COGNITIVE-MOTOR INTERACTION IN HEALTH AND DISABILITY

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Kinesiology
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

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Abstract

Background: Almost all major aspects of daily life revolve around the completion of movements such as locomotion, reaching and grasping. Often these movements are performed in complex and distracting environments with specific goals in mind. Traditionally, habitual motor tasks such as walking have been viewed as unrelated to the cognitive domain; however, there is growing evidence of cognitive-motor interaction (CMI), perhaps associated with the inability to allocate attentional resources during dual tasking and/or damage within shared neural tracts of the brain. Inquiries into the manifestation, mechanisms and implications of CMI are ecologically relevant as we commonly perform tasks concurrently, such as walking and talking on a phone or attempting to recall a shopping list while traversing the grocery store. Moreover, cognitive-motor interactions have been shown to be related to adverse outcomes such as falling in health and disability. It is also apparent that dual tasking can further compound the impairments commonly observed in individuals with neurological disorders. Ultimately, a deeper understanding of CMI could lead to strategies for improving multitasking performance through targeted intervention, training and/or rehabilitation.

Specific Aims: The purpose of the current work was to examine a theoretical basis of CMI through the implementation of experimental manipulations based on an individual, environment and task (IET) centered motor control framework. This work is of both theoretical and clinical importance. The primary aim of this analysis was to present an in depth theoretical examination of CMI that to date has not been explicitly performed in any population. By carrying out an analysis of this nature, future studies examining CMI may be better informed in regards to the responsible mechanisms related to particular observations. Additionally, a better understanding of the individual, environmental, and task factors that relate to CMI could help enhance current dual task interventions and rehabilitation techniques.

Methods: Three experiments were carried out, with each examining manipulations of the key areas outlined in the IET framework. That is, the foundation of this work was to manipulate task and environmental constraints during dual tasking in multiple clinical populations with neurodegenerative disease or injury and healthy control subjects to provide a comprehensive analysis of the driving factors that lead to altered performance when multitasking.

Experiment one aimed to determine the effect of varying environmental complexity (i.e. risk levels) on both task perception and CMI during dual tasking. Participants were asked to simultaneously walk and think in environments with varied difficulty (e.g. narrow walkways, obstacles) to determine how an added environmental stimulus alters dual task performance. Experiment two examined the attentional demands of movement through the use of probe reaction times during different mobility/stability tasks. Participants completed five tasks (sitting, standing, stationary cycling, leaning to stability limits and walking) requiring a range of stability and mobility control while simultaneously responding to randomly presented auditory cues. Experiment three considered the effect of explicit task instructions towards cognitive or motor prioritization and their effect on observed CMI behavior. Participants were asked to walk and think while given instructions on which domain (e.g. cognitive or motor) to prioritize.

Results: All three experiments included samples of both healthy individuals and individuals with neurological impairment (e.g. multiple sclerosis and Parkinson’s disease) The primary result of the present work was a direct comparison of the attentional capacity model, a neuro-resource based framework of dual tasking, compared to the behaviorally based self-awareness prioritization model. Examining the results from the three experiments as a whole suggests that the capacity model in and of itself may not fully describe the changes to gait and balance during concurrent performance. Contrarily, measures similar to the hazard estimate and postural reserve constructs of the prioritization model commonly displayed congruence with the observed CMI outcomes. Additionally, these relationships were primarily present across all groups, healthy and clinical samples, indicating that the level of physiological and/or cognitive impairment in an individual may be more pertinent to dual task costs than the disease or injury that is the root of those impairments.

Conclusions: The current results have worthwhile clinical import. First, they suggest that studies of CMI should consider utilizing methodology that limits task bias in order to get the most valid understanding of prioritization as possible. Moreover, it was determined in the current analysis that in total, the participants tended to adopt a posture second approach for simple motor conditions and later shift this focus towards posture as task difficulty increased. This behavior suggests that cognitive flexibility is present in both the healthy and clinical populations and ultimately could be a target for intervention if possibly unsafe dual task strategies are observed. Additionally, it is of note that overall measures of physiological fall risk, cognition and balance confidence were commonly related to observed DTCs. This suggests that symptoms and not the underlying neurological disorder may drive CMI behavior. Ultimately, the current results serve to provide exciting new evidence in regards to the theoretical underpinnings of CMI.

Acknowledgements

The completion of this project would not have been possible without support of many people in my life. First, I'd like to thank my wife Jennifer for being with me every step of the way. You helped me through all of the adversity that goes along with graduate school and I could not have done this without you. I'm lucky to be able to share this accomplishment with you and I look forward to our next adventure.

I would also like to thank my adviser, Dr. Jacob Sosnoff for his unwavering support of my academic and research goals. From the day I wandered into your office from Engineering to finishing up this project I never doubted that you had my best interests at heart and would do anything you could to help myself and the other students in the MCRL succeed. I will be forever grateful that you taught me how to ask a question and provided the resources to find the answers. I am confident that I will be successful starting my career because of the lessons you have provided over the past years.

I want to thank my committee of Dr. Morrow, Dr. Hernandez and Dr. Lopez-Ortiz. Each one of you brought a different area of expertise to the project and provided me with the necessary insights to design the best studies I could. I greatly enjoyed your willingness to discuss research and your thought provoking commentary on my work.

I want to acknowledge my colleagues in the MCRL. Particularly the grad students, Yaejin, Jong, Katie and Tyler who all pitched in to support data collection or step up on other projects to allow me the flexibility to finish my writing. I wish all of you the best in your careers and hope that we can stay in touch. The MCRL URAs were also instrumental in the completion of the project. I thank you for taking an interest in this work and dedicating your time to it. I

would also like to thank all of the individuals who volunteered to be a part of the MCRLs research. Without your time and willingness to participate none of this would have been possible.

Finally, I would like to thank my family. It has been hard to be so far away for these past years but your support from afar has been greatly appreciated. To my Dad and Mom, thank you for always showing confidence in me and helping me reach my goals. To Laura and Randy, thank you for welcoming me into your family and everything you have done to assist Jen and I. I am lucky to have all of you as examples of great people in my life.

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Chapter 1: Introduction

1.1 Background

Almost all major aspects of daily life revolve around the completion of movements such as locomotion, reaching and grasping. Often these movements are performed in complex and distracting environments with specific goals in mind. Traditionally, habitual motor tasks such as walking have been viewed as unrelated to the cognitive domain based on their rhythmic and automatized nature (Hausdorff, Yogev et al. 2005). However, there is growing evidence of cognitive-motor interaction, perhaps associated with the inability to allocate attentional resources during dual tasking and/or damage within shared neural tracts of the brain (Woollacott and Shumway-Cook 2002; Al-Yahya, Dawes et al. 2011). These observations support the manifestation of cognitive-motor interaction (CMI) almost universally in healthy populations as well as in individuals with neurological impairment/injury such as multiple sclerosis (MS), stroke and Parkinson's disease (PD) (Kelly, Eusterbrock et al. 2011; Plummer, Eskes et al. 2013; Wajda and Sosnoff 2015). For example, there is evidence that walking performance declines when performed in conjunction with a simultaneous cognitive task (i.e., dual task cost [DTC] of walking) and this decline in walking performance is greater in people with neurological damage compared to healthy controls (Al-Yahya, Dawes et al. 2011; Kelly, Eusterbrock et al. 2011; Plummer, Eskes et al. 2013; Leone, Patti et al. 2014). Inquiries into the manifestation, mechanisms and implications of CMI are ecologically relevant as we commonly perform tasks concurrently, such as walking and talking on a phone or attempting to recall a shopping list while traversing the grocery store. Ultimately, a deeper understanding of CMI could lead to strategies for improving multitasking performance through targeted intervention, training and/or rehabilitation.

Generally, CMI is explained through the use of one of three theoretical frameworks. These include the attentional capacity theory (Figure 1a), the attentional bottleneck theory (Figure 1b) and a self-awareness prioritization theory (Figure 2). Perhaps most commonly referenced is the attentional capacity theory (Kahneman 1973; Woollacott and Shumway-Cook 2002). This theory maintains an individual has a finite limit on their attentional capacity and all performed motor or cognitive tasks require a certain amount of attentional capacity. Additionally, it is generally maintained that the individual can flexibly allocate attention. This theory can be conceptualized by thinking of an individual's attentional capacity as a bin with a fixed volume. As tasks are performed, they take up a given amount of space within the bin. By adding multiple tasks, the volume of the bin is eventually exceeded and can no longer contain the entirety of the required processing capacity (see Figure 1a). Based on this framework Kahneman theorized that if the attentional capacity was exceeded when multitasking, then performance on one or both of the tasks would decline (Kahneman 1973).

Similar to the attentional capacity model, the structural bottleneck theory represents another theoretical framework aimed at describing the attentional properties of dual tasking. This theory suggests that due to limited processing resources there is a point in information processing where only one task can be performed at a time thus causing decrements when dual tasking (Pashler 1994). The bottleneck theory can be abstracted as a sort of attentional regulator, which controls the outflow of the many attentional processes entering it. That is, concurrently completed tasks may require the same neurological pathways or processing structures and will therefore be regulated in order to handle the demand. This regulation may lead to the completion of one task being delayed until processing of the other can be concluded. While the attentional capacity and bottleneck theories provide different mechanisms for the allocation of attentional resources both describe a rather mechanistic approach to explaining cognitive-motor interaction

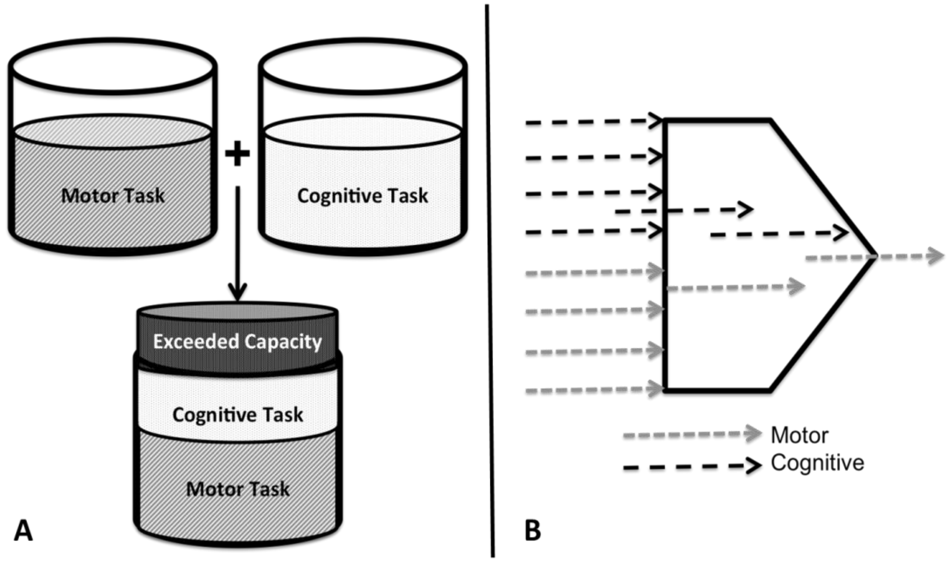


Figure 1: Schematics of the attentional capacity model (A) and bottleneck model (B) for describing dual task performance.

phenomenon with limited input from the individual.

