modality, visual reaction times are generally longer than auditory reaction times, by approximately 30 to 50 ms (Freides, 1974). This is likely due to the greater number of synaptic connections required for visual processing (Kandel et al., 2013), and therefore a slower sensory conduction time than for auditory stimuli (Brebner and Welford, 1980).

When examining attentional effects on reaction time, voluntary and involuntary attention are explored, thought to operate under different mechanisms. In this sense, with voluntary attention, perceptual resources are allocated to the probable target area whereas involuntary attention involves an orienting response even when the target location is not properly cued (Prinzmetal et al., 2005). It has been observed that time taken to detect a stimulus decreases when a cue specifies where the stimulus will occur. It is thought that this relates to aligning the attentional system with the required pathways to process the stimulus (Posner et al., 1980). The warning cue puts the body into a state of preparation for detecting and appropriately responding to a stimulus more quickly through orienting attention (Petersen and Posner, 2012).

2.3.2 Simple and choice reaction time

There are several different types of reaction time experiments employed, including simple and choice reaction time tasks. Simple reaction time involves the presentation of a single stimulus with only one response while in choice reaction time tasks, multiple stimuli could be presented with different responses (Klapp, 1995). As the number of possible stimuli increases in a choice reaction time task, the reaction time increases, following a logarithmic relationship (Hick, 1952). Therefore, simple reaction times are shorter than choice reaction times. The flanker task is a choice task involving distractors around the target, which are required to be inhibited (Eriksen and Eriksen, 1974). In modified versions of the flanker task, the stimuli are arrows pointing in either the left or right direction. In the congruent condition, the flanker arrows or distractors point in the same direction as the target, while in the incongruent condition, the distractors point in the opposite direction as the target. Incongruent trials, in particular, present conflict due to competition between responses. The added inhibition process leads to a longer reaction time, as well as decreased accuracy (Botvinick et al., 1999).

For the purposes of this dissertation, the stages of information processing will be referred to as stimulus detection/discrimination, stimulus evaluation, response selection, and response execution. In simple reaction time tasks, as there is only one stimulus and one subsequent response, the stimulus is simply detected and the response is executed. As it is known in advance, the response can be pre-programmed prior to stimulus onset (Klapp, 1995). In choice reaction time tasks, as there is the possibility of many stimuli to be presented requiring different responses, stimulus discrimination and evaluation, as well as response selection stages may be longer than in simple tasks resulting in longer reaction times. However, it is important to note that the pre-programming of the response in simple reaction time tasks requires undivided attention (Frith and Done, 1986). Therefore, in dual-task situations, the addition of the secondary task actually increases simple reaction time up to the same level as choice reaction time (Frith and Done, 1986; Goodrich et al., 1990). Undivided attention is not present to pre-program the response as attention is required by the secondary task (Goodrich et al., 1990).

2.4 Rationale

Switching attention between two tasks is often used in daily life allowing for cognitive flexibility in an environment that is constantly changing and the speed at which people switch can be critical. Furthermore, the speed at which people switch attention declines with age (Kray and Lindenberger, 2000) and in certain diseases like Parkinson's disease (Cameron et al., 2010). In order to better understand these changes it is first important to gain a better understanding of the factors that contribute to the behavioural switch cost in healthy adults. In the current work both behavioural and electrophysiological markers are used to explore the relationship between task complexity and switch cost.

In order to study behavioural and electrophysiological aspects of attention switching, tasks are needed that demonstrate excellent temporal precision and can be used to examine electrophysiological markers associated with attention switching. In addition, recording reaction times, as opposed to response times, will permit for excellent temporal precision computing more precise switch costs indicating the speed of processing and improving the ability to link behavioural events to electrophysiological changes.

One essential need is a paradigm that will permit measurement of event related potentials tightly time locked to behavioural events. In this respect there is a need for a behavioural task with precise measures of the stimulus to onset of reaction time (not confounded by movement times). It is also necessary that individuals switch between two different modalities in order to separate the event related potentials between the two different tasks. This is due to the potential to examine early stages of processing as performed in attention studies, such as work conducted by Staines and colleagues (2014). Finally, it is necessary that the tasks performed can be monitored and task challenge can be controlled in order to be able to ensure participants are directing attention to the appropriate stimulus response relationship.

Previously conducted studies do not employ tasks that satisfy these important criteria necessary to conduct the study focused on temporally coupled electrophysiological events. As a result, it was considered important in study 1 to develop a unique approach that may allow for a better understanding of the behavioural and underlying electrophysiological characteristics associated with the switch cost. Historically, the three main types of tasks used in task-switching paradigms include: the Wisconsin card sorting task or modified versions (Barceló, 2003; Buchsbaum et al., 2005), computerized rule switching like in the 2 by 2 grid (Rogers and Monsell, 1995; Coles and Tomporowski, 2008) and tasks involving switching between two modalities (Strobach et al., 2012). While these tasks may have their advantages, they have disadvantages which make it difficult to precisely compute switch cost and examine associated electrophysiological markers. Overall one of the main issues with these tasks is that response time is measured as opposed to reaction (premotor) time or in terms of the Wisconsin card sorting task, the time taken to sort all the cards. Response time encompasses both reaction time (processing time) and movement time, so the processing time is an indirect measure not ideal for the temporal precision required in the current work.

It is proposed that the development of a unique task, requiring participants to switch between a near-continuous background auditory task and an unpredictable visual reaction time task, could demonstrate a switch cost and allow for electrophysiological markers to be examined. Norrie et al. (2002) employed a similar task studying attention switching and balance, demonstrating a consistent switch cost. Reaction times to the visual stimulus will be measured, as well as visually evoked potentials. Determining potential electrophysiological markers could provide further insight into executive control functioning of the brain and specific changes in cortical activity that occur with attention switching. As electrophysiological measurements have excellent temporal resolution and can be time-locked to stimulus onset, they can provide an understanding of the processes that occur after stimulus presentation (Hillyard and Anllo-Vento, 1998). This research has the potential to influence our understanding of the important links between speed of information processing and associated electrophysiology. A greater understanding of the associated switch cost could lead to possible ideas on ways in which to improve poor performance when switching attention.

2.5 Research objectives

This thesis is comprised of two studies designed to address the following research objectives:

Study 1: Evaluating a novel approach to measure the temporal properties of task switching

- To evaluate an approach to measure switch cost with temporal precision when switching attention between tasks of two different modalities.
- To determine the relationship between task challenge and switch cost duration.

Study 2: Examining changes in cortical activity and electrophysiological markers associated with attention switching between tasks of different modalities

- To determine changes in cortical activity when switching attention from an auditory to visual reaction time task and associated electrophysiological markers.

Chapter 3: Study 1 – Evaluating a novel approach to measure the temporal properties of task switching

3.1 Introduction

The ability to switch between tasks is important in order to successfully perform multiple tasks that are often executed concurrently or serially during everyday behaviour. Attention switching, an essential element of task switching, is an executive function required in daily life that is of importance in an environment that is constantly changing. For example, when driving on a busy highway, individuals must constantly switch their attention between different objects in the visual scene (cars, signs, pedestrians) and still remain capable of rapid reactions to avoid potential accidents (Anstey and Wood, 2011). Of particular importance in the present study is the time it takes to switch between tasks, which can be an important determinant of success. The speed at which people switch attention can deteriorate with age (Kray and Lindenberger, 2000), as well as in certain diseases, like Parkinson's disease (Cameron et al., 2010). In terms of timing, when comparing reaction times between trials involving switching and non-switch trials, there is a decreased level of performance, as demonstrated through a delayed reaction time, termed the switch cost (Wylie and Allport, 2000). This increase in reaction time for switch trials indicates the extra time needed for control processes so new task parameters may be set, previous task parameters terminated, and interference from previous tasks overcome (Vandierendonck et al., 2010). The focus of the current study is to evaluate a novel approach to quantity the temporal properties of task switching. Timing when switching attention between two tasks or stimuli can be quite critical and focusing on the timing can provide us with information regarding the speed of processing during multitasking activities.

In task-switching literature several different paradigms exist to examine this specific executive function. These paradigms vary with respect to the aspects of the characteristics of the tasks and methods of assessing task switching behaviour. With respect to the characteristics of the tasks, switching has been assessed between two tasks that differ on several features including the sensory, cognitive or motor determinants of the task, how the switch cost is measured and the task instructions. One of the most common approaches in the literature is to reduce the complexity of the switch elements by maintaining similar sensory and motor components and switching between different cognitive components. A common version of this is the 'rule' switch paradigm where individuals are required to switch between different stimulus-response rules. For example, in the presence of a number, they may need to switch between a response decision based on a rule for the size of the number or whether the number is odd or even (Rogers and Monsell, 1995). Different types of rule switch tasks are employed: the Wisconsin card sorting task and modified versions (Barceló, 2003; Buchsbaum et al., 2005) and a computerized switching of rules (Rogers and Monsell, 1995; Coles and Tomporowski, 2008). Alternatively there have been a few studies that have used a task switching model involving switching between stimulus modalities (eg vision and auditory stimuli) (Strobach et al., 2012; Williams et al., 2013). Whether a rule-switching paradigm or switching between stimulus modalities is employed, it is proposed that either approach provides the same message. It is suggested that the underlying processes involved in the resulting switch cost would be the same as both methods involve common task elements including disengaging from the first task (inhibition), and engaging in the second task. Whether the switch occurs between two sets of rules or two different modalities, there's a switch between two different tasks even though the specific aspects of the task may vary (eg different modalities or task instructions).

The switch cost is still the extra time required to respond to a specific stimulus when switching away from another task (switch) as compared to performing the task alone (non-switch).

With respect to how the task switching is measured, these vary from composite measures of overall performance (eg standard Wisconsin card sorting task) to computerized tools that provide measures of response or reaction time (eg responding to the specified task through button press). While composite measures have important clinical utility they provide little information about the performance of a single trial and do not provide adequate temporal resolution as they are based on number of correct responses or total time for performance. In modified computerized versions, button presses allow for response time to be measured for individual trials (Barceló, 2003). When timing can be measured, switch cost has been estimated in a wide range from 12 ms (Strobach et al., 2012) up to 500 ms (Barceló, 2003). The factors that appear to influence the duration of the switch cost are stimulus discriminability and familiarity, task cueing (Barceló, 2003), compatibility of stimulus-response maps, amount of preparation time, variations in task expectancy, task recency (Vandierendonck et al., 2010), as well as the task difficulty or rule complexity (Rubinstein et al., 2001).

Of particular interest in the present study is to develop an approach to provide precise timing information to explore trial related differences in switch cost linked to task difficulty performance and to eventually couple to electrophysiological markers to better understand the source for the switch cost. Utilizing two different stimulus modalities (switching between different stimulus inputs) may provide an opportunity to examine electrophysiological markers of the early sensory processing stages of switching without interference of the other task. In addition, to challenge the temporal properties of task switching one would need to utilize a near-continuous background task to measure switch cost timing (and avoid the potential for individuals to pre-emptively switch attention during lapses in demand for attention). Such a method has been previously employed in a balance study to compute the timing of attention switching (Norrie et al., 2002).

With respect to task difficulty, simple and choice reaction time tasks can be used to vary the level of difficulty. In general, slower reaction times are found for simple versus choice reaction time tasks. For simple reaction time, the response can be prepared in advance of the stimulus and is considered to be “pre-programmed” (Frith and Done, 1986). The route from stimulus to response is fast compared to choice reaction time, as it is only necessary to detect the stimulus and initiate the response and does not require the stimulus to be identified (Frith and Done, 1986). Importantly, undivided attention is essential for this preparatory process (Goodrich et al., 1990). Studies exploring the impact of distraction on simple and choice reaction time have found a greater effect on simple reaction time, increasing reaction time in the simple tasks more than in the tasks requiring a choice (Frith and Done, 1986; Goodrich et al., 1990). With the dual task, simple reaction times were similar to choice reaction times (Frith and Done, 1986). Furthermore, the performance of the secondary distraction task was completed less accurately. These results may occur as dedicated attention required for preparing the response in simple reaction times is not present, as attention is required by the secondary task (Goodrich et al., 1990). Given the results of these dual-task studies, the increased reaction time in simple tasks in the dual-task condition may relate to an increased switch cost. This indicates that switching to a task of lower difficulty would result in a greater switch cost. However, there is some debate in this relationship as another study explicitly using a switching paradigm revealed a greater switch cost with increasing the task difficulty (Rubinstein et al., 2001).

This study investigated whether this approach can adequately quantify the behavioural switch cost. There were two objectives of this study: 1) evaluate an approach to measure switch cost with temporal precision when switching attention between tasks of two different modalities and 2) determine the relationship between task challenge and switch cost duration. It was hypothesized that: 1) there would be a significant switch cost in visual reaction times when comparing reactions with and without the concurrent performance of a near-continuous auditory tracking task and 2) the switch cost would increase as the difficulty of the visual reaction time task increased (switch cost greater for flanker vs choice vs simple reaction time tasks). The results of this study were considered important steps for subsequent studies to be focussed on revealing the neurophysiological substrate for switch cost.

3.2 Materials and methods

3.2.1 Participants

Ten young healthy right-handed adults (5 females; mean age±1 SD: 25±3.9) were recruited for this study. This study received ethics clearance through a University of Waterloo Research Ethics Committee and all participants provided written consent prior to study participation.

3.2.2 Protocol

Participants were seated in a chair with their right arm and hand rested on a table with the thumb pointing upwards. A computer monitor was set up approximately 60 cm in front of them. In this randomized block design study, participants completed two cognitive tasks: a near-continuous auditory tracking task (the task the subjects switched from) and a visual reaction time task (the task the subjects switched to). There were 4 switch blocks and 4 non-switch blocks, which were randomized. Each block included 12 trials (except 24 trials for flanker blocks) with 5 seconds in between each trial. Each switch trial included 11 auditory stimuli and 1 visual stimulus, while a non-switch trial involved the presentation of a single visual stimulus. The switch blocks involved the participant switching between the two cognitive tasks (Figure 3-1). They performed the auditory tracking task until the visual reaction time task appeared on the screen and were instructed to respond to the visual stimulus immediately, and then return back to the auditory tracking task until the end of the trial. The non-switch blocks involved the completion of only the visual reaction time task with no auditory tracking. In all trials, the participants were instructed to fixate on a cross in the middle of the screen. Prior to the start of the testing blocks, practice trials were completed in order to minimize any learning curve. Two trials of the auditory tracking task, consisting of 11 consecutive tones each were completed, along with 10 trials of the visual reaction time task, using the Flanker task. Also, two trials of the switching task were completed.