An alternative to these theoretical models is a framework in which self-awareness of ability and environmental demands elicits a prioritization of one task over the other. This framework permits that an individual may select a different dual tasking strategy based on the specific task goals and environmental conditions within which they are operating. In general, this prioritization framework can be considered as the allocation policy for a model such as the attentional capacity theory. For instance, when walking through a busy shopping center a young healthy adult may choose to attend to an ongoing conversation with little regard for possible changes in gait whereas an individual with mobility impairment may ignore the conversation to avoid falling by concentrating on their gait. These possible outcomes are further illustrated in

Figure 2. Moreover, previous work in older adults and PD has shown that older adults tend to prioritize posture (posture first strategy) (Cordo and Nashner 1982; Shumway-Cook, Woollacott et al. 1997) when dual tasking and individuals with PD utilize a posture second strategy (Yogev-Seligmann, Hausdorff et al. 2012).

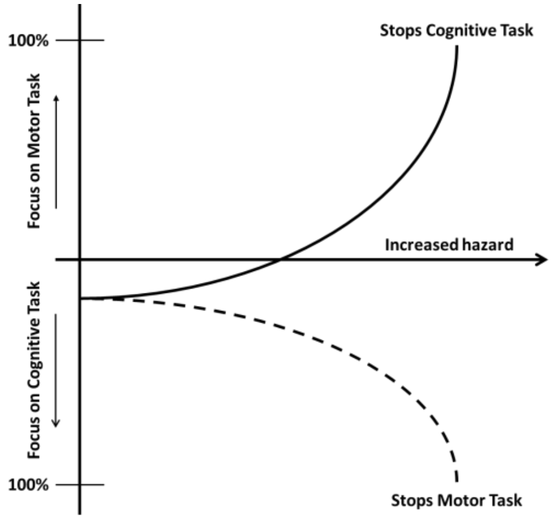


Figure 2: Behaviorally driven task prioritization dichotomy. Adapted from Yogev-Seligmann et al. 2012

Despite the vast amount of empirical evidence confirming the occurrence of CMI (Al-Yahya, Dawes et al. 2011), no theoretical framework has explicitly been linked to the observed outcomes. In order to better understand the interactions between cognition and motor output, it is imperative to conduct experiments based on sound theoretical constructs in order to control for the intricacies of both domains. For instance, while movement represents one of the principal foundations of daily life it is inherently difficult to fully characterize. Even the simplest movements involve a complex interaction between physiological systems and processes, and Bernstein suggests that the available degrees of freedom with which to carry out a given task often permit an endless number of solutions to produce an acceptable movement (Bernstein 1967). From this notion alone, many theories have been formulated in an attempt to best describe the methods by which certain movement patterns are chosen and subsequently carried out by the organism. Movement, and motor control in general, are commonly proposed as the multifactorial interaction between the individual performing the action, the task constraints, and the inherent features of the given environment (Newell 1986). It is through this individual, environment, and task (IET) structure that the current work aims to expand the theoretical underpinnings of cognitive-motor interference (see Figure 3).

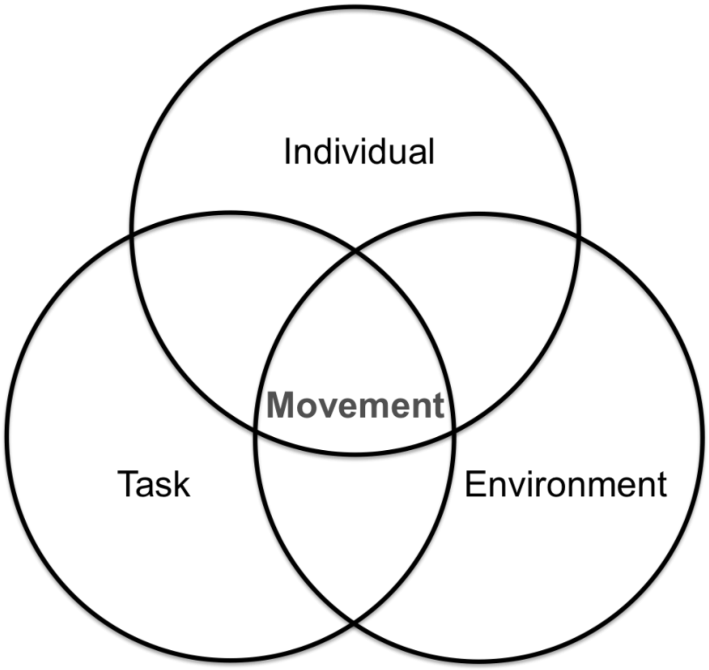


Figure 3: Venn diagram of the Individual-Environment-Task framework of human movement. Adapted from Shumway-Cook et al. 2007

The purpose of the current work was to examine a theoretical basis of CMI through the implementation of experimental manipulations based on the IET motor control framework. This work is of both theoretical and clinical importance. The primary aim of this analysis was to present an in depth theoretical examination of CMI that to date has not been explicitly performed in any population. By carrying out an analysis of this nature, future studies examining CMI may be better informed in regards to the responsible mechanisms related to particular observations. Additionally, a better understanding of the individual, environmental, and task factors that relate to CMI could help enhance current dual task interventions and rehabilitation techniques (Kelly, Eusterbrock et al. 2011).

Three experiments were carried out, with each examining manipulations of the key areas outlined in the IET framework. That is, the foundation of this work was to manipulate task and environmental constraints during dual tasking in multiple clinical populations with neurodegenerative disease or injury and healthy control subjects (individual manipulation) to provide a comprehensive analysis of the driving factors that lead to altered performance when multitasking. Specifically, three clinical populations in particular were selected for this work. These included individuals with multiple sclerosis, Parkinson’s disease and chronic stroke survivors. The selection of these groups permitted an analysis of CMI across a broad range of physiological and cognitive symptoms as well as an in depth look into the relationship between CMI and neurodegenerative disease/injury mechanisms. The advantages of using these clinical groups in particular were the ability to compare neurodegeneration against possible rehabilitation (MS and PD vs. Stroke) as well as variances in general disease onset times (e.g. MS mid-life onset vs. PD older adulthood onset). It was hypothesized that testing based on the IET framework would permit a distinction as to which attentional/behavioral model most closely distinguishes observed motor behavior during studies of cognitive-motor interaction.

Experiment one, outlined in chapter 3, aimed to determine the effect of varying environmental complexity (i.e. risk levels) on both task perception and CMI during dual tasking. This experiment tested the environmental, task, and individual aspects of the IET framework. Participants were asked to simultaneously walk and think in environments with varied difficulty (e.g. narrow walkways, obstacles) to determine how an added environmental stimulus alters dual task performance. The experiment included a diverse sample of individuals (healthy controls as well as individuals with MS, PD and Stroke) in order to investigate how perception of environmental hazard relates to CMI across populations.

Experiment two, outlined in chapter 4, examined the attentional demands of movement through the use of probe reaction times during different mobility/stability tasks. This experiment tested the task and individual aspects of the IET framework. Participants completed five tasks (sitting, standing, stationary cycling, leaning to stability limits and walking) requiring a range of stability and mobility control while simultaneously responding to randomly presented auditory cues. It was anticipated that identifying probe reaction times during these tasks would permit a direct testing of the attentional capacity model of dual tasking. Experiment two also included a diverse sample of individuals (healthy controls as well as individuals with MS, PD and Stroke) to determine how inter-individual differences (e.g. mobility impairment, cognitive decline) alter probe reaction times.

Experiment three, outlined in chapter 5, considered the effect of explicit task instructions towards cognitive or motor prioritization and their effect on observed CMI behavior. This experiment tested the task and individual aspects of the IET framework. The primary purpose of the protocol was to compare and contrast CMI under self-selected performance instructions (i.e. task instructions don't force prioritization) with results from trials where participants are instructed to prioritize either the motor or cognitive component. Once again, individuals from multiple clinical populations were included to permit an analysis of the relationship of inter-individual differences and dual task prioritization strategies.

Chapter 2: Background Literature

2.1 Overview

The current review of literature summarizes the pertinent information for the significance, purpose and development of the conducted experiments. First, the significance of cognitive-motor interaction (CMI) as it pertains to community mobility and dual tasking is outlined. The chapter then highlights the theoretical attention and behavioral models generally associated with cognitive-motor dual tasking performance. It is further illustrated that while these models are assigned to CMI, rarely are they directly tested. Additionally, the neuromechanics of walking, the most pertinent motor outcome to the completed experiments, are described. Next, the testing methodology, a motor control framework based on the individual, environment and task (IET), is described. Finally, the relevant CMI results as they relate to this IET framework are outlined.

2.2 Significance of Cognitive-Motor Interaction

Community mobility as performed daily takes place in a complex and ever changing environment. This environment demands that we attend to our surroundings as well as the task to be completed. Often, these demands lead to the necessity to concurrently perform tasks. Dual tasking largely goes unnoticed in our day to day routines, however, it represents an integral part of the activities we perform. Examples include walking and talking on a cell phone, crossing a busy intersection, attending to a shopping list at the grocery store and others. Therefore, the clinical study of dual tasking lends itself to a more analogous view of an individual’s ability to perform complex mobility tasks similar to those performed in the community. Furthermore, when motor and cognitive functions are impaired, dual tasking demands may serve to compound these impairments. Thus, cognitive-motor dual tasking represents a rich paradigm to further parallel lab based measures with those of the real world as well as challenge the capabilities of an individual's cognitive and motor systems.

Previously, motor and cognitive impairments were commonly examined independently of each other. However, research of simultaneous performance of motor and cognitive tasks has identified an interaction between them (Woollacott and Shumway-Cook 2002). CMI is common in both healthy and neurodegenerative populations such as dementia (Camicioli, Howieson et al. 1997), stroke (Plummer, Eskes et al. 2013), Parkinson's disease (Kelly, Eusterbrock et al. 2011) and multiple sclerosis (Leone, Patti et al. 2014). With these observations have come an increased interest in determining the mechanisms related to and the training of dual tasking abilities across populations. It has been suggested that creating a theoretical basis on which to test CMI may lead to improvements in treatment standards (Wajda and Sosnoff 2015).

It is possible to observe multiple ways in which cognition and motor function interact while performed simultaneously. Predominantly, the changes in performance when cognitive and motor tasks are performed concurrently are termed dual task costs (DTC). These dual task costs represent an operationalization of CMI and are often calculated by computing the percentage change in outcome measures (Baddeley, Della Sala et al. 1997) from performance in isolation to dual tasking performance. Plummer and colleagues have outlined nine possible changes observed during the concurrent performance of cognitive and motor tasks (Plummer, Eskes et al. 2013). These include four major isolated changes (i.e. motor task facilitation, motor task interference, cognitive task facilitation, and cognitive task interference) as well as the possible combinations of these observations or no changes at all.

2.3 Theoretical Models of Cognitive-Motor Interaction

Despite the vast amount of interest in the study of CMI, as evidenced by a multitude of review articles (Al-Yahya, Dawes et al. 2011; Kelly, Eusterbrock et al. 2011; Plummer, Eskes et al. 2013; Wajda and Sosnoff 2015), there is no consensus regarding the underlying mechanisms leading to observed results. Commonly, CMI is described to be a result of stressing available attentional resources in order to complete two simultaneously performed tasks. Two theoretical models have primarily been used to further understand the allocation of attentional resources to either the cognitive or motor task. These theories, the capacity model and bottleneck model, provide a more computational and mechanical approach to dual tasking. Contrastingly, a third theoretical model has also been proposed which takes a more behavioral based approach to describing dual task outcomes. This self-awareness framework states that an individual's perception of the task and environment, coupled with their abilities, drives changes during concurrent performance of tasks.

2.3.1 Attention Capacity Model

Originally proposed by Kahneman (Kahneman 1973) the attentional capacity model suggests that attention represents a finite processing resource. Any task then that is completed by an individual which is non-automatic thus requires some of these resources. In regards to multi-task performance then, each task will utilize a portion of the available attentional resources leading to one of two possible scenarios. In the first case, the tasks may require so few resources that both can be executed concurrently with no reduction in performance. This would indicate that the attentional capacity limit was not reached. The second scenario is one in which the attentional resource capacity is exceeded during dual tasking, thus leading to a performance decrement. In this case, by surpassing the finite limit on capacity an individual's completion of one or both tasks will suffer.

Due to its simplicity in defining attention as an available resource, researchers commonly turn to the capacity model when describing cognitive-motor tradeoffs during dual tasking. Often it is not determined whether or not the two concurrent tasks are sharing distinct neural pathways which might lead to interference and therefore the generalization to both tasks drawing from the same global pool of resources is advantageous. Through the use of this broad approach, dual task costs can be identified and attributed to capacity overflow; however, few inferences can be drawn on the neurological mechanisms surrounding these costs.

Within the overall domain of the attentional capacity framework researchers have proposed multiple variations. These include models taking into account the flexible allocation of resources as well as multiple resource models. Flexible allocation interpretations revolve around the notion that the individual can directly choose which task to allocate greater attention to when multi-tasking. This ability to directly prioritize performance thus describes a model that is a blend between a theoretical attention approach and a behavioral model (explained below). To date, no studies have directly tested this flexible allocation model in regards to CMI. On the other hand, multiple resource models closely mimic traditional attentional capacity models with the caveat that attention is broken up based on dedicated functions (e.g. auditory or visual attention). The assumption with this version of the model is that there is still a finite limit on each resource type. However, tasks which do not overlap in attentional resource subtype will not interfere with each other. For instance, two tasks which utilize common resources such as visual or auditory resources.

2.3.2 Bottleneck Model

The bottleneck theory of dual tasking relies on a more structurally grounded approach. That is, rather than two tasks drawing from a pool of attentional resources they are competing for processing time on shared neural pathways (Wickens 1991). Under this assumption, the processing of tasks requiring the same structures will be completed one at a time leading to the processing of one task occurring before the other. The sequential manner of the bottleneck model then leads to deficits in dual tasking. Experimentally, this model is commonly tested through experiments manipulating the psychological refractory period. In these tests, two tasks which are generally assumed to access similar neural structures are performed concurrently with varying levels of time lag between the stimuli related to each task. If the process time for each task performed in isolation is known then the amount of delay due to the bottleneck can be calculated (See Figure 4).

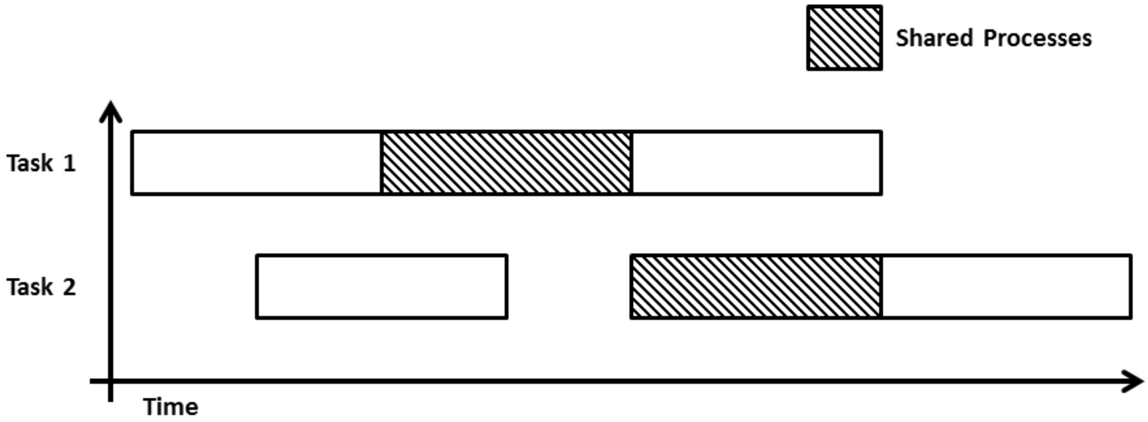


Figure 4: Visual Representation of Bottleneck Processing Delay. Processing of task 2 is delayed due to shared resources being utilized to complete task 1.

Despite being hypothesized as possible model related to dual tasking deficits observed in CMI studies, there is limited work directly examining this link. The primary assumption for any task considering this framework would be that the processing of the motor task and cognitive task utilized shared neural pathways. Commonly, walking and balance are considered to be primarily automatic spinally modulated tasks; however, each does require the processing of sensory information which could lead to deficits in performance if that processing interferes with the cognitive task being completed. Therefore, without the use of sophisticated imaging equipment and methodologies (i.e. imagined movement while dual tasking) it would be difficult to directly test the bottleneck model for CMI.

2.3.3 Behavioral Model

While the attention capacity and bottleneck models entail a more mechanistic approach to describing CMI, it is possible that the observed interactions are due to a broader behavioral theory. That is, where the previously mentioned models take into little account the characteristics of the individual outside of “available resources” the behavioral model places the burden of performance strictly on the participant. This model therefore suggests that factors such as self-efficacy, task perception and individual goals can greatly influence dual task performance. For instance, when walking in an open hallway with little distraction an individual may decide to prioritize their phone conversation over the maintenance of steady gait. However, if the same conversation was being held while walking on a busy sidewalk the same individual may prioritize their gait in order to avoid running into others. A behavioral model of this nature for CMI has most notably been proposed by Yogev-Seligmann and colleagues (Yogev-Seligmann, Hausdorff et al. 2012). In their model, two constructs are utilized (i.e. Hazard Estimate and Postural Reserve) to describe when and why certain responses are observed during cognitive-motor dual tasking scenarios (see Figure 5). The first of these constructs is termed ‘hazard estimate.’ This is a combination of the individual’s characterization of task difficulty and self-perception of their own abilities. It is reasonable to speculate that an individual with high hazard estimate would prioritize gait over the performance of the secondary task in high risk situations (e.g. the busy sidewalk suggested above). While hazard estimate is an important factor for strategy determination, it remains only one half of the puzzle. The second construct is ‘postural reserve’ and relates to the actual physical abilities of the individual. Postural reserve has the ability to effect performance based on the fact that while a person may understand they should prioritize walking or balance in certain situations, they may lack the motor adaptability to do so. Thus, the behavioral model represents a complex balance between perception and action that can describe a wide range of outcomes observed in studies of CMI.

Direct evidence for the behavioral model is limited. Since the model is centered on the abstract constructs of hazard estimate and postural reserve, there is room for interpretation regarding their specific makeup. One study by Holtzer and colleagues attempted to test this model in a walking and talking study by choosing measurable representations of hazard estimate and postural reserve (Holtzer, Wang et al. 2014). Accordingly, they defined hazard estimate based on a measure of executive function and postural reserve based on a clinical balance exam. Based on these definitions, high hazard estimate showed a protective effect on gait speed and cognitive response accuracy. Further, low postural reserve showed a protective relation to gait speed under dual task conditions but not response accuracy suggesting a concentration on maintaining normal gait speed. Other investigations of the behavioral model have relied on observational inferences from studies examining motor and cognitive changes during dual tasking. Work in varying populations has previously shown that older adults tend to prioritize posture (posture first strategy) (Cordo and Nashner 1982; Shumway-Cook, Woollacott et al. 1997) during dual tasking and individuals with Parkinson's disease utilize a posture second strategy (Yogev-Seligmann, Hausdorff et al. 2012).