3.2.2.1 Background auditory tracking task

The auditory tracking task involved the presentation of tones of either a high (1000 Hz) or low (200 Hz) frequency (at approximately 75 dB), which were randomized. Prior to the start of the trials, the two different tones were presented to the participant so it was known how the two frequencies differed. In testing trials, each individual tone had a duration of 150 ms with 600 ms between each tone. Using their left hand, the participant pressed the left mouse button after the presentation of a high frequency tone and the right mouse button after a low frequency tone. The participants were instructed to respond as quickly as possible. The auditory tracking task was performed continuously until the visual stimulus appeared on the screen, which randomly occurred after the presentation of 2 to 8 auditory tones and was presented for 900 ms.

Response times for the background auditory task were calculated by measuring the timing of mouse clicks in response to auditory tones, sampled at approximately 12000 Hz. Errors were determined based on which mouse button was pressed with respect to the specific tone frequency.

3.2.2.2 Visual reaction time task

There were four different blocks of the visual task. One block was a simple reaction time task involving the presentation of a left pointing arrow, after which the participant was to flex their right wrist as quickly as possible, while keeping their arm stationary. In the second simple reaction time task, the stimulus was a right pointing arrow, and the participant then extended their wrist. Another block was a choice reaction time task where the participant was presented with either a left or right arrow. They were to subsequently extend their wrist if the arrow was pointing to the right, and flex their wrist if the arrow was pointing in the left direction. The left and right conditions were randomized. The fourth block involved the use of a modified Eriksen Flanker task (Eriksen and Eriksen, 1974; Botvinick et al., 1999). There were four task conditions for this block: right congruent, right incongruent, left congruent, and left incongruent which were randomized. The congruent trials involved an arrow flanked by four arrows facing in the same direction of the middle arrow. In incongruent trials, an arrow was flanked by four arrows facing in the opposite direction of the middle arrow. There were equal numbers of incongruent and congruent trials. The participant was required to respond to the arrow in the middle while ignoring the flanker arrows by either wrist extension or flexion as in the other blocks. For all visual reaction time task blocks, participants held their right hand in a neutral position, with the thumb up, before wrist extension or flexion, and then returned it back to the neutral position following contraction. Reaction time to the presentation of the visual stimulus was measured using the onset of electromyography and accelerometers were used for a kinematic verification of the EMG.

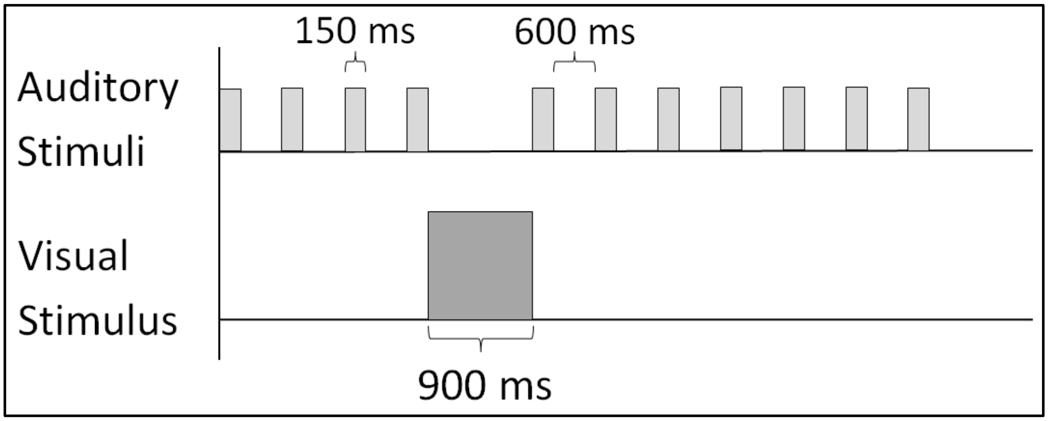

Figure 3-1: Set-up of a switch trial illustrating the presentation of the auditory and visual stimuli. Each rectangle represents a stimulus. Auditory tones were presented until the presentation of the visual stimulus, which occurred randomly after the presentation of 2 to 8 auditory stimuli, and then auditory tones were presented again until the end of the trial.

3.2.2.3 Electromyography (reaction time for visual reaction time task)

Electromyography (EMG) was collected from the extensor carpi radialis and flexor carpi radialis of the right wrist and was the primary measure of reaction time to the visual stimulus. The self-adhesive electrodes (Kendall Foam Electrodes) were placed in close proximity, over the muscle belly, in alignment with the muscle fibers. A ground electrode was placed on the clavicle. Prior to the application of the electrodes, the skin was abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. EMG was collected continuously using a custom LabVIEW^{TM} (National Instruments, Austin, Texas, USA) program, amplified at a gain of 500, band-pass filtered on-line from 10-1000 Hz and digitized at 1000 Hz.

3.2.2.4 Accelerometers (error rate for visual reaction time task)

Accelerometry was used to confirm the direction of the movement. A tri-axial MTw accelerometer (Xsens, Enschede, The Netherlands) was strapped onto the palm of the right hand. Accelerometer data were collected for each block using Xsens MT Manager, sampled at 100 Hz. The data was then exported to be analyzed for acceleration in the Z direction.

3.2.3 Data analysis

A customized LabVIEW^{TM} program was used to analyze the collected data. Synchronization pulses were sent to the collection program at the presentation of the visual stimulus, so EMG onset could be determined, time-locked to the visual stimulus. A synchronization pulse was sent from the LabVIEW^{TM} program collecting the EMG data to the Xsens MT Manager program.

EMG signals were dual band-passed filtered at 20-450 Hz using a 2nd order Butterworth filter, baseline corrected, full-wave rectified, and smoothed using a dual pass low-pass 5 Hz 2nd order Butterworth filter. EMG onset occurred when the full-wave rectified signal crossed a threshold of the baseline (200 ms prior to stimulus presentation) mean plus 3 standard deviations and the smoothed data remained above the threshold for 25 ms (adapted from an approach by Hodges and Bui (1996)). Mean reaction times for switch trials and non-switch trials were computed for all the blocks based on EMG onset latencies. The switch cost was calculated as the difference in reaction times between switch and non-switch trials.

Accelerometer data were dual-passed through a low-pass 20 Hz 4th order Butterworth filter and then baseline corrected by subtracting the mean. Accelerometer onset was determined at the point where the signal crossed a threshold of the mean of the baseline (20 ms prior to stimulus presentation) plus 5 standard deviations. The direction of the acceleration was determined as either positive or negative at onset, indicating left or right wrist movement respectively.

Visual trials were deemed an error in direction if the wrong wrist was moved in the incorrect direction. Directional errors for the auditory task occurred if the wrong button was pressed (demonstrating an incorrect left/right response). In addition if the visual reaction time was longer than 1200 ms, that trial was coded as an error in timing and disregarded for subsequent analysis. Overall, 22 out of 1200 trials, or 1.83%, of visual trials were errors and therefore excluded. The highest visual error rate, 4.58%, was in the switch condition for the flanker task, with all other error rates being 2.50% and below. Responses to auditory tones were also considered errors in timing if the response time was shorter than or equal to 150 ms or longer than 750 ms. Overall, prior to the presentation of the visual stimulus, 368 auditory responses were determined errors out of 2999 trials, or 12.27% of trials. Of the 2999 trials, 216 trials (7.20%) were directional errors in which the incorrect button was pressed, 115 trials (3.83%) were slow errors (>750 ms) and 37 trials (1.23%) were anticipation errors (≤150 ms). Auditory errors were excluded from response time analysis.

3.2.4 Statistical analysis

To test the initial hypothesis that a significant switch cost will occur between single and dual task conditions and to examine differences in the switch and non-switch conditions between tasks, a 2-factor repeated measures analysis of variance (ANOVA) was performed. The two factors were: 1) switch condition (2 levels: switch and non-switch) and 2) task difficulty (4 levels: simple-left, simple-right, choice, and flanker). To test the second hypothesis that switch cost will increase as task difficulty increases, a 1-way ANOVA was run on the calculated switch cost, the factor being task difficulty (4 levels). A significance level of

$\alpha=0.05$ was used for statistical analysis. The original data was tested for normality and found to be in slight violation, as the data was skewed to the right. This data was subsequently log-transformed to normalize the distribution. A Tukey-Kramer adjustment for multiple comparisons was made on the log-transformed data.

3.3 Results

Hypothesis 1: Reaction times (switch versus no switch)

The grand mean reaction times for each level of task difficulty for switch and non-switch trials are shown in Figure 3-2. There was a main effect of switch condition on reaction time, in that reaction times were longer in the switch condition than the non-switch condition ($F(1,9)=156.27$, $p<0.0001$). Post-hoc analysis revealed statistically significant differences in reaction times between switch and non-switch conditions for the simple and choice levels of task difficulty (Figure 3-2; $p<0.0001$). For the flanker task, the differences approached statistical significance between switch and non-switch conditions ($p=0.0739$). There was a main effect of congruency for the flanker task where reaction times were longer for incongruent than congruent trials ($F(1,9)=21.02$, $p=0.0013$) as well as a significant interaction between congruency and switch condition ($F(1,9)=7.35$, $p=0.024$). Reaction times for the flanker task separated by congruency are shown in Figure 3-3.

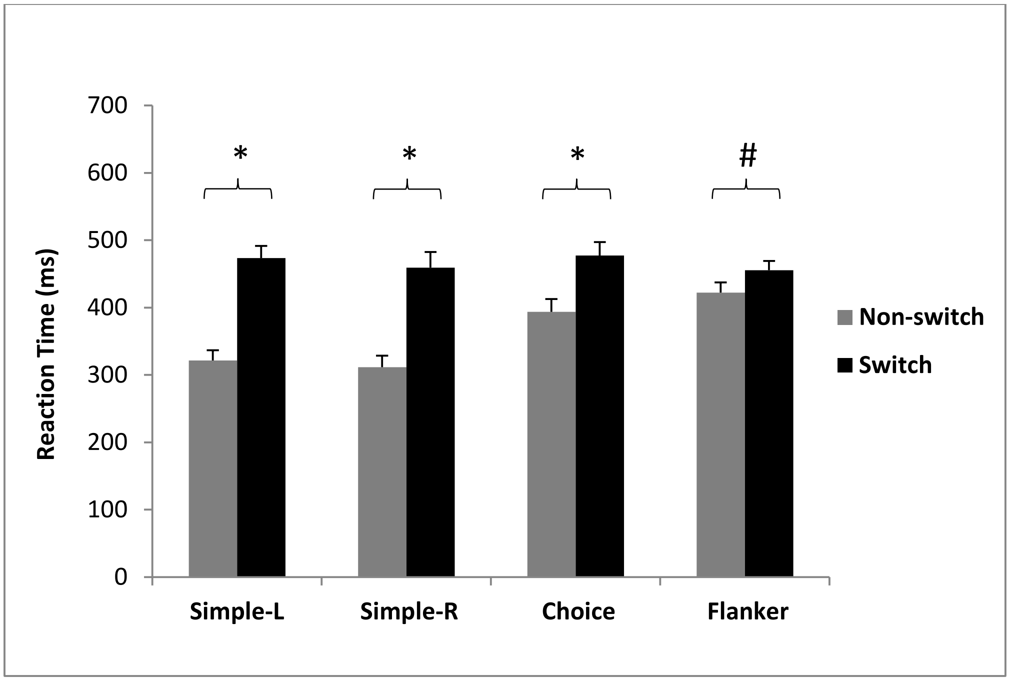

Figure 3-2: Average reaction times (n=10) for switch and non-switch trials across each level of task difficulty. The blue bars represent the non-switch trials while the orange bars represent the switch trials. The flanker data is collapsed across congruent and incongruent trials. Error bars represent standard error. The * denotes statistical significance (p's <0.0001); # denotes a trend towards statistical significance (p=0.0739).

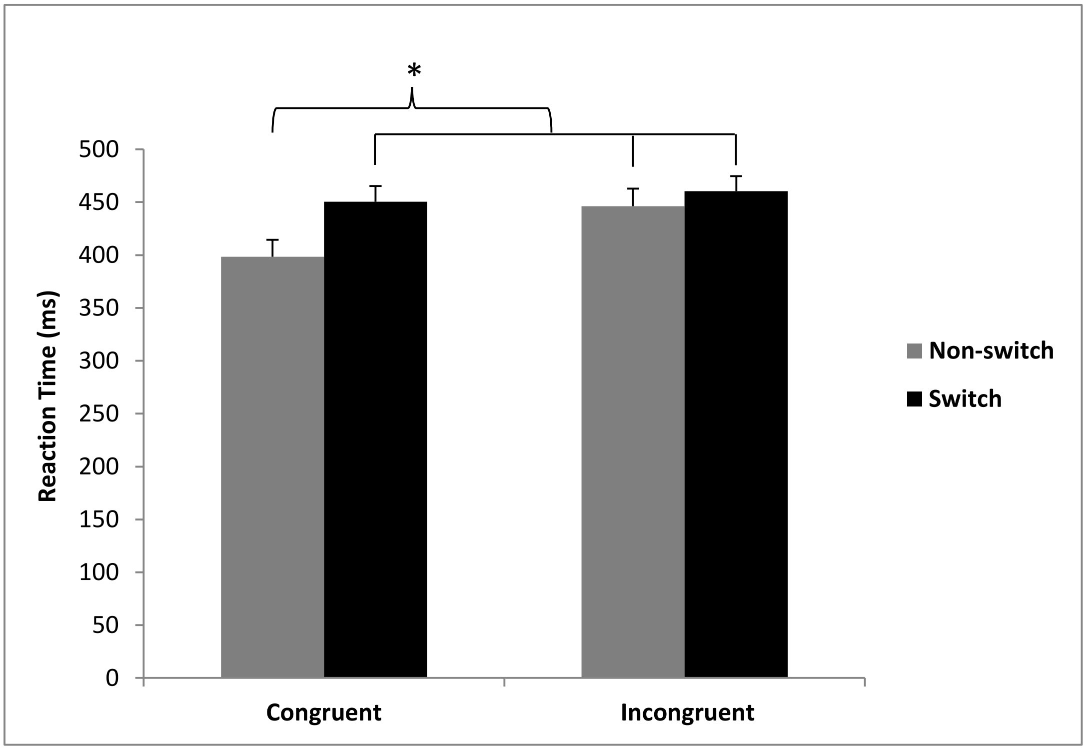

Figure 3-3: Average reaction times (n=10) for switch and non-switch trials for the flanker task, separated by congruency. Error bars represent standard error. The * denotes statistical significance (p's <0.0029).