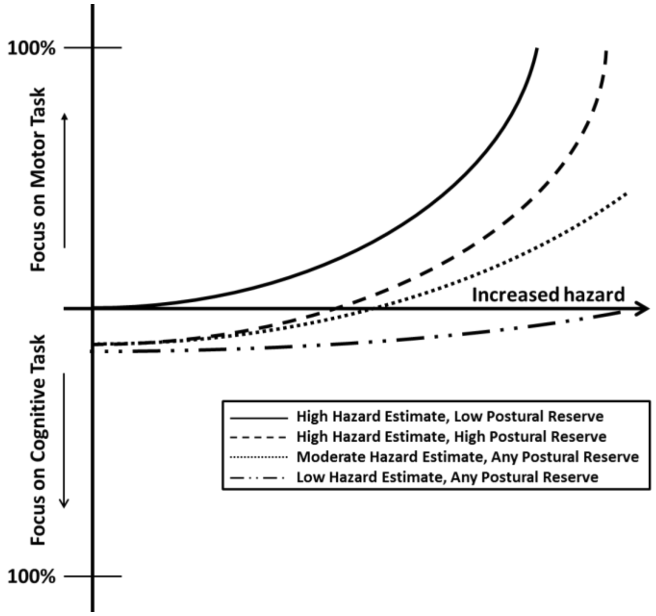


Figure 5: Hypothesized interaction between hazard estimate and postural reserve during walking and thinking dual task scenario. Adapted from Yogev-Seligmann et al. 2012

2.4 Individual, Environment and Task Framework of Movement

Since the formulation of Bernstein's degrees of freedom problem for movement (Bernstein 1967), one of the primary aims of the field has been to develop testable theories regarding the subject. The primary "problem" being the seemingly infinite number of ways in which a particular movement can be carried out and the manner in which a certain trajectory is selected. Undeniably, the many degrees of freedom available for human movement permit an undeniable advantage in regards to completing task goals; however, they also present a major obstacle for the study of movement and its control. Based on the complexity associated with the observation of motor behavior it is essential to base experiments on testable theoretical frameworks of motor control.

Selecting a framework to work from in and of itself provides a daunting task. The description of motor control is an abstract one and has been attempted through models with varying levels of complexity and interaction (Turvey and Fonseca 2009). There are no less than four perspectives that have been built upon to create varying motor control theories. These include neuroanatomy, robotics, self-organization and ecological approaches (Turvey and Fonseca 2009). Each of these perspectives must then incorporate considerations such as how movement is planned or enacted, the levels and direction of feedback being processed, and how task context are handled. Early simplifications of motor control tend to hinge on the basis of an intelligent executive enacting a desired movement with varying levels of dependence on lower level structures. From those original formulations, motor control theories have moved away from the concept of a higher level executive to a stance where movement comes about based on interactions between the organism and its environment (Beer 2009).

These later models of motor control provide an appropriate framework on which to test motor outcomes during the study of CMI. This arises from the congruence of elements which are considered to be key factors in dual tasking to those proposed by the individual, environment and task (IET) interaction framework (Newell 1986; Shumway-Cook and Woollacott 2007). From an ecological perspective, cognitive-motor dual tasking in the community potentially relates to each of these domains. It largely centers on the specifics of the individual and outcomes could be closely driven by the type of environment (e.g. crowded vs. open) the tasks are being completed and the tasks themselves (e.g. walking and recalling a shopping list/carrying on a conversation). Furthermore, outcomes can be influenced not just by the characteristics of these domains but also by their interactions. For example, the importance of attending to a certain cognitive distractor may influence motor performance regardless of what is suitable in a given environment.

Examining motor outputs based on the IET frameworks consequently requires a firm understanding of each of the three primary domains. Perhaps the most complex of these is the individual themselves. Shumway-Cook and Woollacott proposed that the investigation of an individual's contribution to movement could be examined through action, perception and cognition (Shumway-Cook and Woollacott 2007). Action pertains to the specific movement type that is to be completed, for example walking or reaching. The individual controls motor outputs, namely muscle movements, in order to complete a desired action. Movement is further refined by the individual through perception as it can pertain to inferences about the state of the body, the environment, and the inherent constraints of an action. Often, perception is thought of as the incorporation of sensory feedback (visual, somatosensory, proprioceptive) in order to refine the executed movements of any action. Additionally, perception can be interpreted as a means for evaluating risk in order to alter an action such as adopting a cautious gait on slippery sidewalks. Therefore, an understanding of an individual's ability to perceive the factors related to an effective movement is essential when interpreting observed motor behavior. Finally, the cognitive abilities of the individual can heavily influence the selection of action and processing of perception. Cognitive processes in general are consequently essential for the voluntary selection and implementation of a movement and the understanding of all applicable constraints. It is of note that these task constraints may be dependent on the motor and cognitive function of the individual thus providing a primary example of the interconnectivity of the domains of the IET framework.

In addition to the specifics of the individual performing a given action, the restrictions of the environment must also be considered. The environment may influence a given movement by both adding constraints and impacting the regulation of a movement. For example, walking in a busy train station can be inherently different than a quiet hallway based on added complexities such as background noise, possible obstacles, and variable sensory feedback such as visual distractions. Based on the variable complexities of the environments in which movements are performed it is crucial to factor in these differences when examining changes in motor output for similar tasks.

Finally, the particular task being performed itself has a great influence on observed motor behaviors. Shumway-Cook and Woolacott proposed that movement tasks generally encompass three common structures (Shumway-Cook and Woollacott 2007). These include mobility, stability and manipulation. In general, tasks may draw on one or all of these functional areas and thus certain constraints will be applied to the corresponding movements in order to successfully accomplish the action. Other aspects that may influence performance are familiarity with the task and the relative demands associated with each of the stated components such as stability.

2.4.1 Influence of the Individual on Cognitive-Motor Interaction

The characteristics of the individual, such as overall physiological and cognitive status, can substantially contribute to observed outcomes during CMI investigations. These influences can be observed on the person to person level as well as on the population level. For instance, researchers can investigate the differences in CMI for a given set of tasks within a hypothetically homogeneous sample (e.g. young adults) or between different samples (e.g. young vs. old adults). Ultimately, the goal of any such study is to determine the characteristics of CMI and its mediating factors.

In regards to the utilized sample populations for the current investigation a great deal of work has been enacted to observe CMI; however, research is lacking regarding underlying theoretical mechanisms. Accordingly, multiple systematic reviews have been completed to compile these results together and offer a clearer picture CMI primarily during walking and balance in the general population (Al-Yahya, Dawes et al. 2011), MS (Leone, Patti et al. 2014; Wajda and Sosnoff 2015), PD (Kelly, Eusterbrock et al. 2011) and stroke (Plummer, Eskes et al. 2013). These reviews provide a clear view of both the abundance of research into CMI and the issues, which arise when trying to compare results between studies. Regardless, differences between populations are commonly observed but the basis of those observations is indeterminable in the absence of a consistent testing framework.

Specifically within the walking and thinking literature, the addition of a concurrent cognitive task has a significant impact on gait outcomes (e.g. gait velocity, stride length) in both healthy and neurological populations. In general across populations, average gait speed has been shown to typically be reduced under dual task conditions regardless of the type or difficulty of the cognitive challenge (Al-Yahya, Dawes et al. 2011). These results imply that walking cannot be thought of as a strictly automated task and one must consider its attentional demand for any CMI study being performed.

CMI results become more nuanced when the investigation occurs within sample populations with distinct characteristics. These observations permit a deeper investigation of unique variables, which may directly influence CMI. For example, in healthy populations greater age is commonly associated with higher DTCs of walking (Priest, Salamon et al. 2008). Within neurological populations the analysis extends to additional factors such as disease related symptoms, disease severity and medication. This added layer of complexity can be seen when reviewing the CMI literature for various neurological populations.

Studies examining CMI in individuals with PD have reported on the effects of disease severity, medication status and freezing of gait. Overall, individuals with PD have greater DTCs of walking compared to their healthy counterparts. Additionally DTCs are shown to increase with higher disease severity scores (Unified Parkinson's Disease Rating Scale) in this population. In regards to dopamine replacement therapy, most studies tested their participants in the 'On' state and it was further observed that DTCs were reduced while on medication compared to off of it (Kelly, Eusterbrock et al. 2011). Finally, those individuals with PD who exhibited the symptom of freezing of gait showed greater DTCs of walking than individuals who did not (Hackney and Earhart 2009).

CMI in stroke has also been extensively examined. Special considerations within this population primarily includes the time since injury. As an individual progresses farther from the occurrence of the event there is an associated decline in DTCs related to CMI. It is hypothesized that this relationship is driven by the reautomization of walking in time and with rehab for stroke patients. Theoretically, the attentional demand of walking becomes less overtime permitting the individual to maintain a dual task gait speed closer to that of single task performance (Plummer, Eskes et al. 2013).

Within the literature for MS samples, disability status represents a frequently utilized measure in exploratory analysis focusing on factors related to DTC. An investigation consisting of a large range of SR-EDSS levels (median SR-EDSS = 3.5, IQR = 3.0), disability was associated with DTC of walking velocity such that worse disability was related to higher DTC

(Motl, Sosnoff et al. 2014). In contrast, another recent investigation with similar range of disability scores (median EDSS = 4, IQR=2.75) found no correlation between EDSS scores and DTCs of spatiotemporal gait parameters (Learmonth, Sandroff et al. 2014). A possible reason for the inconsistent findings could be related to the methodological differences between investigations including differences in quantification of disability (e.g. self-report vs. clinically determined) and cognitive task utilized. Symptom and demographic factors such as fatigue, depression, spasticity, pain, age, education and disease duration have also been examined as correlates of DTC of walking. One investigation (Hamilton, Rochester et al. 2009) observed a relationship between dual task cost in walking with fatigue. In addition to disability, symptoms and demographic characteristics, mobility and cognition have been examined as correlates of CMI of walking. Walking tests in MS generally consist of tests of walking speed such as the timed twenty-five foot walk and walking endurance as quantified by the six minute walk. Indeed, performance on both these measures has been shown to be correlated with DTCs of gait (Sosnoff, Socie et al. 2013; Motl, Sosnoff et al. 2014) suggesting that general mobility performance influences the impact on walking when adding a concurrent cognitive challenge. Similarly, cognitive processing speed as determined by the symbol digit modalities test has also been shown to correlate with the DTC of walking velocity (Motl, Sosnoff et al. 2014).

Overall, these results display that while CMI is a general phenomenon between populations, it is imperative to take into consideration differences between samples and individuals. This is primarily due to the unique characteristics of individuals such as age, level of motor/cognitive impairment and disease symptoms that may mediate the observed interactions type of CMI.

2.4.2 Influence of the Environment on Cognitive-Motor Interaction

When considering CMI outcomes it is imperative to consider that movement is performed in complex and stimulating environments. These environments often include other objects in relative motion to the individual which require attention (Merchant, Zarco et al. 2009). It is reasonable to expect then that the characteristics of an environment may directly influence the outcomes observed in a study of CMI. For example the performance of walking within one's own home may result in slightly different motor behavior compared to walking in a busy public setting. While the environment represents one of the main underpinnings of the IET framework, it has not been a predominantly studied factor in previous studies of CMI.

Manipulating the environment during research lends itself to the ecological validity of a task being performed. That is, how can experiments in the laboratory setting better mimic conditions that will be experienced in the community. Moreover, environmental constraints are often time dependent and fluctuating compared to the carefully controlled lab setting. Few studies have explicitly attempted to employ environmental factors in CMI experiments. Those which do often rely on a manipulation of the motor task (e.g. simulated obstacle crossings and narrow walkways) (Schrodt, Mercer et al. 2004; Kelly, Schrager et al. 2008). These manipulations serve to add a layer of constraint onto the dual tasking scenario, which may be conceivably experienced at times in real world scenarios. Results of these studies have shown that individuals can perform the concurrent tasks but the environment may lead to a shift in prioritization. Schrodt and colleagues determined that while older adults didn't reduce gait speed while faced with an obstacle during dual tasking, cognitive performance suffered (Schrodt, Mercer et al. 2004). One additional study showed that older adults faced with multiple high risk challenges (i.e. walking on an elevated narrow platform) attempted to increase velocity under concurrent cognitive load and exhibited a greater number of missteps (Schaefer, Schellenbach et al. 2015). This result was also attributed to an altered prioritization scheme due to environmental hazard.

Recently, the use of virtual reality and community environments has been incorporated into CMI protocols. Virtual environments permit the researcher to maintain some uniformity within the study while also augmenting the lab setting with real world tasks. An example of this setup is simulating a street crossing during distraction. Neider and colleagues utilized an immersive environment and passive treadmill to examine the effect of talking on a cell phone on street crossing (Neider, Gaspar et al. 2011). They determined that older adults were more likely to display delayed crossing initiation while talking on a cell phone leading to a higher rate of failed trials based on the specified trial time limit. These results highlight the impact of CMI on a task, which is both completed regularly and requires precision for safe execution. Using a similar distractor (cell phone), a study by Plummer and colleagues compared walking and texting in the laboratory to walking and texting in a real world setting (Plummer, Apple et al. 2015). It was determined that young adults prioritized the texting task when completing it in the lab environment; however, they utilized a more even prioritization when walking and texting in the busy hallway of the local student union.

Taken together these studies emphasize that the influence of environmental factors on CMI is significant and that dual tasking can alter performance on common functional tasks performed in the real world. Based on these findings it is important that future studies on CMI consider the environment they are being performed in (lab v. virtual v. community) and interpret results accordingly. The primary goal should be continuing to understand how CMI is altered based on a complex environment compared to a simplified one.

2.4.3 Influence of the Task on Cognitive-Motor Interaction

Perhaps the most commonly manipulated and analyzed piece of the IET framework in regards to CMI is that of the task. When studying CMI the task can represent one of two structures. That is to say that the actual cognitive and motor tasks can be prescribed and also task instructions such as where to focus attention can be manipulated. One consequence of the essentially limitless combinations of tasks available is the general heterogeneity of study methodology. This ultimately leads to difficulties when trying to interpret results from one CMI study to the next.

In regards to the motor domain, the most commonly utilized tasks are by far walking and maintaining upright stance. In addition to these some specialized tasks such as upper limb dexterity have also been considered (Learmonth, Pilutti et al. 2015). Walking and standing represent two of the more ubiquitous motor outputs that an individual performs on any given day. Since they are so integrated into our lives, it is not surprising that they are largely employed in CMI studies. Further, each task is capable of being modified to provide varying levels of difficulty. In walking tasks one can consider how CMI impacts the phases of the task such as initiation (Wajda, Moon et al. 2015), steady-state walking (Al-Yahya, Dawes et al. 2011) and termination (Roeing, Wajda et al. 2015). For balance tasks, the primary manipulation is that of base of support (e.g. normal v. narrow stance) (Stelmach, Zelaznik et al. 1990). No matter what motor task is being performed it is important that the selected outcome measures both accurately portray the task performance as well as convey the impact of CMI.

It is evident the choice of motor task can possibly have a large impact on CMI outcomes. This is generally due to the differences in the complexity of sensory processing and movement requirements for a given motor task. Looking, for example at walking, multiple systems are working together congruently to maintain both the rhythmic movement and stability requirements of bipedal locomotion. While walking represents one of, if not the primary mode of locomotion for humans, it is possible that the familiarity of the task skews the viewpoint in terms of what processes are required for successful gait. First, while highly automated gait does require input from supraspinal control centers. This is due to the fact that gait is often goal orientated (e.g. getting from point A to point B) as well as that gait is voluntary and requires both initiation and termination commands. Second, walking is often performed in complex environments requiring careful monitoring to maintain upright posture and avoid unwanted object interaction. These requirements therefore make gait a complex control task that is influenced by inputs on varying levels of the nervous system. Therefore, perhaps the most complex aspect of the neural control of gait is in the brain itself. The three primary functions of higher-level control are to activate spinal processes required for initiation and speed modulation of walking, make alterations to the walking pattern in response to feedback and integrate visual information (Kandel, Schwartz et al. 2000). In regards to activating walking, the supplementary motor area and premotor cortex aid in movement planning and sequencing. This information is transmitted to the motor cortex for movement generation. The cerebellum is primarily responsible for monitoring feedback. It receives information about the body’s current state from proprioceptors as well as the intended state from CPGs through ascending neural tracts. The cerebellum then computes any errors between these sets of information and sends commands for alteration if required. In regards to visual incorporation, the motor cortex receives visual information from the visual cortex and can manipulate spinal processes based on this information through direct connections. Based on these complexities of higher-level control, it is apparent how motor tasks such as gait can be attentionally demanding and interfered with through concurrent cognitive challenge.

The cognitive domain also offers a great deal of flexibility in regards to task selection. In their review of walking while thinking studies, Al-Yahya and colleagues identified a myriad of cognitive tasks performed between the studies included in the meta-analysis. These tasks were broken up into domains such as reaction time, decision making, mental tracking, working memory and verbal fluency (Al-Yahya, Dawes et al. 2011). Findings from the meta-analysis showed that in healthy adults, CMI (e.g. reduced gait velocity) occurred regardless of cognitive task domain and interaction was greatest for concurrent verbal fluency tasks. In neurological populations gait speed also reduced regardless of cognitive domain with the largest declines occurring while performing mental tracking. It has also been suggested that those tasks relying on the same neural structures as gait may elicit greater DTCs. For instance, gait speed has been determined to be dependent on the prefrontal cortex which can also be associated with executive function (Al-Yahya, Dawes et al. 2011). It is rare in the literature for studies to directly assess this link as activation imaging during walking is often complex. Holtzer and colleagues, however, previously utilized functional near-infrared spectroscopy during a walking while talking study and observed increases in activation of the prefrontal cortex during dual tasking compared to normal walking in old and young adults (Holtzer, Mahoney et al. 2011). Other studies have investigated the effect of modulating cognitive task difficulty on a standard motor task such as walking, for example, walking and talking while counting forward, backward or completing a verbal fluency task (Beauchet, Dubost et al. 2005; Allali, Laidet et al. 2014). Similarly, titrated concurrent cognitive loads based on individual cognitive ability have also been employed (Hamilton, Rochester et al. 2009). This range of cognitive tasks difficulty manipulations represents one of the primary reasons for the need of developing CMI studies based on a testable framework such as the IET. Such a framework would permit an investigation into the mechanisms of CMI rather than the continued observation of CMI by swapping in various concurrent challenges.

Not only are the selected motor and cognitive tasks important during the study of CMI, but also the instructions the participant is given to perform them. The aspect of instruction that is of greatest concern is that of which task to prioritize, if any. Indeed, some studies have utilized instructions which gave no indication as to which task to prioritize (Wajda, Motl et al. 2013; Wajda, Sandroff et al. 2013) while others have asked participants to try and focus an equal amount of attention on both the cognitive and motor tasks (Verghese, Kuslansky et al. 2007). Further, studies have indicated that dual task performance in older adults can be adapted to prioritization instructions requiring gait or cognition to be the primary focus (Verghese, Kuslansky et al. 2007; Yogev-Seligmann, Rotem-Galili et al. 2010; Kelly, Eusterbrock et al. 2012). Based on these instruction centered changes observed in previous CMI studies, it is important that researchers utilize standardized instruction within a study to limit unintended performance variations. Those instructions should then be based on the behavior that is being observed such as what is the natural prioritization that arises (i.e. no explicit prioritization instructions given) compared to can individuals modulate their performance (i.e. forced prioritization instructions).

In summary, it cannot be understated that the study of CMI must be multifaceted and attempt to take into account the many factors that influence performance. Based on this notion, utilizing the IET framework as a foundation for studying CMI, primarily in walking and thinking studies as performed here, permits a strong structure from which to test various dual tasking hypotheses. From these tests, valuable inferences about cognitive-motor dual tasking behaviors and strategies can be produced.

Chapter 3: Environmental Hazard and Perceived ability

3.1 Introduction

3.1.1 Complex Mobility Tasks

Major aspects of daily life revolve around successful locomotion through an often complex and distracting environment (e.g. crossing a busy street on a crowded crosswalk). Safely navigating this environment necessitates higher-level coordination and the control of many physiological and cognitive systems. It is reasonable to assume that the ability to negotiate one's progress through a complex area without incident may be limited and/or altered in individuals with motor and/or cognitive impairment associated with disease or injury.

Traditionally, gait research is commonly conducted utilizing steady state tests in the laboratory setting. While these tests can offer valuable information in regards to normal and maximal performance, it is possible that they are not entirely indicative of community ambulation. When walking in the community, individuals commonly need to adapt their performance from a steady state in order to interact with objects, navigate the environment and attend to other stimuli. Additionally, gait is often performed concurrently with a secondary task such as talking with friends or utilizing a cell phone. It is reasonable to assume that gait tasks requiring dual tasking are therefore more representative of gait outside the laboratory. Tasks utilizing this methodology generally require participants to walk while performing a concurrent cognitive task.