Hypothesis 2: Task difficulty

There was a main effect of task difficulty (F(3,27)=15.21, p<0.0001) on reaction times. The higher levels of difficulty had longer reaction times in the non-switch condition. There was a significant interaction between switch condition and task difficulty (F(3,27)=32.86, p<0.0001) with post hoc test showing significantly longer reaction times in the switch condition for both simple tasks compared to the flanker and choice levels of difficulty (p<0.0001). There were no differences found in reaction times for switch trials between the four tasks (p>0.76). In addition, there were no statistically significant differences in reaction times between the two simple tasks (L vs R) in either switch condition (p>0.96).

When expressing differences as switch costs, there was a main effect of task difficulty level (F(3,27)=22.05, p<0.0001), where the switch cost was the lowest for the flanker task, greater for the choice reaction time task, and then largest for the simple tasks. Mean switch costs for each task are presented in Figure 3-4. Computed switch costs were 151.9 ms, 147.9 ms, 83.4 ms, and 33.1 ms, for the simple-left, simple-right, choice, and flanker tasks, respectively. Significant differences were measured between flanker, choice and simple tasks. There was no statistically significant difference between the switch costs for the two simple tasks (L vs R) (p=0.99).

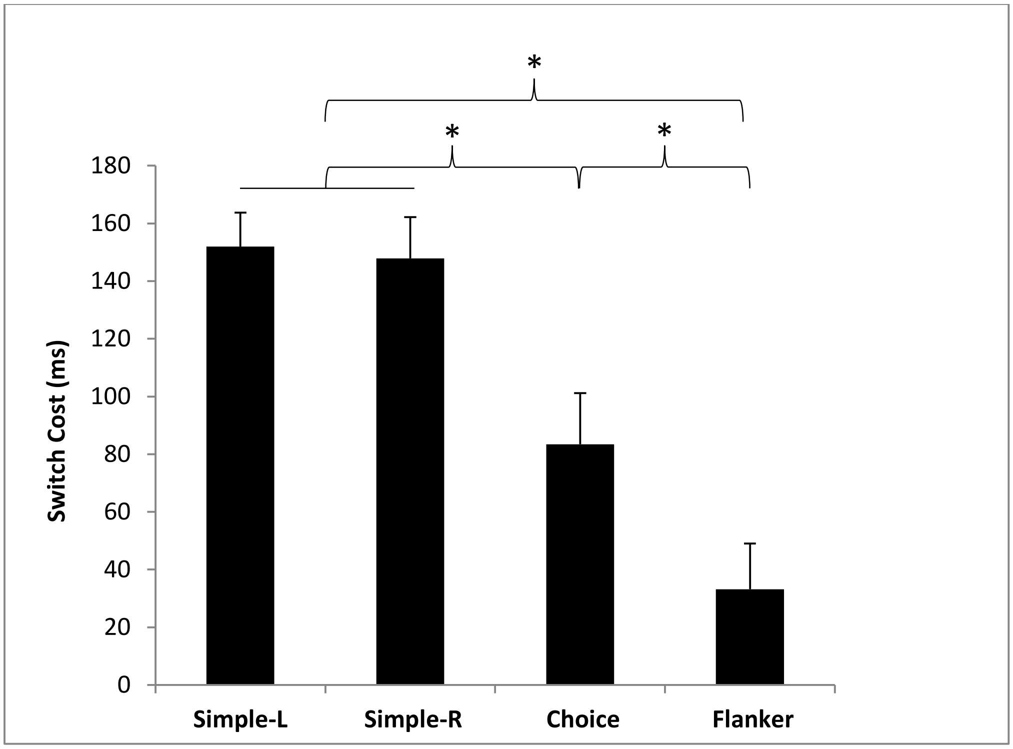

Figure 3-4: Average (n=10) switch costs for each task. Switch cost was calculated as the difference in mean reaction times for switch trials and non-switch trials. Error bars represent standard error. The * denotes statistical significance (p's <0.032).

Background auditory tracking task performance

In order to assess task performance on the background auditory task, response times were measured and compared. There was no main effect of task difficulty on response times measured in correct trials (F(3,27)=0.14, p=0.935), presented in Figure 3-5a. Error rates for the auditory tracking task were analyzed for the auditory stimuli that occurred prior to the onset of the visual stimulus. Individual participant error rates, as well as the number of errors, separated into directional, anticipation (fast), or slow error categories are displayed in Table 3-1. Error rates across subjects ranged from 0.00% to 26.53% across all error types. Focusing on only errors in direction, a main effect of task difficulty level on error rate approached statistical significance (F(3,27)=2.81, p=0.059).

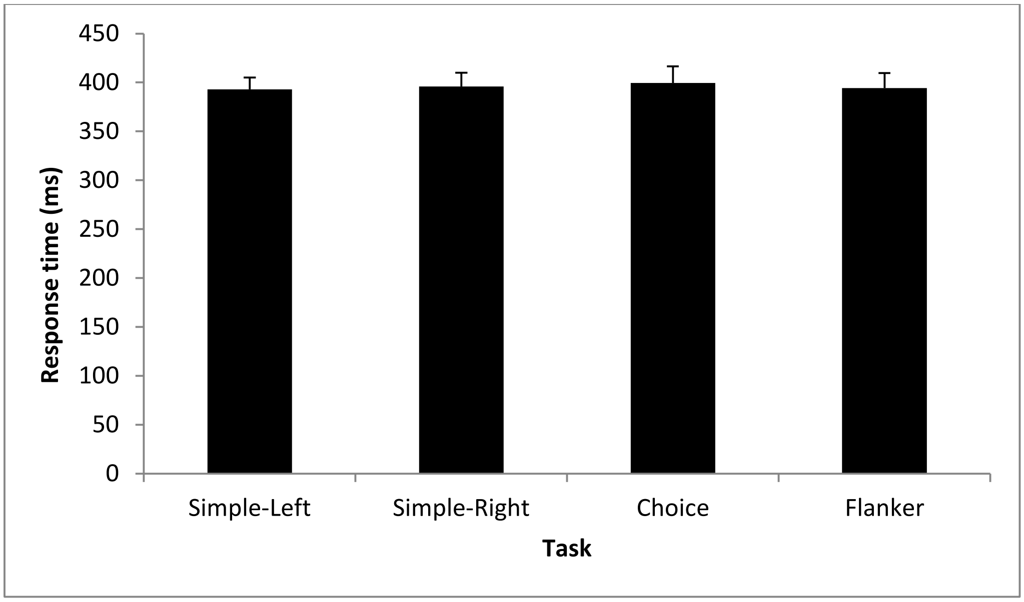

Figure 3-5a: Average (n=10) auditory response times for each task, as measured from the presentation of the auditory tone to the click of the mouse. Error bars represent standard error.

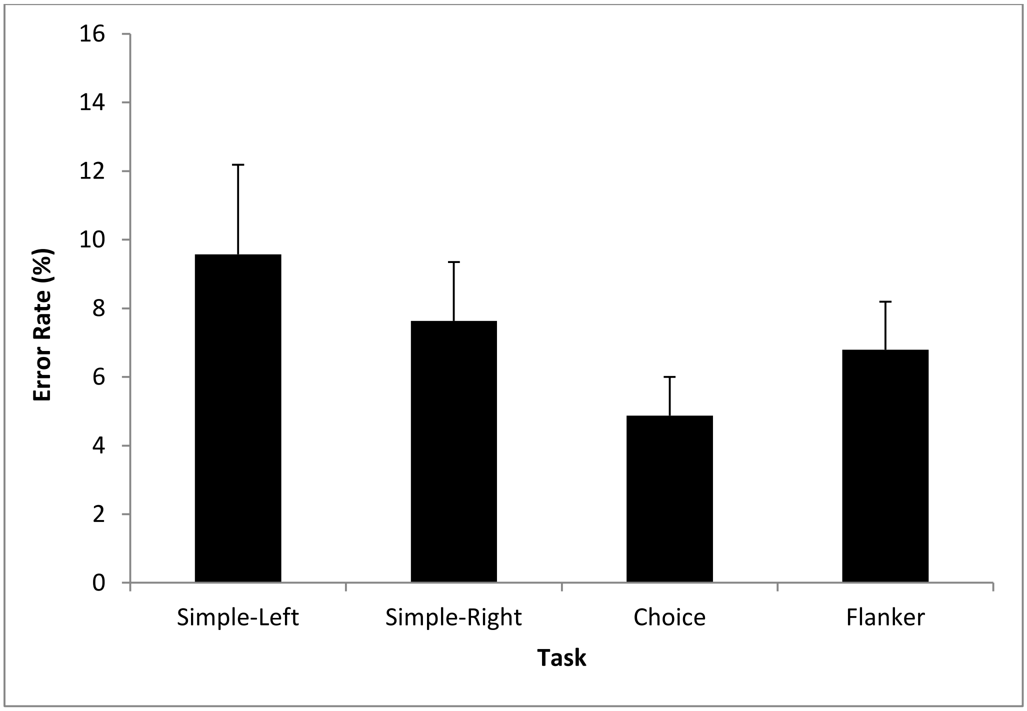

Figure 3-5b: Average (n=10) auditory directional error rates for each level of task difficulty. Error bars represent standard error.

Given the differences in error rates it is possible that certain individuals may have performed differently during background auditory task and that may have led to different visual switch costs. In order to determine if there was a relationship between the visual switch cost and the auditory error rates across individuals a correlational analysis was performed for each task condition. Overall there was no statistically significant association in error rate versus the switch cost performance within specific task conditions (0.061>r>-0.129, p>0.72) (Figure 3-6).

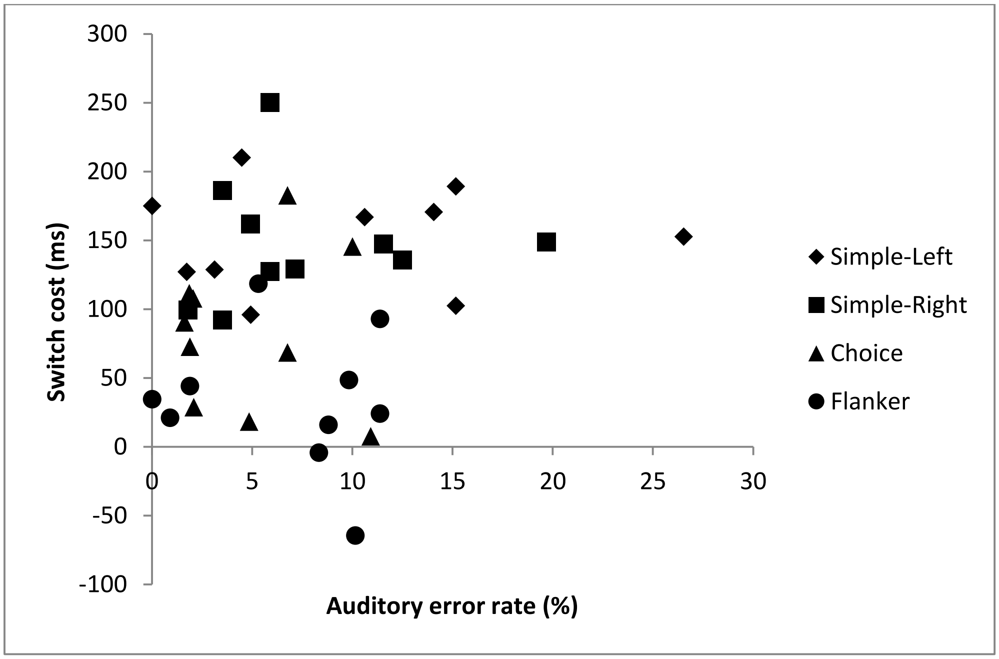

Figure 3-6: Relationship between average error rates (within subjects) of the background auditory task and average switch cost when executing the visual reaction time test during switch trials. Each data point reflects a single participant. There was no statistically significant relationship between visual switch cost and auditory error rates (p's>0.72).

Table 3-1: Error rates and number of errors in the background auditory task for each participant, separated into 3 categories for each level of task difficulty.