Generally, research into cognitive-motor interaction (CMI) during walking has still taken place in highly controlled lab based experiments. It is common during these tests that participants are asked to walk and concurrently perform a given cognitive task (Al-Yahya, Dawes et al. 2011). For the most part, the walking performed in these studies is steady state and in the absence of environmental hazards (e.g. obstacles, tripping hazards). Some studies have investigated the effect of cognitive distraction on obstacle avoidance (Kim and Brunt 2007). Results of these studies suggest that at least in aging populations the inclusion of a distracting task can reduce the associated safety margins observed during obstacle clearance/crossing (Harley, Wilkie et al. 2009). While current dual task research attempts to integrate factors encountered in the community, it is reasonable to assume that incorporating tasks with varying levels of environmental complexity could produce more advanced levels of ecologically validity.

3.1.2 CMI and Environmental Demands

When considering the effect that environmental complexity may have on dual task performance, one must begin by considering the possible frameworks associated with CMI. Within the constructs of an attentional capacity model approach, it would be anticipated that CMI of gait would increase as environmental factors further constrained movement. That is, environmental characteristics (e.g. other individuals, obstructions, tripping hazards, etc.) which force the individual out of a steady and automated gait pattern into one requiring greater planning and sensory input may lead to an increase in required attentional resources required for these movements. Therefore, during dual tasking the capacity model would predict that increased environmental complexity could lead to greater deficits in one or both of the concurrently performed tasks; however no insight would be given as to which task may see the greatest decrements based on the ability to flexibly shift attention. Similarly, the bottleneck theory may predict an increased demand for resources based on the increased demand for processing visual cues within a complex environment. These demands may lead to processing interference with the motor and cognitive tasks leading to observed performance decrements.

Interestingly, the control and planning aspects of the individual are essentially ignored within the capacity and bottleneck models. Theoretically, changes in CMI during locomotion performed in increasingly complex environments may be attributed to prioritizations by the individual rather than a general attentional demand or interference. This concept has previously been explained through a self-awareness framework (Yogev-Seligmann, Hausdorff et al. 2012). This theoretical model represents a framework in which self-awareness of limitations and environmental demands elicit a conscious prioritization of one task over the other. The main constructs of this self-awareness framework are postural reserve and hazard estimate. Yogev-Seligmann and colleagues proposed that as the difficulty/hazard of a task increases, individuals may shift attention towards the motor task to avoid falling and subsequently sacrifice performance on the concurrent cognitive task (see figure 6). It is important to note that hazard estimate and postural reserve are theoretical constructs unique to each individual. That is, we'd expect that someone with motor impairment might shift prioritization towards stable motor performance more quickly during dual tasking. However, this tradeoff could be offset in some individuals who lack effective hazard estimation leading to a prioritization of the cognitive task. This is often suggested to occur in individuals with Parkinson's Disease (PD). Thus it is imperative to consider all aspects of the individual including self-perception of one's own abilities prior to making the assumption of a general prioritization strategy. Research in this area has shown that older adults tend to prioritize posture (posture first strategy) (Cordo and Nashner 1982; Shumway-Cook, Woollacott et al. 1997) during dual tasking and individuals with Parkinson's disease utilize a posture second strategy (Yogev-Seligmann, Hausdorff et al. 2012).

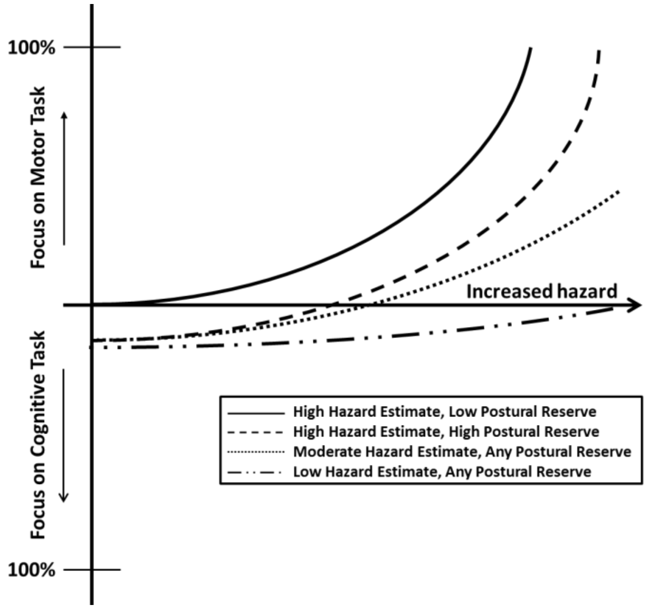


Figure 6: Relationship between hazard estimate, postural reserve and task difficulty during cognitive-motor dual tasking. Adapted from Yogev-Seligmann et al. 2012

3.1.3 Perception of Abilities and CMI

Humans have the innate ability to mentally simulate anticipated movements prior to the actual execution of said movements (Jeannerod and Frak 1999). This simulation is commonly termed as motor imagery and is thought to share many of the same neurocognitive structures as executed movement (Beauchet, Dubost et al. 2005). Indeed, multiple imaging studies have identified that imagined and executed movements activate the same regions of the motor cortex up until the movement is started (Shumway-Cook and Woollacott 2007). Based on the ability to simulate a given movement, motor imagery has been proposed as a tool to assess both an individual’s perception of task difficulty as well as their perception of their own abilities (Ryckewaert, Luyat et al. 2015). One common method to assess mental performance is through the use of mental chronometry. Mental chronometry is a subset of motor imagery during which an individual is given explicit detail about a movement (e.g. walking through a busy corridor) and asked to provide an estimated time to complete the task based on mental simulation of that task. Following the imagined performance of a task, the participant is asked to physically execute the movement in order the permit a comparison of imagined versus executed times. Generally, in healthy individuals these times are similar indicating a correspondence between one's internal models of the environment and actual capabilities. For individuals with cognitive and motor impairment, however, differences in simulated performance can be an indication of a failure to update internal models or perceive and account for impairments (Lafargue, Noël et al. 2013).

In relation to CMI it stands that motor imagery may provide an indication of perception of abilities and how those perceptions relate to observed prioritization strategies and alterations in cognitive or motor performance while dual tasking. For example, an individual with no impairment should be able to account for the addition of a concurrent cognitive task and/or environmental hazard and accurately adjust for these factors during mental performance. In regards to an individual with motor and/or cognitive deficits there are two possible outcomes. First, they may accurately perceive their impairments and alter performance in order to account for the environmental challenges. Conversely, they may not perceive their impairment and adapt an inherently risky strategy during dual tasking (e.g. not prioritizing stability of gait) based on an overestimate of ability. Previous studies have provided evidence of both conditions as it was shown that a failure to update internal models lead to over-optimistic predictions of planned actions in the elderly (Lafargue, Noël et al. 2013) while individuals with PD were capable of perceiving their impairment to accurately estimate performance on a reaching task (Ryckewaert, Luyat et al. 2015).

3.1.4 Purpose

The purpose of this study is twofold. The first aim is to analyze the impact of increased environmental demands on measured CMI. It was hypothesized that this obstacle-based protocol would more closely approximate the multifaceted nature of activities of daily living compared to standard clinical mobility tests. It was expected that greater changes to walking and cognitive performance would be observed as motor demands increased (i.e. as walking tasks became more difficult). In addition to the actual walking tasks, perception of difficulty and personal ability was assessed in all participants utilizing a motor imagery and mental chronometry approach. It was hypothesized that mental chronometry values would be associated with observed dual tasking strategies during the actual walking trials.

3.2 Methods

3.2.1 Design

The study utilized a cross-sectional design. Participants attended a laboratory based one-hour assessment. In addition to walking while thinking tasks, measures of demographics, mobility and cognition were also completed.

3.2.2 Participants

A total of 70 participants, took part in this study. This included 21 individuals with MS, 9 with PD, 5 with chronic stroke (i.e. >6 months since injury) and 35 healthy controls. Recruitment took place through a combination of informational flyers, online advertisements and local newsletters. Additionally, we recruited individuals from the Motor Control Research Laboratory participant database. Finally, PD and stroke participants were also recruited through informational visits to local support groups (4 PD and 2 Stroke).

Inclusion criteria for the patient groups included a physician’s confirmed diagnosis; the ability to walk without bilateral support; self-reported gait impairment and self-report of attentional/multi-tasking difficulties. Patient groups were matched based on scores from the upper and lower limb disability subsections of the Guy’s neurological disability scale (Sharrack and Hughes 1999). Guy’s neurological disability scale was originally developed for use in individuals with MS but permits an accurate and simple analysis of function (e.g. assistive device use), which is applicable to the included neurological populations. Inclusion criteria for the control group was no diagnosis of a neurological disease and no walking issues (e.g. orthopedic problems). Control participants were chosen such that their ages fell within the ranges of the recruited patient samples. Additionally, all participants (i.e. controls and clinical populations) were required to score above a set cutoff point of 20 on the modified telephone interview for cognitive status TICS-M [REF].

3.2.3 Procedures and Outcome Measures

All procedures were approved by the University of Illinois Institutional Review Board and participants completed written informed consent upon arrival to the research laboratory. The primary outcome measure for the study were dual task costs (DTCs) of gait and cognition during four distinct walking tasks (see figure 7). For the purposes of the proposed experiment, DTC was characterized as the percentage change of completion time from single task conditions to concurrent cognitive task conditions. Each of the four different walking settings covered a distance of 7.62m. The conditions were as follows:

1) No obstacles, normal (60cm) width walkway

2) 5cm wide x 2cm high obstacles placed across the normal width walkway

3) No obstacles, narrow width walkway
4) 5cm wide x 2cm high obstacles placed (same placement as condition 2) across the narrow width walkway (same width as condition 3)

All of the stated conditions were performed in isolation and while completing a concurrent cognitive task. The utilized concurrent cognitive challenge was serial 7 subtractions from a given two-digit number. Serial subtraction tasks have been utilized previously to quantify CMI in control subjects (Springer, Giladi et al. 2006), individuals with MS (Gunn, Creanor et al. 2013), PD (Plotnik, Giladi et al. 2011) and Stroke (Dennis, Dawes et al. 2009). Prior to dual tasking participants performed the serial 7 task in isolation while seated to allow for the computation of dual task costs of cognitive performance. Condition order was randomized and each condition consisted of two single task trials followed by two dual task trials. The width for the narrow walkway will be set as 50% of the distance between the participant's anterior superior iliac spines. This procedure has previously been utilized to provide a similar challenge to individuals with varying body morphologies (Kelly, Schrager et al. 2008). For all tasks the participants were asked to walk at whatever pace they felt was appropriate to successfully complete the task.