Participant	Simple-Left (% (# of errors))			Simple-Right (% (# of errors))			Choice (% (# of errors))			Flanker (% (# of errors))		
	D	**F**	**S**	**D**	**F**	**S**	**D**	**F**	**S**	**D**	**F**	**S**
1	1.72 (1)	0.00 (0)	3.45 (2)	7.14 (4)	0.00 (0)	0.00 (0)	1.89 (1)	0.00 (0)	1.89 (1)	0.00 (0)	0.00 (0)	0.00 (0)
2	10.61 (7)	3.03 (2)	13.64 (9)	4.92 (3)	1.64 (1)	1.64 (1)	10.00 (6)	1.67 (1)	10.00 (6)	9.82 (11)	0.89 (1)	8.04 (9)
3	4.48 (3)	2.99 (2)	4.48 (3)	3.51 (2)	3.51 (2)	3.51 (2)	1.61 (1)	0.00 (0)	1.61 (1)	5.31 (6)	1.77 (2)	3.54 (4)
4	26.53 (13)	0.00 (0)	12.24 (6)	19.67 (12)	6.56 (4)	21.31 (13)	10.91 (6)	0.00 (0)	5.45 (3)	10.14 (14)	4.35 (6)	5.07 (7)
5	3.12 (2)	1.56 (1)	0.00 (0)	1.79 (1)	0.00 (0)	0.00 (0)	2.04 (1)	0.00 (0)	2.04 (1)	1.89 (2)	0.00 (0)	0.00 (0)
6	15.15 (10)	0.00 (0)	4.55 (3)	5.88 (4)	0.00 (0)	7.35 (5)	6.76 (5)	1.35 (1)	2.70 (2)	11.38 (14)	0.81 (1)	4.07 (5)
7	4.92 (3)	3.28 (2)	1.64 (1)	11.54 (6)	1.92 (1)	1.92 (1)	4.84 (3)	0.00 (0)	0.00 (0)	8.80 (11)	0.80 (1)	0.00 (0)
8	15.15 (10)	0.00 (0)	11.11 (1)	5.88 (4)	0.00 (0)	4.55 (3)	6.76 (5)	1.35 (1)	2.70 (2)	11.38 (14)	0.81 (1)	4.07 (5)
9	0.00 (0)	0.00 (0)	0.00 (0)	3.51 (2)	0.00 (0)	0.00 (0)	2.08 (1)	0.00 (0)	2.08 (1)	0.90 (1)	0.00 (0)	0.00 (0)
10	14.06 (9)	1.56 (1)	9.37 (6)	12.50 (7)	0.00 (0)	3.57 (2)	1.85 (1)	3.70 (2)	1.85 (1)	8.33 (10)	3.33 (4)	4.17 (5)
Mean	9.57 (6)	1.24 (1)	5.39 (3)	7.63 (5)	1.36 (1)	4.67 (3)	4.87 (3)	0.81 (1)	3.03 (2)	6.80 (8)	1.28 (2)	2.90 (4)
Standard Error	2.61 (1.43)	0.45 (0.29)	1.52 (0.92)	1.72 (1.01)	0.69 (0.42)	2.04 (1.27)	1.13 (0.71)	0.39 (0.22)	0.88 (0.53)	1.40 (1.77)	0.47 (0.62)	0.88 (1.05)

D=directional error (wrong button pressed); F=fast or anticipation error (≤150 ms); S=slow error (>750 ms)

3.4 Discussion

The results of this study supported the first hypothesis revealing differences in reaction times between switch and non-switch trials resulting in a behavioural switch cost. In terms of the second hypothesis, while it was originally hypothesized that switch cost would increase as the level of difficulty of the visual reaction time task increased, opposing results were found. On average, the switch cost was lower for more challenging task conditions (choice reactions) as compared to simpler tasks.

The novel task involving the quantifiable background auditory task and switching to visual reaction time tasks appeared to be an effective approach to reveal the behavioural switch cost and control task challenge. On average in this study the switch cost was between 33 ms and 152 ms (depending on the visual task) which is within the range of those observed in other task-switching studies. When switching between two modalities, Strobach et al. (2012) demonstrated a lower mean switch cost (12 ms) in the visual modality and studies employing rule-based switching, have presented average switch costs of greater than 200 ms (Rogers and Monsell, 1995). While the current study was within this range, the very wide range of switch costs across different studies does raise some concern about comparing studies. This variability in switch costs may arise from methodological differences. As a result, it is difficult to directly compare the results of this study to another study due to differences in the task switching paradigm.

One important difference in terms of methodology featured in this study is the near-continuous nature of the background auditory task. This was an attempt to maintain attention directed to the background task as continuously as possible to avoid anticipatory attention switching. The auditory tones were rapidly presented and randomized in an attempt to ensure the participant focused their attention on the auditory task, when required to do so. The cognitive processing time after the presentation of the visual stimulus was measured through the onset of EMG, which allowed for a precise measure of the visual reaction time. This visual stimulus was also presented at a random time point, with no cueing, in order to lower the predictability of when the switch will occur, as predictability and cues have been shown to lower switch cost (Vandierendonck et al., 2010). According to the two prominent views in task-switching literature, switch cost may be due to interference from the previous task or the extra time required to reconfigure the task-set (Vandierendonck et al., 2010). While an adequate amount of preparation time before switching tasks may lower this switch cost (Vandierendonck et al., 2010), this task does not give the participant preparation time between tasks due to the near-continuous nature of the auditory task. In this task, there is only 600 ms in between each tone and was selected to avoid pre-emptively switching but preserve one's ability to perform the task. Increasing the interstimulus interval would provide time between stimuli that may allow subjects to switch attention, even briefly, in anticipation of the visual stimulus which would lower the switch cost. This was actually confirmed in pilot studies where longer interstimulus intervals lowered switch cost by presumably resulting in a greater possibility of pre-emptively switching attention. The work by Norrie et al., (2002) used a continuous tracking task in order to maintain attention on the background task. However that approach makes it more difficult to document the background task performance which was possible in the current design using response time and error rates. The benefit to the latter was ability to confirm, in this study, no difference in the performance of the background task across the different task conditions providing indirect support for the idea that subjects maintained attention directed to the background task prior to the presentation of the switch task.

In regards to the second hypothesis, the greatest switch cost was demonstrated when switching to the visual simple reaction time task, whereas switching to the flanker task resulted in the lowest switch cost duration. This is interesting considering the flanker task is the most difficult, while the simple reaction time task is the least difficult. While task difficulty or rule complexity are factors affecting switch cost duration (Rubinstein et al., 2001), in the case of this task, it does not appear to impact the switch cost as expected. It is unlikely that this is associated with any unique task-specific performance of the specific tasks (simple, choice, and flanker) as the reaction times for this in non-switch conditions were similar to the literature. In contrast, as discussed in more detail later, it is proposed that this unusual finding of greater switch cost in simple tasks is due to an inability to pre-program a response in the switch task conditions due to the nature of the near continuous auditory background task.

As anticipated, reaction times in the non-switch trials were shortest for the simple task, longer for the choice task, and longest for the flanker task. Whereas, mean reaction times in the switch condition for each of the visual reaction time tasks were very similar. When switching to the simple reaction time tasks, the reaction time increased up to approximately the same reaction time as in the choice and flanker tasks. This is comparable to results seen in studies utilizing dual-task paradigms with simple versus choice reaction time where adding in a secondary task increases reaction times for the simple task by a greater amount than with the choice task (Frith and Done, 1986; Goodrich et al., 1990). These results have also been revealed using multiple modalities (Goodrich et al., 1990). Overall the timing of the background task was the same across different switch conditions tasks so that differences in background task are unlikely to account for differences in switch cost. While the error rates on the auditory tracking task varied between individuals, overall, error rates were fairly low indicating that participants were focused on that task prior to switching to the primary visual task. There was no statistically significant correlation found between switch cost and the auditory error rates for any task. Overall it is unlikely that the switch cost differences between tasks can be attributable to differences in auditory task performance.

Potential factors leading to the greater switch cost with lower levels of task difficulty are: 1) ability to pre-program a response and 2) disengagement from the background task. From studies of simple reaction time, it has been postulated that there is a preparatory process, requiring undivided attention, allowing for the response to the stimulus to be pre-programmed since there is only one response. In choice reaction time tasks, the response cannot typically be pre-programmed as it is not known in advance of the stimulus onset (Frith and Done, 1986; Goodrich et al., 1990). In the case of the switching task examined in this study, attention would be required by the auditory tracking task and so undivided attention is not available in order to pre-program the response for the visual task. As the response cannot be pre-programmed, in theory, there would be an added response selection processing stage, resulting in a longer reaction time for the switching condition, much like a choice task. The theoretical differences in information processing for simple and choice reaction time for non-switch trials are highlighted in Figure 3-7.

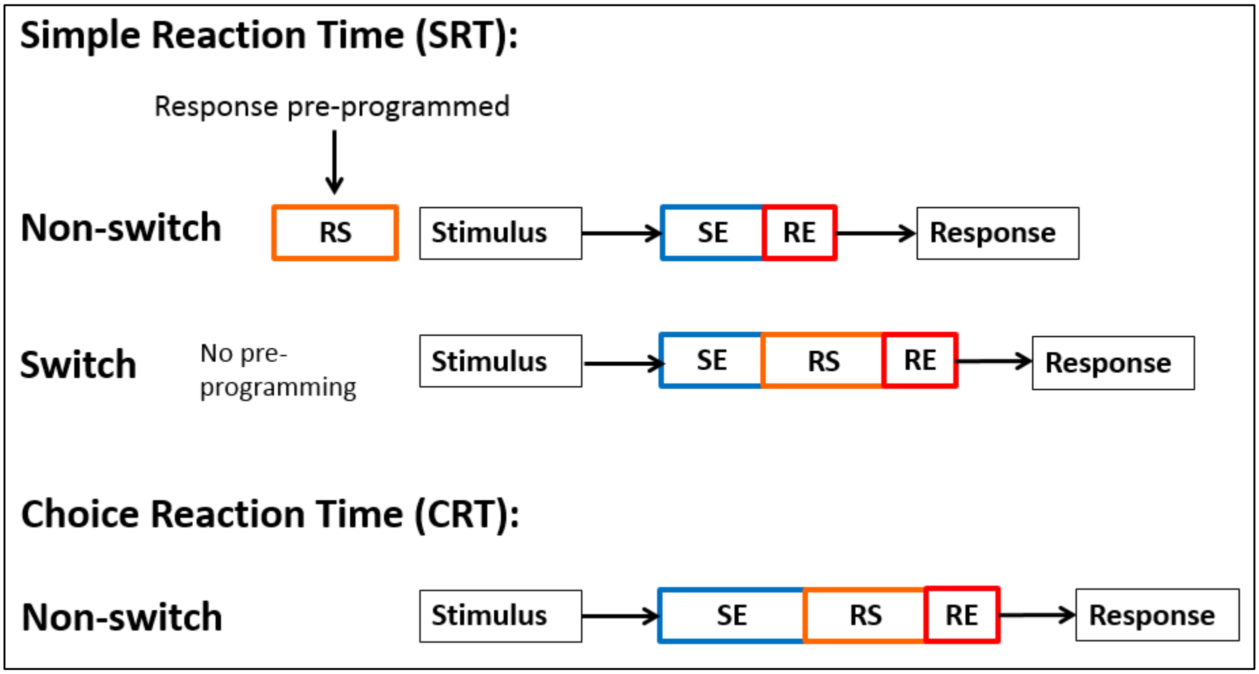

Figure 3-7: Information processing in simple non-switch and switch trials as well as choice reaction time non-switch trials. SE=Stimulus detection and evaluation; RS=Response selection; RE=Response execution.

Alternatively, the task-related differences in switch-cost may be associated with the disengagement process. This is the process involved when switching attention from the first task to inhibit the task-set in order to engage in the next task (Monsell, 2003). It is hypothesized that this disengagement process may run in parallel with stimulus identification and evaluation. However, response selection may not occur until disengagement from the previous task has fully occurred. As a result, the timing of response selection would be delayed. As the level of task difficulty of the visual task increases, the time taken to evaluate the stimulus increases. It would take the longest to evaluate the stimulus in the flanker condition, as it involves making a choice between two responses, as well as the inhibition of the distractors (Eriksen and Eriksen, 1974). If disengagement can occur at the same time as stimulus evaluation and disengagement timing is the same across all levels of task difficulty, then this would result in lower switch costs as the stimulus evaluation time increases. This may be the reason for the lowest switch cost when switching to the flanker task and an even lower switch cost when switching to incongruent flanker trials, if separated by congruency. Figure 3-8 illustrates the non-switch and switch conditions for each level of task difficulty, highlighting the potential role of the disengagement process and the resulting switch costs.

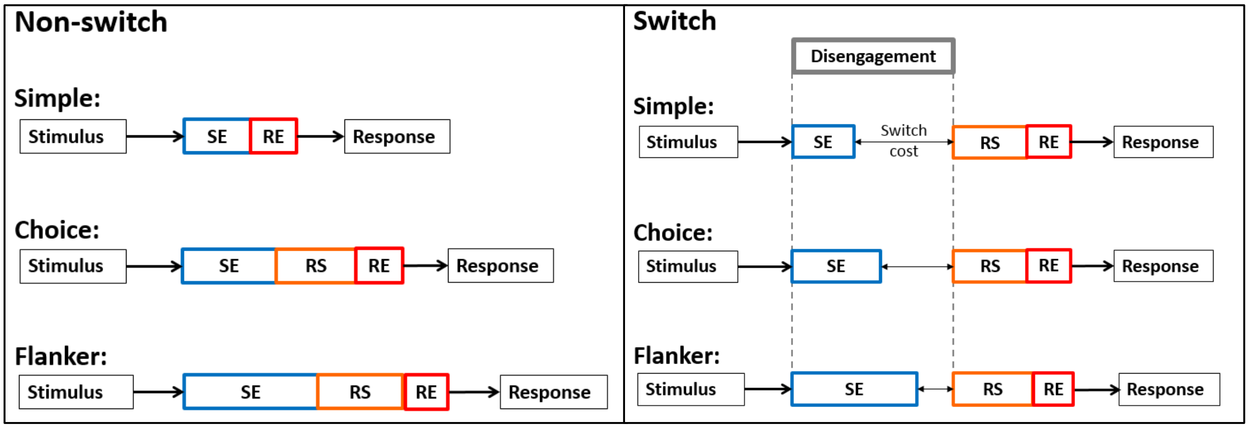

Figure 3-8: Information processing in the non-switch and switch conditions for simple, choice, and flanker tasks. The resulting switch cost is shown by the double arrows. For the simple task, the total calculated switch cost is shown by the double arrows plus the timing of the added response selection stage. SE=Stimulus detection and evaluation; RS=Response selection; RE=Response execution.

3.5 Conclusions

In conclusion, this approach utilizing a near continuous background auditory tracking task with an unpredictable switch to a visual reaction time task is effective at measuring switch cost with temporal precision. The outcome of this study indicates that for this switching task, the visual task demonstrating the greatest switch cost in terms of magnitude was the simple reaction time task. It was also determined that as the difficulty of the task increased, the switch cost decreased. This task can be used in subsequent studies to examine the electrophysiological aspects of the switch cost. Electrophysiological markers at multiple stages of information processing should be studied to give an indication as to differences in processing between switch trials and non-switch trials. Future studies, employing electrophysiology, could examine switch cost using this attention switching paradigm in order to further understand information processing when switching attention between tasks of different modalities. This future work may provide an indication as to which processes are impacted by the switch cost and the source of this delay in reaction time with task switching.

Chapter 4: Study 2 – Examining changes in cortical activity and electrophysiological markers associated with attention switching between tasks of different modalities

4.1 Introduction

Multi-tasking, a common demand of daily life, involves switching attention between two tasks, termed attention switching. This ability to disengage from one task and engage in another is an executive function allowing for cognitive flexibility in a dynamic environment (Hyafil et al., 2009). Attention switching can, however, result in a decreased level of performance as demonstrated by a behavioural switch cost (Monsell, 2003). This switch cost is the difference in reaction times between trials involving a switch between tasks and trials in which a single task is performed (non-switch) (Wylie and Allport, 2000). Attention switching is associated to the speed of information processing and may reveal an increased length of a specific stage of information processing or the addition of another process (Hsieh, 2006). There are inconsistencies in the literature as to whether the switch cost is more involved in the response selection or perceptual stages (Hsieh, 2006). Investigating the electrophysiological correlates of attention switching at early and late stages of information processing can provide further insight into the underlying mechanisms or factors contributing to the switch cost.

There are a number of various techniques used to assess switch cost, which vary on specific factors, including the characteristics of the tasks and how the switching is measured. The two tasks may differ on several features such as the sensory, cognitive or motor determinants of the task and the task instructions; however, to reduce complexity, a common approach is to maintain similar sensory and motor components and switch between cognitive elements. This ‘rule’ switch paradigm requires individuals to switch between different stimulus-response rules. For example, when presented with a number, the individual may need to switch between a rule-based response based on the size of the number or if the number is odd or even (Rogers and Monsell, 1995). Some task switching paradigms involve a switch between stimulus modalities, such as auditory to visual stimuli (Strobach et al., 2012; Williams et al., 2013). The methods in which switch cost is measured involve composite measures of overall performance (eg standard Wisconsin card sorting task) (Buchsbaum et al., 2005) and computerized tools providing response or reaction times for individual trials (Rogers and Monsell, 1995). While composite measures have clinical utility, they do not provide adequate temporal resolution as they are based on a number of correct responses or total time for performance. With the use of computerized tools, there is more information regarding timing for individual trials; however, it is usually known when the switch will occur, as tasks are alternated every couple of trials or every other trial.

Previous work (Study 1 of this thesis; Chapter 3:) evaluated a novel approach to precisely measure and assess timing information related to the switch cost. The task consisted of a background task involving a choice response to auditory stimuli and then switching to a visual reaction time task. An important rationale for this task was the use of two different stimulus modalities allowing for electrophysiological markers of early sensory processes to be examined attempting to reduce interference of the previous task. In addition, the measurement of reaction time using electromyography (EMG) provides a precise index of processing time to be used during data analysis of electrophysiological responses. The utilization of a background task that is near-continuous allows for attention to be focused on this task without the potential to switch attention during lapses in attentional demand. This previous work revealed a significant switch cost when switching from this background auditory task to a visual reaction time task, as measured through the mean difference in reaction times to the visual stimulus when switching between the two tasks, and when performing the visual task alone. This switch cost was apparent even when switching to a simple visual reaction time task, in which the same single stimulus was presented requiring the same response. While this previous study focused on the behavioural aspects of the switch cost, examining electrophysiological markers during this task could help reveal the neurophysiological basis of the switch cost.

Electrophysiological measurements have excellent temporal resolution and when time-locked to the presentation of a stimulus can give an indication of the processes that are taking place after stimulus onset (Hillyard and Anllo-Vento, 1998). To examine changes in brain activity in the early and later stages of information processing, it was the intent to examine the N1 and P3 components of an event-related potential, time-locked to the presentation of the visual stimulus. The N1 and P3 components are both influenced by attention, and can therefore indicate attentional resource allocation when completing a task. The visual N1 component, peaking approximately 150 to 200 ms after stimulus presentation (Luck, 2005), reflects discriminative processing of stimulus attributes (Fonaryova Key et al., 2005). The P3, a positive component peaking 300 ms or more post-stimulus, is evoked when individuals attend to a stimulus and distinguish its characteristics (Herrmann and Knight, 2001). The P3 amplitude is reflective of the amount of attentional resources allocated to a specific task, while its latency indicates the speed of processing and stimulus evaluation (Polich, 2007).

In terms of task switching, imaging studies have demonstrated increased activation in areas of the dorsal lateral prefrontal cortex (Brass and von Cramon, 2004) and the parietal cortex, with task-relevant regions in the prefrontal cortex being more active when switching between two tasks (Yeung et al., 2006). In EEG studies, a large negative posterior slow wave has also been noted following stimulus presentation in non-switch trials, but not in switch trials. This negativity is thought to indicate anticipatory activity involving thalamo-cortical pathways (Goffaux et al., 2006). Furthermore, there may be differences in the length of a specific stage of information processing or an additional process between the switch and non-switch conditions and inconsistencies in the literature on whether the switch cost is more involved in perceptual or response selection stages warrants further investigation (Hsieh, 2006).

Studies specifically examining the stimulus-locked P3 component of an event-related potential (ERP) during task-switching have demonstrated attenuated amplitude and similar latency during switch trials as opposed to non-switch trials (Hsieh, 2006; Gajewski and Falkenstein, 2011). This attenuated amplitude indicates that when switching there is greater demand for attentional resources and interference from the previous task consuming the resources (Polich, 2007). An enhanced N2 component during switching could also lead to the attenuated P3 amplitude, meaning task switching has greater response selection demands and is difficult (Gajewski and Falkenstein, 2011). Similar P3 latencies indicate that the time taken to evaluate the stimulus is comparable between switch and repetition trials (Kamijo et al., 2007). The lack of delay in the P3 in the face of significant switch cost is somewhat surprising given the relationship between speed of processing and P3 timing (Polich, 2007). Arguably the absence of a delay in P3 during switch trials may suggest no relationship between the temporal properties of the P3 and behavioural responses (reaction time) or that the delay in processing is not linked to attentional processes associated with the P3. In contrast, it is possible that the methodological approaches adopted (eg strategy to maintain attention directed to the background task and provide a precise timing of the onset of switching) may have limited the ability to detect changes in P3 latency. As a result, the current study set out to investigate the timing and amplitude of cortical potentials during switch and non-switch trials. Using the task developed in study 1 of this thesis that employs a near continuous auditory background task and an unpredictable switch to the visual task allows for the switch cost to be precisely measured and coupled with electrophysiological measures will provide insight on the neurophysiological substrate for the switch cost.

The objective of this study was to examine changes in cortical activity and electrophysiological markers associated with attention switching between tasks of different modalities to reveal the neurophysiological basis of the switch cost. Furthermore, this study investigated the relationship between switch cost timing specific electrophysiological markers specifically the N1 and the P3. There was some concern with potential interference of the cortical events associated with the background auditory task and the early N1 so this was specifically investigated prior to analyzing the N1 response. A primary focus was on the P3 waveform. In spite of previous literature, it was hypothesized under the current paradigm, that the P3 component of a stimulus-locked event-related potential will have decreased amplitude and delayed latency in switch trials as compared to non-switch trials. It is proposed that this would reflect a delay in the stages of processing, specifically the events related to attending to the visual stimuli that underpin the behavioural switch cost. In light of the hypothesized link between the reaction time and the delays measured cortically it was also hypothesized that there would be a positive correlation between the switch cost and differences in P3 latency between the switch and non-switch condition.

4.2 Materials and Methods

4.2.1 Participants

Twenty young healthy right-handed adults (10 females; mean age±1SD: 25±3.7) were recruited for this study. This study received ethics clearance through a University of Waterloo Research Ethics Committee and all participants provided written consent prior to study participation. Participants were instructed to refrain from heavy physical activity on the day of the testing session and to perform their normal daily activities.

4.2.2 Protocol

Participants were seated in a chair with their head approximately 60 cm in front of a computer monitor. Their right arm and hand rested on a table with their thumb pointing upwards, while their left hand was positioned on a computer mouse. The electroencephalography (EEG) cap was set-up on the participant's head according to the international 10-20 system and connected to a digital EEG amplifier (NeuroScan SynAmps^2). In this randomized block design, participants completed two cognitive tasks including: 1) a near-continuous auditory tracking task and 2) a visual simple reaction time task. The switch blocks involved switching from the background auditory tracking task to the visual reaction test, while the non-switch blocks involved responding to the visual task only. There were 8 testing blocks including 4 switch and 4 non-switch; each block consisting of 25 trials. Each trial was 8 seconds in duration with 5 seconds in between each trial. In switch trials participants began with the auditory tracking task until the visual stimulus appeared on the computer monitor and were instructed to respond to the visual stimulus immediately and then return back to the auditory tracking task until the completion of the trial. In all trials, participants were instructed to fixate on a cross in the centre of the computer screen.

Participants were given a 2 minute break after every second block. Practice trials were completed before the 8 testing blocks in order to minimize a learning curve. Two trials (22 beeps total) of the auditory tracking task were completed, followed by 10 trials of the visual simple reaction time task, and then 2 trials of the switching task. The entire testing session was approximately 2 hours long and all testing was conducted in the morning, starting between 8:00 am and 9:30 am.

4.2.2.1 Background auditory tracking task

The auditory tracking task involved the presentation of a series of randomized tones of either high (1000 Hz) or low (200 Hz) frequency at approximately 75 dB level. These tones were presented to the participant prior to the practice trials so they were familiar with how the two frequencies differed. For this task, each tone was 150 ms, with a fixed interstimulus interval of 600 ms. Participants were instructed to respond as quickly as possible, pressing the left mouse button after a high frequency tone and the right mouse button after a low frequency tone. This task was performed continuously until the visual stimulus appeared on the screen for 900 ms, which randomly occurred after 2 to 8 auditory tones were presented.

Response times for the auditory tracking task were calculated by measuring timing of mouse clicks in response to auditory tones, sampled at approximately 30000 Hz. Errors were determined based on which mouse button was pressed with respect to the specific tone frequency.

4.2.2.2 Visual Reaction Time Task

For the visual reaction time task, the participant began with their right arm resting on the table with their thumb pointing upwards. A left pointing arrow was presented for 900 ms and the participant was instructed to flex their right wrist as quickly as possible, pointing in the direction of the arrow.

4.2.2.3 Electromyography (reaction time for visual reaction time task)

Electromyography (EMG) was collected from the flexor carpi radialis of the right wrist to measure reaction time to the visual stimulus. The skin was first abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. Two self-adhesive electrodes (Kendall Foam Electrodes) were placed close together over the muscle belly, in alignment with the muscle fibers. The ground electrode was placed on the right clavicle. EMG was collected continuously using a custom LabVIEW^{TM} (National Instruments, Austin, Texas, USA) program, amplified, band-pass filtered on-line from 10-1000 Hz and digitized at 1000 Hz.

4.2.2.4 Electroencephalography (EEG) and Electrooculography (EOG)

The skin above and below the left eye, lateral to both eyes and on mastoid processes was abraded with NuPrep skin preparation gel and then cleaned with rubbing alcohol. Electrodes were filled with conductive gel and attached to these sites with adhesive tape. The participant’s head was measured and marked halfway between the nasion and inion as well as halfway between the pre-auricular points on either side of the head. A Lycra cap containing electrodes was placed on the participant’s head, so that electrode Cz was at the connection of the markings that were just made. A disposable, blunt needle was inserted into the reservoir between the electrode and scalp through a hole in the electrode. It was moved in a circular motion to move the hair out of the way and conductive gel was released from the syringe into the reservoir. This was repeated for 32 electrodes (Figure 4-1), according to the 10-20 international system, on a 64 channel Quik-Cap (Compumedics Neuroscan, Charlotte, North Carolina, USA). EEG and EOG were collected continuously through SCAN 4.3 throughout each of the testing blocks, amplified (x19) and filtered at a band-pass of DC to 200 Hz and digitized at 1000 Hz. Synchronization voltages were also collected on the EEG system to denote the timing of the presentation of the visual and auditory stimuli. Impedances were kept below 8 kΩs.

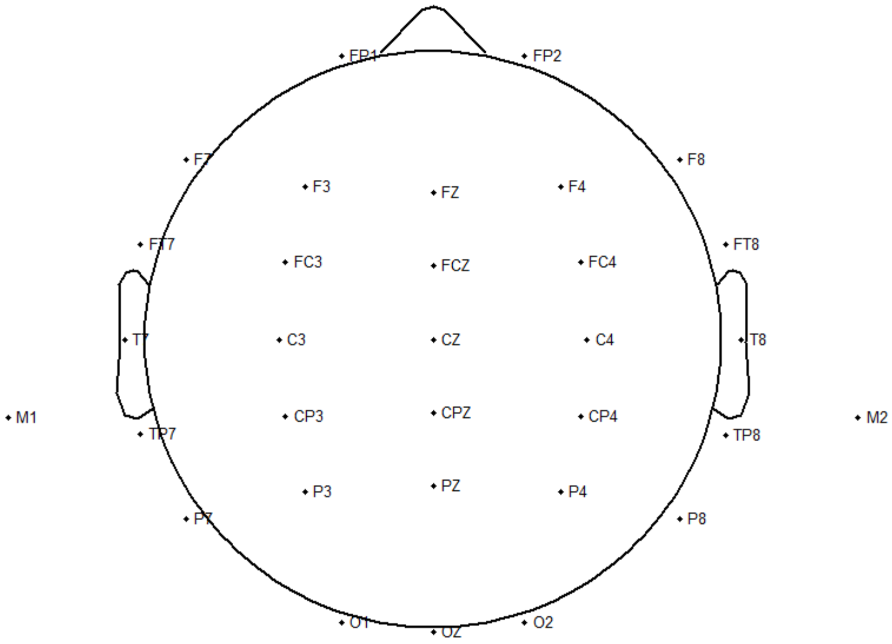

Figure 4-1: Locations of the electrodes used on the Quik-cap, including the mastoid processes.

4.2.3 Data Analysis

A customized LabVIEW™ program was used for visual reaction time and auditory response time data analysis. Synchronization pulses were sent to the collection program indicating the presentation of the auditory and visual stimuli, so that EMG could be time-locked to the visual stimulus and EEG data epoched around auditory and visual stimuli.