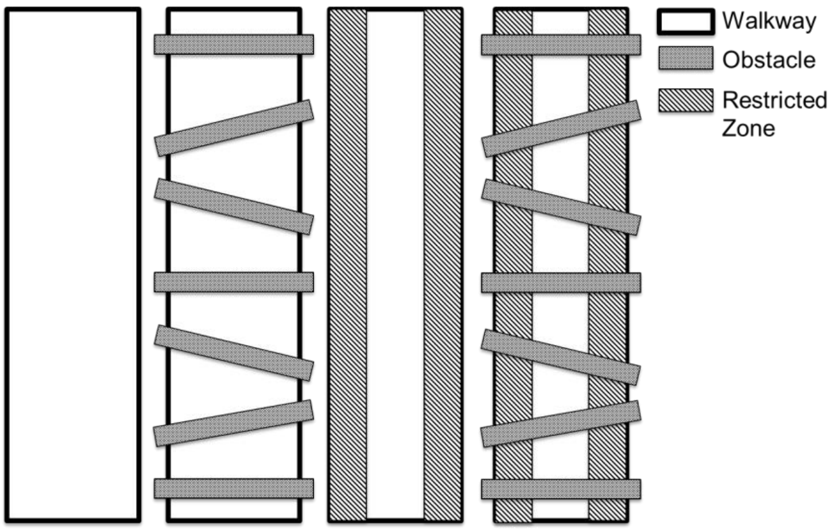


Figure 7: Summary of walkway configurations

To investigate prioritization strategies across the conditions, the proportion of participants in each group were determined based on the dual task outcomes identified by Plummer and colleagues (Plummer, Eskes et al. 2013). We then considered changes to these proportions across the four walking difficulty conditions. This permitted inferences to be drawn on the ability to shift and/or prioritize attention in the face of complex walking requirements. Completion of the walking tasks was also measured through error rates. For all conditions, the trial was scored no error if the participant kept their feet within the boundary, a minor error if a portion of their foot contacted the boundary and a critical error if they stepped completely outside the boundary. During trials with obstacles, participants were rated on contacting no obstacles, a single obstacle or multiple obstacles.

Self-perception of abilities was assessed through mental chronometry. Prior to walking, participants sat at the starting point of the walkway and were visually presented with each walkway layout. Participants were then instructed to imagine that they are traversing the walkway from start to finish from the first person perspective. Participants were further instructed to try to have as vivid an image in their mind as they could as if they were actually performing the task. To mirror the actual walking trials, participants were instructed to imagine walking at whatever pace they felt was appropriate to accomplish the presented walking task. Imagined trials began with a 3-2-1-Go countdown and ended when the participants indicated reaching the end of the walkway by saying “stop.” During dual task imagined movement trials, participants were given the additional instructions to imagine subtracting 7s from a given number in their head. That is, imagine doing two things at once. The imagined time to complete the trial was the primary outcome for mental chronometry. To reduce variability, one researcher administered all imagined walking trials throughout the study. Mental chronometry has previously been utilized to examine the relationship between imagined and executed movements for both single and dual tasks (Blumen, Holtzer et al. 2014). All motor imagery trials were completed before the actually executed walking trials and performed in the same randomized order as the actual trials. As a means to investigate the adjustment of perceptions, participants also imagined their movements following the completion of all actual walking trials. In order to avoid any testing biases, participants were not informed they would be doing a second set of imagined trials until after the actual trials were completed. Mental chronometry was further quantified by subtracting the actual performance times from imagined times. With this computation a positive value represented an underestimate of actual performance and a negative value represented an overestimation of performance.

Aside from the imagined and actual walking tasks, additional outcomes were also collected. Physiological fall risk was quantified with the physiological profile assessment (PPA) (Lord, Menz et al. 2003). The PPA was originally developed for use in older adults and later validated for individuals with neurological impairment/injury (Jankovic 2008). The PPA consists of five tests examining vision, reaction time, proprioception, knee extensor strength and standing balance. The results on these assessments are then combined together and compared to age matched norms. Physiological fall risk is presented as an individual z score with larger values representing a higher risk. Based on previous results (Wajda, Motl et al. 2013; Hoang, Cameron et al. 2014), it was expected that PPA scores would be related to performance on the mobility tasks. Cognitive outcomes included the symbol digit modalities test (SDMT) and the trail making test (TMT) parts A and B. The SDMT requires participants to match numbers to a provided set of symbols based on their pairing in a response key. The scoring for the test is represented as the total number of correct responses given during a 90s trial. The SDMT has been suggested as a measure of cognitive processing speed (Sheridan, Fitzgerald et al. 2006). Further, it has been utilized in both healthy and clinical populations. The TMT is a neurocognitive test of visual attention and task switching (Tombaugh 2004). It consists of two parts, which require participants to connect dots of numbers and/or letters in a specific order as accurately and fast as possible. For part A of the TMT, participants connect numbered circles in order from 1-25. Part B of the TMT has participants alternate connecting numbers and letters sequentially (i.e. 1-A-2-B-3…). The difference in time between the two trials (i.e. TMT B – TMT A) represents the primary outcome of the TMT. Lower difference scores between conditions A and B are indicative of increased cognitive flexibility, divided attention ability, and processing (Tombaugh 2004).

3.2.4 Data Analysis

All statistics were performed in SPSS version 22.0 (IBM, Inc., Armonk, NY). Descriptive statistics (mean ± standard deviation) were calculated for all of the demographic and spatiotemporal gait parameters of interest. One-way analysis of variance tests were used to compare the average age and physiological fall risk of the groups.

Two 3 x 4 repeated-measures analysis of variance tests were conducted to examine the effects of group (MS vs. PD vs. Control) and conditions (Basic Course vs. Obstacle Course vs. Narrow Course vs. Narrow and Obstacle Course) on observed DTCs of gait and cognition. DTCs of gait were operationalized as the percentage change in gait velocity and DTCs of cognition were the percentage change in correct response rates. The level of significance was set at $p \leq 0.05$ and Sidak corrections were utilized for multiple comparisons.

Cross tabulation analyses were utilized to compare the proportion of utilized CMI strategies across groups and walking conditions. These strategies included mutual facilitation, gait facilitation, cognitive facilitation and mutual interference as outlined by Plummer and colleagues (Plummer, Eskes et al. 2013). Differences in proportions were examined with Fisher’s exact tests based on the low sample size for some of the characterizations. These techniques were also applied to the analysis of error rates and obstacle interactions. P values for multiple comparisons with the Fisher’s exact test were adjusted based on Bonferroni corrections to maintain a family p value of 0.05.

A correlation analysis was performed to investigate the relationship between calculated mental chronometry times and actual walking times. Spearman correlations were utilized to limit the effect of mild outliers in the data. Correlations were also examined between observed DTCs and measures of physiological fall risk (PPA), cognition (SDMT and TMT) and self-rated balance confidence (FES-I).

Based on the low sample size and high variability within the outcomes, the stroke group was excluded from the main analyses of this experiment. Data relative to their performance is presented as a pilot analysis separately in the Appendix B.

3.3 Results

3.3.1 Participant Characteristics

The mean age of participants was 62.8 ± 8.2yrs for the controls, 57.8 ± 9.0yrs for the MS group and 61.8 ± 8.8yrs for the PD group. A one-way ANOVA revealed showed no significant difference in age between groups ($F = 2.3$, $p = 0.11$). The control group consisted of 22 females and 13 males compared to 12F/9M for the MS group and 4F/5M for the PD group. Physiological fall risk scores for the group averaged 0.48 ± 0.83 for the control group, 2.00 ± 1.17 for the MS group and 1.79 ± 1.22 for the PD group. The comparison of means showed that the MS and PD group did not differ ($p = 0.99$) from each other in terms of fall risk and both groups had significantly ($p < .001$ and $p = .003$ respectively) elevated fall risks compared to the control participants. SDMT scores averaged 55.6 ± 7.8 for the controls, 54.9 ± 13.4 for MS and 48.9 ± 8.4 for PD. A one-way ANOVA on cognitive processing speed showed that there were no differences across groups on the SDMT ($F = 1.65$, $p = .20$). The control group had mean differences of 26.1 ± 16.5s on the TMT compared to 26.4 ± 12.0s in MS and 29.9 ± 17.3 in PD. Performance on the TMT was consistent across all three groups ($F = 0.23$, $p = 0.80$).

In regards to the clinical populations, average disease duration was 16.8 ± 8.1yrs for the MS group and 6.4 ± 5.9 for the PD group. For MS specifically, the self-reported expanded disability status scale score median value of 4.0 and interquartile range of 2.8-5.8. None of the

PD participants utilized assistive devices while 6 of the MS participants utilized unilateral support.

3.3.2 DTCs and Environmental Difficulty

Figure 8A displays the average DTCs of gait for each group across the four walking conditions. The 3x4 ANOVA examining task and group effects revealed no main effects on DTC of gait (Task: $F = 2.85$, $p = 0.07$, Group: $F = 0.30$, $p = 0.74$). Additionally, no significant group by task interaction was observed ($F = 0.77$, $p = 0.53$). While it appeared there was a trend for the main effect of task, adjustments for multiple comparisons yielded no significant difference in the observed DTCs between any of the walking conditions.

Figure 8B shows the results for the DTCs of cognition. The ANOVA displayed a significant effect of task ($F = 27.4$, $p < 0.001$) and no main effect of group ($F = 2.24$, $p = 0.12$) on cognitive performance changes during dual tasking. There was not a significant group by task interaction ($F = 1.73$, $p = 0.12$). Post hoc analyses of the task effect revealed that DTCs in cognition during the simple walk condition (i.e. no obstacles and 60cm width) were significantly less compared to the obstacle condition, narrow walk with no obstacle conditions and narrow walk with obstacles condition (all p's < 0.001). There was no significant difference of the obstacle condition compared to the narrow walk condition ($p = 0.62$) as well as the narrow/obstacle condition ($p = 0.45$). Finally, DTCs of cognition during the narrow/obstacle condition were significantly less than the narrow only walking condition ($p = 0.003$).