EMG signals were run through a 60 Hz notch line filter and dual-passed through a band-pass 2nd order Butterworth filter at 20-450 Hz. They were then baseline corrected, full-wave rectified and smoothed using a dual-pass low-pass 5 Hz 2nd order Butterworth filter. EMG onset was determined as the time at which the full-wave rectified signal crossed a threshold of the baseline (200 ms pre-stimulus) mean plus 3 standard deviations and the smoothed data remained above the threshold for 25 ms (adapted from an approach by Hodges & Bui (1996)). These latencies were used to determine mean reaction times for all testing blocks. Switch cost was then computed as the difference in mean reaction times between switch and non-switch trials.

EEG data was analyzed using EEGLAB (http://sccn.ucsd.edu/eeglab). EEG data was digitally filtered with a high-pass filter of 0.1 Hz and low-pass filter of 50 Hz, re-referenced to the mastoid processes and down-sampled to 250 Hz. Epochs were extracted 200 ms before stimulus presentation to 1000 ms after stimulus onset. Baseline correction was performed using a baseline of 200 ms prior to the presentation of the auditory stimulus and for visual epochs, a baseline of 150 ms prior to stimulus onset to 50 ms prior to stimulus presentation was used. Epochs were visually inspected for excessive noise. An Independent Component Analysis (ICA) was run for each condition (switch and non-switch) separately and components were removed based on the occurrence of artifacts.

Auditory epochs were separated into those directly before a switch to the visual and epochs not including the tone directly before a switch. The average auditory ERPs were overlapped with the visual switch and non-switch average ERPs to visually determine the extent to which the auditory ERP is included in the visual switch ERP, as this could affect the interpretation of the visual ERP.

To examine visual ERPs, the waveforms were dual-pass low-pass filtered at 30 Hz. Following the pattern of the visual ERP in the non-switch condition, the switch waveform was compared to match up deflections. The N1 was identified as the largest negative component within 150 to 200 ms post-stimulus at the Pz electrode site. The P3 component was identified as the largest positive peak following the N1-P2-N2 complex, if present in the average waveform, or as identified following the non-switch waveform pattern. The latency was determined from the presentation of the stimulus to the time point of maximum amplitude. The P3 was examined at the Pz electrode site. The mean P3 amplitude and latency were determined for each individual as well as the overall grand average (n=19) for each condition. One participant was excluded from the P3 analysis, as given the average ERP it was unclear as to which component of the waveform was the P3 peak.

For behavioural data, trials were deemed an error in direction if the incorrect button was pressed. Errors in timing were determined as a visual reaction time longer than 1200 ms or an auditory response time shorter than or equal to 150 ms or longer than 750 ms. Overall, 12 out of 3988 trials, or 0.30%, of visual trials were errors and therefore excluded. Examining visual errors separated into the switch and non-switch conditions, error rates were 0.35% and 0.25%, respectively. Focusing on the auditory tones prior to the presentation of the visual stimulus, 1048 auditory responses were errors out of 9906 trials, or 10.58%. Of the 9906 trials, 706 trials (7.13%) were directional errors, 262 trials (2.64%) were slow errors (>750 ms) and 80 trials (0.81%) were anticipation errors (≤150 ms). These trials were excluded from reaction time and response time analysis.

In terms of electrophysiological data, for auditory epochs, 1033 out of 20834 epochs (4.96%) were rejected. For epochs time-locked to the presentation of the visual, 122 out of 1900 epochs (6.42%) were rejected in the switch condition, while 167 out of 1900 epochs (8.79%) were rejected in the non-switch condition. The average number of epochs that were used in the computation of the grand average ERPs are depicted in Table 4-1.

Table 4-1: The average number of epochs used in the computation of average event-related potentials in the auditory domain and the switch and non-switch condition for the visual domain.

	Average number of epochs	Standard deviation	Range
Auditory ERP	1042	112.77	699-1097
Visual ERP – switching	94	12.68	48-100
Visual ERP – non-switch	91	2.96	50-100

4.2.4 Statistical analysis

For the behavioural reaction time data, a 1-way analysis of variance (ANOVA) was performed, with the switch condition (2 levels: switch or non-switch) as the factor. The original reaction time data was found to be in slight violation of the normality assumption and was subsequently log-transformed to normalize the distribution. To test the initial hypothesis that the P3 ERP will have a decreased amplitude and delayed latency in switch compared to non-switch trials, both P3 amplitude and P3 latency measures were examined using separate 1-way ANOVAs. To test the second hypothesis, a Spearman's rank correlation was run between the individual differences in P3 latency between switch and non-switch conditions and the associated switch cost. A significance level of $\alpha=0.05$ was used for all statistical analysis.

4.3 Results

Reaction time data

Overall, there was a main effect of switch condition on reaction time demonstrating longer reaction times for the switch condition as opposed to the non-switch condition ($F(1,19)=174.43$, $p<0.0001$). For non-switch trials, the mean reaction time was 319.7 ms (SD: 30.62), while for the switch trials, the mean reaction time was 469.1 ms (SD: 61.46). The mean switch cost was 149.4 ms (SD: 57.43) and switch costs ranged from 52.1 ms to 282.8 ms. Even though there was variability across subjects, every subject demonstrated a switch cost (delay in reaction time in switch trials compared to non-switch trials).

Visually evoked potentials

The visually evoked potentials in the non-switch condition are displayed in Figure 4-2. The data highlights a large P3 response. Generally the N1 response was more difficult to detect in some individuals and not strongly reflected in the average data. More problematic was that the N1 response due to the visual stimulus may be influenced by the events associated with the background auditory task during the switch tasks. Overlap of visual switch and auditory ERPs are shown in Figure 4-3 and reveal that the auditory-related potential extends into the timing that would be associated with the visually evoked N1 response. This made it difficult to detect/interpret the expected N1 response. As a result the current study focused on the P3 waveform properties.

Hypothesis 1: P3 amplitude and latency

There was no main effect of switch condition on P3 amplitude (F(1,18)=1.27, p=0.2743); however, there was a main effect of switch condition on P3 latency (F(1,18)=23.40, p=0.0001). In the switch condition, the P3 latency was longer. The grand average visual ERPs presented in Figure 4-2 illustrate differences in P3 latencies between the conditions. In the switch condition, the peak P3 amplitude was 15.84 µV at a latency of 478.1 ms while the non-switch peak P3 was 14.16 µV at a latency of 406.9 ms. Therefore, the mean difference in P3 amplitude was 1.68 µV (SD: 6.49) and mean difference in P3 latency was 71.2 ms (SD: 64.12). Individual P3 amplitude and latency data are presented in Table 4-2. Of specific note, in spite of the variability across subjects, 18 of the 19 subjects demonstrated a delay in the P3 responses in the switch condition.

Table 4-2: Individual participant data for P3 peak amplitude and latency in switch and non-switch conditions and difference values between the two conditions.

Participant #	P3 peak amplitude (µV)			P3 latency (ms)		
	Non-switch	Switch	Difference	Non-switch	Switch	Difference
1	12.6431	17.8520	5.2089	372	440	68
2	6.4781	6.9644	0.4863	308	420	112
3	16.1808	17.8055	1.6247	376	400	24
4	2.8517	14.9780	12.1263	348	552	204
5	16.7689	18.9437	2.1748	376	540	164
6	17.8620	19.6526	1.7906	424	468	44
7	16.9559	15.2881	-1.6678	284	476	192
8	10.6961	12.9229	2.2268	368	384	16
9	12.1901	12.2655	0.0754	364	396	32
10	27.8436	28.5360	0.6924	432	508	76
11	27.9334	34.9275	6.9941	412	468	56
12	21.7287	21.9345	0.2058	392	440	48
13	8.5574	7.9207	-0.6367	564	520	-44
14	7.6096	20.2709	12.6613	416	500	84
15	21.9219	3.2210	-18.7009	396	456	60
16	5.4963	9.6236	4.1273	356	368	12
17	1.7103	6.6221	4.9119	760	816	56
18	18.4629	14.6036	-3.8593	412	540	128
19	15.1848	16.6203	1.4355	372	392	20
Average (n=19)	14.16	15.84	1.68	406.9	478.1	71.2
Standard deviation	7.66	7.69	6.49	102.58	99.62	64.12
Standard error	1.76	1.76	1.49	23.53	22.85	14.71

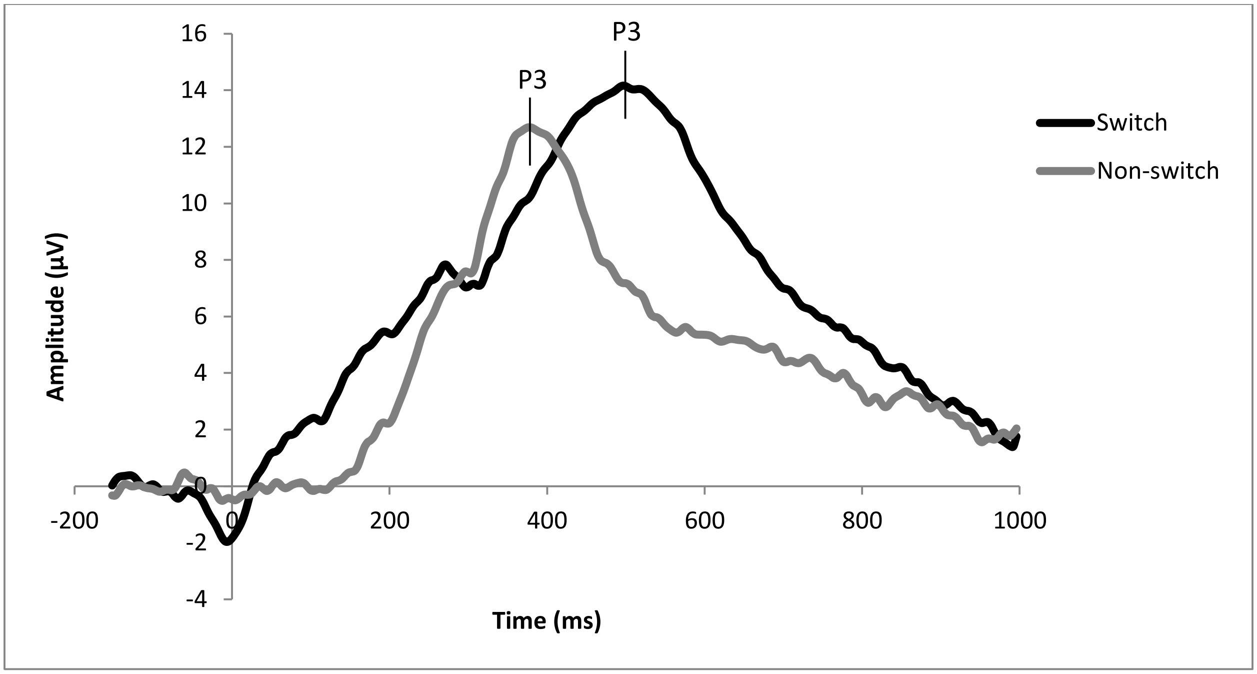

Figure 4-2: The overall average (n=19) visual event-related potentials for the switch and non-switch conditions at the Pz electrode site. The presentation of the visual stimulus is at time 0 ms. The P3 is seen as the largest positive potential and there is a statistically significant difference in P3 latency between the two conditions (p=0.0001).

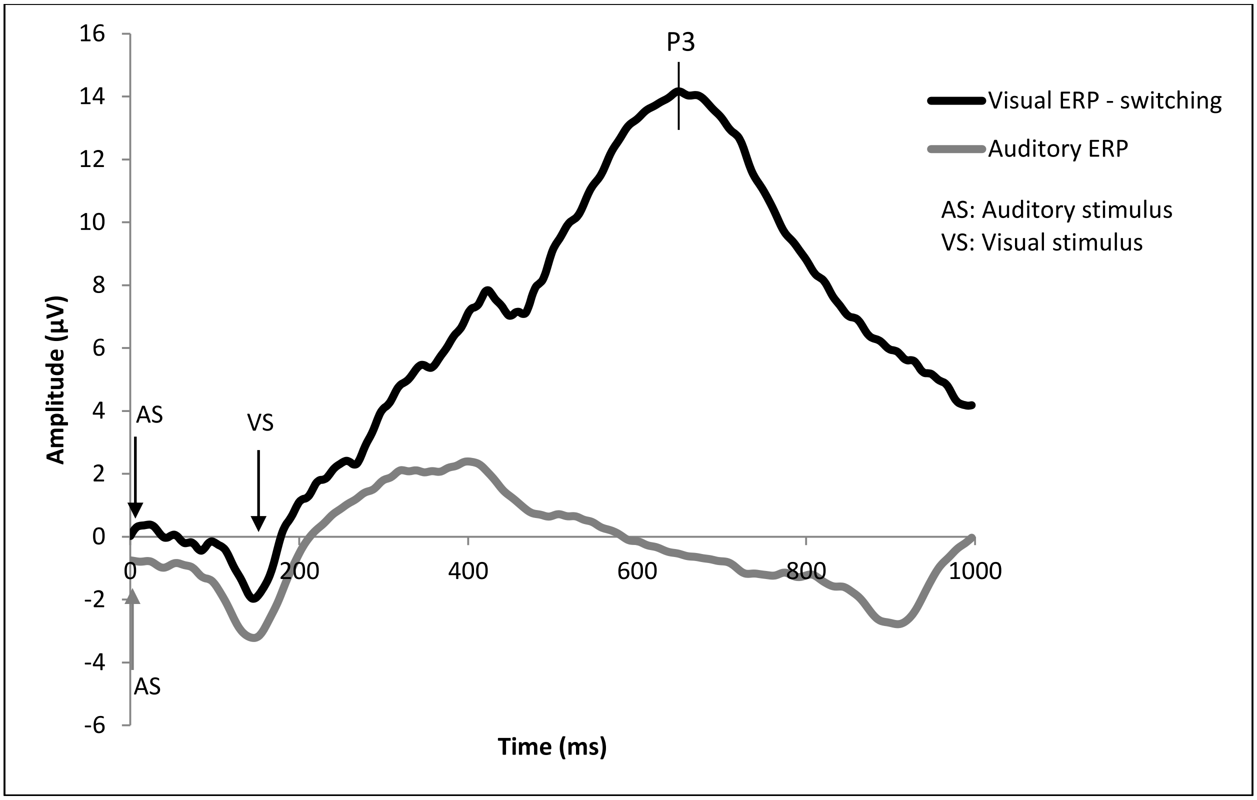

Figure 4-3: The overall average (n=19) visual event-related potential for the switching task and auditory event-related potential for the auditory tracking task showing the overlap (Pz electrode). The presented average auditory event-related potential does not include auditory trials directly before the presentation of the visual stimulus. The onset of the auditory stimulus occurs at time 0 ms, while the presentation of the visual stimulus occurs at 150 ms on the time scale.

The individual average event-related potentials show the between-subject variability for switch and non-switch conditions (Figure 4-4 and Figure 4-5). These figures display the shape of the waveforms and provide a clear picture of the individual ERPs that comprise the grand average waveform. Examining the variability between these individual waveforms may aid in the explanation of observed differences in mean P3 amplitude and latency. First, in both conditions, P3 responses were consistently evident across all subjects. It also appears in both conditions that the P3 waveforms are centralized within a certain time frame, which occurs later in the switch condition. This contrasts a possible scenario where differences in the P3 waveform observed on grand averages are associated with significant between-subject variability. In these cases, at least qualitatively, the waveform patterns appear relatively consistent. The individual ERPs in the non-switch condition show very clear P3 peaks and also appear to be relatively consistent with respect to timing.

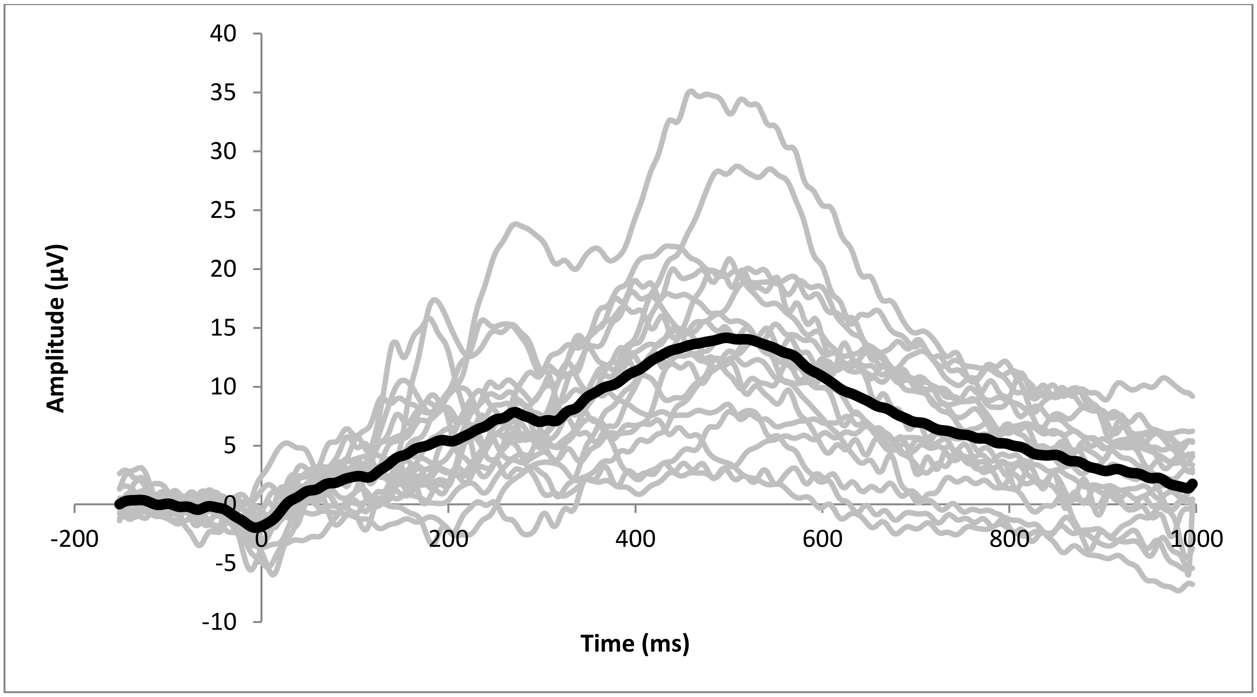

Figure 4-4: Individual average visual event-related potentials at the Pz electrode for the switching condition (grey). The black line represents the overall average event-related potential (n=19) time-locked to the presentation of the visual at time 0 ms.

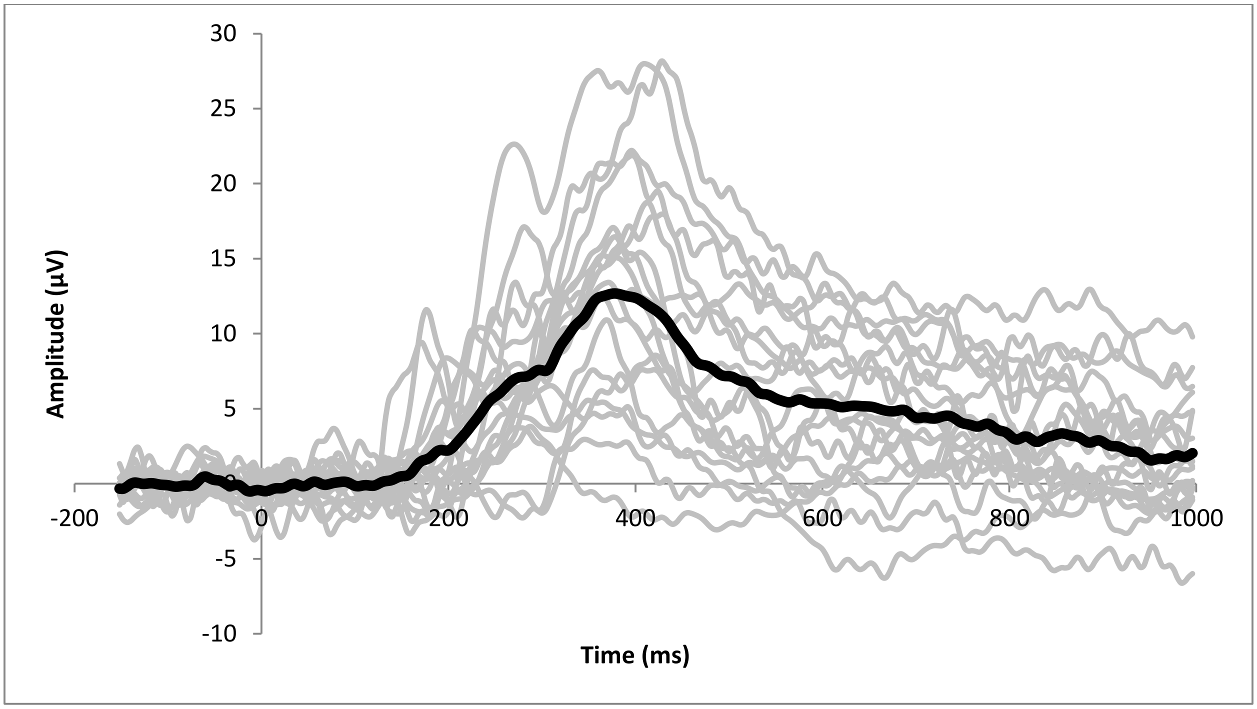

Figure 4-5: Individual average visual event-related potentials at the Pz electrode site for the non-switch condition (grey). The black line represents the overall average event-related potential (n=19) time-locked to the presentation of the visual at time 0 ms.

Hypothesis 2: Correlation between switch cost and P3 latency differences

As noted all subjects (19) demonstrated a behavioural switch cost and 18 of 19 demonstrated a delay in the P3 latency. However, in contrast to the hypothesis, the correlation between the behavioural switch cost and differences in P3 latency between switch and non-switch conditions was not statistically significant (r(19)=0.20, p=0.41). Figure 4-6 displays the relationship between the behavioural switch cost and the delay in P3 latency across subjects.

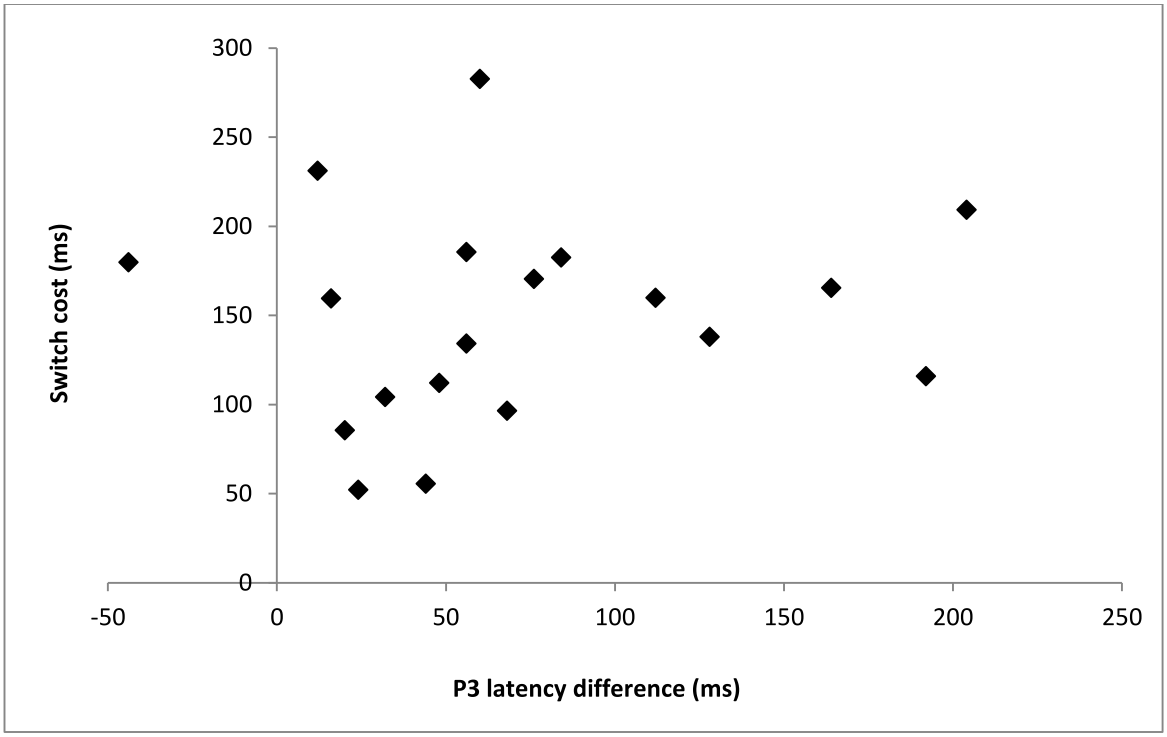

Figure 4-6: Relationship between differences in P3 latency between the switch and non-switch conditions and the behavioural switch cost. No statistically significant relationship was observed (p=0.41).

Background auditory task performance

Performance of the auditory task, as measured by response time and error rates, was compared across the task conditions to determine if the participants' attention was focused on the background task. Errors prior to the presentation of the visual stimulus were analyzed for the auditory task. Three types of errors were determined: 1) directional errors (responding in wrong direction), 2) anticipatory errors (responding too fast; ≤150 ms) and 3) responding too slowly (>750 ms). The error rates, for each participant, are displayed in Table 4-3, separated into directional, anticipation (fast) or slow errors. The error rates of greatest interest were the directional error rates as these demonstrate an incorrect response and provide an indication of the ability to choose the correct response during the auditory task. However, the anticipation and slow error rates, while low, provide an indication of errors in timing. Errors provide an indication, in addition to reaction time, of the subject's focus of attention during performance of the background auditory task. Overall, the error rates were low at 7.15%, 0.80% and 2.66% for the directional, fast, and slow errors, respectively. Across subjects errors ranged from 0.00% to 19.29% across all error categories. Including correct trials only, the mean response time was 388.4 ms (SD: 40.1).

Table 4-3: Error rates and number of errors in the background auditory task during the switch cost trials for each participant, separated into 3 categories of errors.

Participant	(% (# of errors))		
	Directional	**Anticipation**	**Slow**
1	1.95 (10)	0.19 (1)	0.58 (3)
2	1.22 (6)	0.41 (2)	1.01 (5)
3	9.26 (49)	3.97 (21)	4.54 (24)
4	11.06 (53)	2.30 (11)	12.32 (59)
5	5.19 (24)	0.22 (1)	4.55 (21)
6	4.39 (22)	0.00 (0)	5.19 (26)
7	19.29 (93)	2.07 (10)	1.04 (5)
8	4.96 (27)	0.92 (5)	2.21 (12)
9	3.56 (18)	0.99 (5)	1.58 (8)
10	7.11 (35)	0.61 (3)	1.02 (5)
11	5.08 (26)	0.20 (1)	1.76 (9)
12	12.75 (63)	1.62 (8)	5.67 (28)
13	11.18 (55)	0.81 (4)	0.81 (4)
14	3.90 (18)	0.22 (1)	0.87 (4)
15	14.60 (74)	0.39 (2)	1.38 (7)
16	3.06 (15)	0.41 (2)	1.84 (9)
17	2.04 (10)	0.82 (4)	0.00 (0)
18	7.58 (37)	0.41 (2)	3.69 (18)
19	9.87 (47)	0.21 (1)	1.26 (6)
20	4.85 (24)	0.00 (0)	1.01 (5)
Average (n=20)	7.15 (35)	0.80 (4)	2.66 (13)
Standard Error	1.07 (5.22)	0.22 (1.15)	0.63 (3.02)

4.4 Discussion

The behavioural data of this study demonstrates a significant switch cost, as observed through statistically significant differences in reaction times between switch and non-switch trials. In terms of electrophysiological data, the results of this study support the hypothesis that there would be a delay in the P3 latency during switch versus non-switch trials. There was, however, not a significant difference in P3 amplitude. Also in contrast to the hypothesis, while there were slowing of both reaction times and P3 latencies there was no significant positive correlation between switch cost and differences in P3 latency.

In terms of P3 amplitude, it was originally hypothesized that there would be decreased amplitude in switch trials as opposed to non-switch trials; however, in this study, there was no statistically significant difference in peak amplitude between switch and non-switch trials. Previous studies examining a stimulus-locked P3 component during task switching have observed an attenuated amplitude but not a latency shift (Gajewski and Falkenstein, 2011). Since P3 amplitude is linked to the amount of attentional resources (Kok, 2001) this might indicate that there is interference from the previous task consuming attentional resources (Polich, 2007). However, in this study, there was no observed amplitude attenuation but rather a delay in the response latency. One possibility is that more variability in the reaction time and P3 latency data from trial to trial as well as inter-individual variability could result in smaller amplitudes when waveforms are averaged together (Goffaux et al., 2006). This study forces subjects to maintain attention to the background task and then to switch as soon as the visual stimulus is presented, which may reduce some of the temporal variability that may occur if participants were able to pre-emptively direct attention to the primary task. A second possibility is the potential influence of the ERPs from the auditory task influencing P3 amplitude in the visual task. Due to the near-continuous nature of the background auditory task used in this study, the interval between the presentation of the visual stimulus when switching and the previous auditory tone was 150 ms. As these potentials are stimulus-evoked, when the visual stimulus was presented, the processing of an auditory tone may still be occurring. This can be seen visually in Figure 4-3, where the P3 of the average auditory ERP peaks is during the time period in which the visual N2 component would occur. It has been shown that the P3 amplitude can be affected by the amplitude of the N2, where a more negative N2 component is associated with an attenuated P3 (Gajewski and Falkenstein, 2011). Due to the overlap of the auditory ERP, the N2 component may be more positive, resulting in no attenuation of the P3 amplitude in switch trials. While this slight overlap of ERPs may somewhat affect the ability to interpret the P3 amplitude, this would not greatly impact the visual P3 latency and this is the primary measure of interest.

The P3 latency of switch trials was found to be longer than non-switch trials, which is consistent with the original hypothesis. As P3 latency reflects the time taken to evaluate a stimulus (Polich, 2007), this result infers that in switch trials, the stimulus evaluation stage of information processing takes longer or is delayed in switch trials. However, it is thought that this delay is reflective of other processes involved in the switch, possibly disengagement including the updating of the mental representation of the task in working memory. As noted, this result is inconsistent with previously conducted studies which demonstrate no differences in P3 latency between switch and non-switch trials (Hsieh, 2006; Gajewski and Falkenstein, 2011). Hsieh (2006) also examined the stimulus-locked lateralized readiness potential (LRP) component finding differences between switch and non-switch trials. It was suggested that switching occurs after stimulus evaluation involving response selection (Hsieh, 2006). Results from above, of this thesis, indicated that when switching to the primary task, the response selection stage of information processing was delayed until disengagement from the previous task had taken place, suggesting that the switch occurs prior to response selection. When switching to a simple reaction time task, the response can no longer be pre-programmed as in the performance of repetitions of just the simple task as this preparatory process requires undivided attention to the stimulus, not present in the switching tasks (Goodrich et al., 1990). The added response selection component to the processing of the visual stimulus causes the reaction time to be longer, as well as the disengagement from the auditory task, which may be required prior to the response selection phase. It is interesting to note that when examining the ERPs at an individual level for the switch and non-switch conditions, as presented in Figure 4-4 and Figure 4-5 respectively, the P3 waveforms do centralize around a certain time period. There appears to be less variability in the timing at which these P3 components peak across subjects and is delayed in the switch condition compared to the non-switch. This indicates that this delay in latency in the switch condition cannot simply be due to inter-individual variability.

In spite of the significant differences in switch cost and P3 latency, there was no statistically significant relationship found between the behavioural switch cost and differences in P3 latency between switch and non-switch trials. While no statistically significant relationship was observed, examining Figure 4-6, it appears as if there is some trend between differences in P3 latency and switch cost where greater differences in P3 latency result in a longer switch cost. Potential reasons for this result are: 1) underpowered to detect change (too few subjects relative to the effect size and variability), 2) the delay in latency of the P3 may account for only a portion of the duration of the switch cost or 3) a delay in the timing of the P3 may not be related at all to the delay in reaction time.

Increasing the power of the study may allow for the ability to detect a correlation and so more subjects may be required to demonstrate a statistically significant correlation. Based on the current data a sample size of 29 would be required to reveal a moderate association (r=0.50). While there is no definitive evidence of the link between delay in P3 and switch cost the fact that 18 out of the 19 subjects demonstrated a delay in P3 latency while all showing a switch cost leads to speculation about an association. However, the mean difference in P3 latency between switch and non-switch trials was 71.2 ms while the mean switch cost was 149 ms. This result may be accounted for if some of the timing of the switch cost may be attributable to a longer stimulus evaluation phase of information processing but there are other processes increasing the reaction time in switch trials. Finally it is possible that the timing of the P3 is not at all related to the switch cost timing.

Even though examining the mean values for the different conditions provides value, there is some between-subject variability, as seen through P3 amplitude and latency values for each individual and standard deviations of the means as well as on the overlapped individual waveform graphs for each condition. These inter-individual differences could be due to many factors; natural factors such as circadian rhythms and arousal levels, as well as environmental factors like exercise, sleep deprivation, caffeine, and alcohol (Polich and Kok, 1995). There is some evidence that these factors can influence P3 amplitude and/or latency. While performance on tasks varies with time of day, weak relationships have been found between circadian rhythm and P3 measures; however, this may be influenced by several factors. For example, physiological changes occurring throughout the day, such as increases in body temperature and heart rate, have been associated with decreases in P3 latency. This is linked to changes in arousal levels of the individual. Some studies have found that P3 amplitude increases and latency decreases with exercise, while caffeine has been shown to lead to a small increase in P3 amplitude, not affecting latency. Factors that lower arousal levels, namely sleep deprivation and alcohol, decrease P3 amplitude and increase latency, demonstrating a lower availability of attentional resources and slower speed of processing (Polich and Kok, 1995). Some of these factors were controlled for in this study by executing the protocol near the same time of day (morning) for all participants, while maintaining regular daily activities, without fatiguing exercise before the study.

While one of the original objectives of this study was to examine electrophysiological markers in early and late stages of information processing, by analyzing the N1 and P3 ERP components, the N1 component was not always present in the average visual ERPs of individuals even when examined more occipitally. This may be due to the number of trials used to create the average ERPs for each individual. On average there were 94 visual epochs and 91 visual epochs averaged for the switch and non-switch conditions, respectively. As these are small components, they may actually require 300 to 1000 trials in order to be accurately quantified (Woodman, 2010). However, with the task used in this study, especially in the non-switch condition, with increasing the number of trials, this could lead to larger alpha waves due to the participant becoming bored or sleepy, increasing noise in the data (Woodman, 2010). Another potential reason is due to the simplicity of the visual stimulus. The stimulus was a single black left arrow presented on a white screen. There are few attributes to discriminate, and as this was a simple task requiring only one response, there may not have been much discriminative processing taking place. The N1 component is larger when performing a discrimination task as opposed to a simple detection task (Luck, 2005). While the early perceptual stages of information processing could not be examined with this dataset, the analysis of the later P3 component provides interesting details about information processing involved in stimulus evaluation stages in switching attention between tasks.

The properties of this task switching paradigm allowed for timing information of the switch cost to be examined from both behavioural and electrophysiological perspectives. Due to the near-continuous nature of the background auditory task, participants could focus attentively on this task before switching at an unpredictable time point to the visual task. The low error rates for the auditory task (mean of 7.15% for directional errors) as well as average response time (mean of 388.4 ms) demonstrate that participants were attending to the auditory task. As the auditory task was near-continuous, this did not allow participants to switch attention prior to the presentation of the visual stimulus. Due to this property as well as the unpredictability (random time point and not cued) of when the switch would occur really probed the timing of the switch cost allowing for the source of the delayed reaction time to be examined with temporal precision. While these properties allowed for a temporally precise measure of the switch cost, there are some limitations. The interpretation of the visual ERPs was limited by the overlap of auditory processing. The approach of using a real continuous task (Norrie et al., 2002) may be a more effective choice in order to avoid potential overlap of event related potentials from different stimuli. The trade-off using that approach would be the ability to precisely confirm task performance on the background task.

4.5 Conclusions

The results from this study revealed differences between switch and non-switch trials in terms of behaviour as well as electrophysiology. Switch trials resulted in longer reaction times as well as P3 latencies compared to non-switch trials. However, no differences were found in P3 amplitudes. Differences in P3 latency indicate that more processes are involved when switching to the second task including disengagement, which may include the updating of working memory, and suggests that some of the resulting switch cost encompasses time prior to response selection. Future studies could utilize this paradigm to evaluate exercise-induced changes on the temporal characteristics and electrophysiological events associated with attention switching to determine if exercise can be employed to improve switching performance.

Chapter 5: General Discussion

5.1 General discussion

In this age of advancing technology, people are constantly trying to multi-task, which actually involves attention switching; that is, disengaging from one task or stimulus and engaging in another (Posner and Presti, 1987). The speed at which people switch attention can be critical in certain situations, like while driving a car, and this seems to decline with age (Kray and Lindenberger, 2000) and with specific diseases, like Parkinson's disease (Cameron et al., 2010). The purpose of this thesis was to further investigate the behavioural and electrophysiological properties of the switch cost associated with attention switching through the use of a paradigm requiring switching between tasks of different modalities.

In Study 1, the unique approach utilizing a background auditory choice reaction time task and unpredictably switching to a primary visual reaction time task proved to demonstrate a consistent behavioural switch cost. Results revealed a relationship between the difficulty of the primary task and the switch cost, in that as the task difficulty increased, the switch cost decreased. In other words, switching to a simple reaction time task as opposed to a flanker task resulted in a greater switch cost. It was interpreted that this unexpected relationship was associated with the influence of preventing pre-programming during simple reactions in the switch condition when switching and disengagement processes require time. It is hypothesized that the disengagement processing runs parallel with stimulus identification and evaluation; however, the response selection stage of information processing does not occur until disengagement from the previous task, in turn, delaying response selection. Overall, the paradigm was an effective method of evoking a behavioural switch cost and in light of the larger delay associated with the simple reaction time task, was considered an appropriate model for use in study 2 to explore electrophysiological markers of the switch cost.

Study 2 investigated an electrophysiological marker of attention switching, the P3, utilizing the same paradigm as in Study 1. Results revealed a difference in P3 latency between switch and non-switch trials, but no difference in P3 amplitude. While this did contrast previous studies, the results supported a model that there may be more involved processes when switching (eg disengagement and updating of mental representation in working memory) and the increase in reaction time with the switch cost is partially occurring in the stimulus evaluation stage of processing, prior to response selection. However, in spite of delays in both P3 timing and reaction time during switch trials the amplitude of the delays were not correlated suggesting that while the time taken to evaluate the stimulus does account for some of the switch cost duration, there are other processes involved in delaying the reaction time. Together these results help to further our understanding of the neurophysiological substrate for switch cost and linked the behavioural data to electrophysiology.

5.2 Limitations

While this study investigated the electrophysiological aspects of attention switching, it was limited by the ability to examine early visual ERP components due to the overlap of auditory ERPs with the visual switch ERPs. This resulted in the inability to examine early stages of information processing which would potentially have provided more information on which components are delayed that may be associated with an increase in reaction time in switch trials. Furthermore, as this study focused on a population of healthy young adults, it is limited by its generalizability to other populations, such as older adults. Certainly, in the future, the use of this approach would be appropriate in order to determine the ability to detect age-related differences in the capacity for attention switching. This work may also have been limited by the sample size for study 2. Increasing the sample size for the electrophysiological study may provide a better opportunity to reveal associations between changes in P3 latency and switch cost. Part of the limitation in relying on ERPs is the need to average across trials in order to reduce noise to reveal time-locked signals such as the P3. Unfortunately this means that analyses of associations across measures are performed using average data rather than exploring associations across individual trials. As a result one loses the opportunity to explore within-subject trial to trial variability which may provide important insight into associations between electrophysiological events and behavioural responses potentially hidden by between subject variability.

5.3 Future directions and applications

Future research could be targeted towards further investigation of specific components of the switch cost (eg disengagement timing). Previous studies investigating disengagement timing from stimuli have used saccadic eye movements, both in the auditory and visual modalities, to determine disengagement of attention (Braun and Breitmeyer, 1988; Shafiq et al., 1998), so this method could possibly be applied to disengagement from tasks when switching. The relationship between time taken to disengage and the resulting switch cost could be examined to provide insight on the timing of this switch cost component. If utilizing this method measuring saccadic reaction time, it would be beneficial to use visual stimuli for the background task with gaze fixed in order to provide more accurate measures. It is hypothesized that the time taken to disengage would be greater for more difficult tasks. In this task switching paradigm, the background task could be manipulated by either adding more stimuli and responses (more choices) to the task or altering the interstimulus interval while still maintaining the near-continuous nature of the task.

Furthermore, while this study was limited by its ability to examine the N1 component during switching, some changes to the task may allow for this early ERP to be explored. Jittering the timing of the last tone of the background task prior to the switch to the visual stimulus may result in less overlap of the auditory ERPs with the visual switch ERPs to observe a clearer N1 component. This suggestion, along with the addition of more trials, may provide a better opportunity to examine this electrophysiological marker, so that it can be confirmed whether early stages of information processing are impacted in switch situations.

Future applications of this research could probe individual characteristics that influence switch cost. As attention switching capabilities have been shown to decrease in aging (Kray and Lindenberger, 2000) populations and those with certain neurological disorders (Cameron et al., 2010), this task switching paradigm could potentially be used in two different manners. One of which is as a diagnostic test for attention switching. The studies in this thesis focused on populations of young healthy adults providing a foundation of performance for this paradigm with which to compare to other populations. So performance on this test could indicate if attention switching is impaired depending on the resulting switch cost. Secondly, this paradigm could be used as a functional assessment of an individual (eg for driving). As attention switching is an important component of driving, and is affected by age, individual performance on this task could be an indication of how well individuals would be able to rapidly switch attention to an unpredictable stimulus.

If attention switching capabilities are impaired, there is the possibility for improvement. It has been shown that with extensive practice, task switching performance can be improved (Strobach et al., 2012). In a study by Strobach et al. (2012) participants completed 7000 trials of task switching dispersed over 8 sessions resulting in lower switch costs after the extensive practice. The task employed in this thesis could be a useful tool for practicing attention switching to improve performance, especially as it involves switching to an unpredictable task. Furthermore, as aerobic exercise has been shown to affect the speed of processing as well as attentional processes (Tomporowski, 2003), it may prove to be another method in order to improve attention switching capabilities. Future work employing an exercise protocol with this attention switching paradigm may lead to a greater understanding of the important connections between aerobic exercise and cognitive function.

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