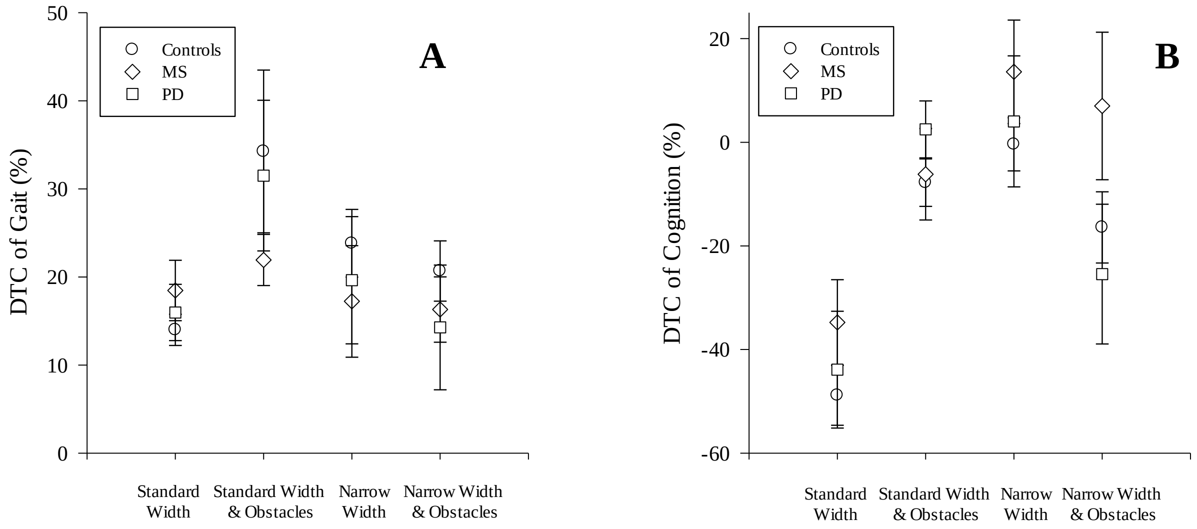


Figure 8: DTCs of Gait (A) and Cognition (B) Across Group and Task

3.3.3 CMI Spectrum Outcomes

Table 1 outlines participant performance on the three dual tasking conditions based on how the observed DTCs would fall on the CMI spectrum proposed by Plummer and colleagues (Plummer, Eskes et al. 2013). During the standard width condition, the most common outcome across groups was that of a cognitive priority tradeoff. That is, participants experienced slowing of gait while dual tasking accompanied by either no change on or improvement on the cognitive task. During the standard width and obstacles condition, an increase in participants experiencing mutual interference was observed compared to the no obstacle configuration. The narrow walkway condition saw an increase in individuals falling into the mutual interference, gait prioritization and mutual facilitation categories compared to the standard walkway condition. The narrow walkway with obstacles condition saw a similar pattern to that of narrow walking alone when compared to the standard walkway condition.

For each walking condition, the relationship between group and CMI outcomes was examined using Fisher's exact test. Only in the narrow walking conditions (with and without obstacles) was there statistically significant evidence that the groups differed in regards to proportion of individuals in each of the CMI outcome categories. Further analysis of this relationship comparing the pairs of samples within the condition (i.e. Control v. MS, Control v. PD, MS v. PD) showed that there were significant differences in the proportions of CMI outcomes between the control and MS samples. This was due to a greater number of individuals with MS adopting a gait prioritization strategy during the narrow walking conditions. No differences were observed between controls and PD participants or MS and PD participants.

Table 1: CMI outcomes based on group and walking condition

	Standard Width				Standard Width and Obstacles			
	MI	GI	CI	MF	MI	GI	CI	MF
Controls	4 (11.4)	30 (85.7)	0 (0.0)	1 (2.9)	11 (31.4)	23 (65.7)	0 (0.0)	1 (2.9)
MS	1 (4.8)	19 (90.5)	0 (0.0)	1 (4.8)	9 (42.9)	11 (52.4)	1 (4.8)	0 (0.0)
PD	1 (11.1)	8 (88.9)	0 (0.0)	0 (0.0)	5 (55.6)	3 (33.3)	1 (11.1)	0 (0.0)
	Narrow Width				Narrow Width and Obstacles			
	MI	GI	CI	MF	MI	GI	CI	MF
Controls	14 (40.0)	19 (54.3)	0 (0.0)	2 (5.7)	11 (31.4)	21 (60.0)	1 (2.9)	2 (5.7)
MS†	4 (19.0)	10 (47.6)	5 (23.8)	2 (9.5)	8 (38.1)	8 (38.1)	5 (23.8)	0 (0.0)
PD	3 (33.3)	4 (44.4)	2 (22.2)	0 (0.0)	4 (44.4)	3 (33.3)	0 (0.0)	2 (22.2)

Note: Values are N (% within Group), † represents significant difference in proportions v. controls, MI: Mutual Interference, CP: Cognitive Priority Tradeoff, GP: Gait Priority Tradeoff, MF: Mutual Facilitation

3.3.4 Walking Condition Error Rates

Error rates were calculated for all trials and are compiled in Table 2. No boundary errors (i.e. stepping on or outside the walkway boundary) were observed during the standard width walkway conditions, therefore those data are excluded from the tabulation. Results are presented for the number of obstacles contacted during the standard width obstacle condition, boundary errors during the narrow width condition and obstacle contacts/boundary errors during the narrow width with obstacles condition. As 4 trials (2 single task, 2 dual task) were completed by each participant on each walking condition, results are based on examining the outcome of each trial within a group rather than a combined measure of performance for each participant.

Results of the Fisher's exact tests revealed significant differences in error rates between the groups across each walking condition. Further analysis examined the differences between pairings of each sample (i.e. Control v. MS, Control v. PD, MS v. PD). For the obstacle condition, it was determined that the MS sample had a higher proportion of trials where multiple obstacles were contacted compared to the control participants. This was true under dual task conditions as well. PD participants did not differ in obstacle hit rate from controls in the single task condition, but did have a higher percentage of trials with multiple obstacles struck during dual task obstacle walking. During narrow walking there was a significant difference in error rates only between the control and MS participants for both single and dual task trials. This was based on the MS group having a greater proportion of trials with critical errors (i.e. stepping completely outside the boundary). For the narrow walking with obstacles condition, there were no significant differences in obstacle contact rates between the groups. In terms of boundary errors during the narrow obstacle condition, the control group had significantly fewer errors than the MS and PD groups during single task performance and significantly less errors than the MS group during dual tasking.

Table 2: Obstacle contacts and boundary error rates across group and task

	Obstacles Contacted ST				Obstacles contacted DT			
Group	None	Single	Multiple	Total	None	Single	Multiple	Total
Control	66	4	0	70	69	0	0	69
MS	33	3	6	42	32	6	4	42
PD	16	1	1	18	14	1	3	18
Total	115	8	7	130	115	7	7	129
	Narrow Error Rate ST				Narrow Error Rate DT			
Group	No Error	Minor Error	Critical Error	Total	No Error	Minor Error	Critical Error	Total
Control	55	15	0	70	61	8	1	70
MS	15	14	9	38	20	13	3	36
PD	10	6	2	18	12	6	0	18
Total	80	35	11	126	93	27	4	124
	Narrow/Obstacles ST (Obstacles Contacted)				Narrow/Obstacles DT (Obstacles Contacted)			
Group	None	Single	Multiple	Total	None	Single	Multiple	Total
Control	63	6	1	70	56	10	4	70
MS	24	6	4	34	20	7	7	34
PD	12	2	4	18	14	1	3	18
Total	99	14	9	122	90	18	14	122
	Narrow/Obstacles ST (Error Rate)				Narrow/Obstacles ST (Error Rate)			
Group	No Error	Minor Error	Critical Error	Total	No Error	Minor Error	Critical Error	Total
Control	58	8	3	69	58	11	1	70
MS	12	14	8	34	11	13	10	34
PD	8	7	3	18	10	7	1	18
Total	78	29	14	121	79	31	12	122

Note: Values represent # of trials observed for exhibiting each outcome.

The effect of concurrent cognitive challenge on error rates was also examined within groups for all conditions. This analysis revealed that there were no statistically significant differences in the number of error trials observed between single task and dual task performance for any of the quantified error rates.

3.3.5 Motor Imagery and Task Perception

The mean ± standard deviation mental chronometry outcomes for each group and condition are displayed in Table 3. In general, participants across all groups were on average very accurate in estimating their single task performance. All groups tended to overestimate (i.e.

imagine faster than actual performance) their performance during single task and underestimate their ability during dual task performance. Examining the changes in mental chronometry from pre trials to post trials, it was observed that only the control participants consistently updated their performance for the unfamiliar task conditions (e.g. obstacles and dual tasking), indicating a change to imagined movement based on actually performing the task. These changes were also observed for imagining tasks with obstacles (standard and narrow width) during single task and for all conditions during dual task. In all cases, the significant change from pre to post performance served to bring the average mental chronometry times closer to the average actual walking times. That is, after limited physical practice of a testing condition, control subjects were able to update their perception of the task for improved imagined walking accuracy. In the MS and PD groups only one condition saw a significant change in mental chronometry. This result was for the MS group imagining the narrow obstacle condition under dual task circumstances. These results suggest a limited ability of clinical populations to adjust internal models of a task after physical practice.

Imagined DTCs of gait were calculated for the mental chronometry trials conducted before and after imagined movement. Spearman correlations revealed that only during the obstacle walking conditions did imagined DTCs of gait relate to DTCs of gait during physical performance of the task across groups. These correlations were significant for DTCs computed from both pre and post imagined walking times.

Table 3: Mental Chronometry Outcomes

	Standard Width Walkway					
	No Obstacles			Obstacles		
	Control	MS	PD	Control	MS	PD
ST Pre	-0.46 ± 1.28	-0.90 ± 2.77	-0.84 ± 2.02	0.18 ± 1.78	-0.77 ± 3.50	-0.67 ± 3.56
ST Post	-0.48 ± 1.30	-0.74 ± 2.61	-0.51 ± 2.26	-0.51 ± 1.55	-1.11 ± 3.35	-0.77 ± 1.59
DT Pre	4.16 ± 5.3	3.90 ± 4.12	3.70 ± 5.28	2.93 ± 5.38	3.44 ± 5.17	3.23 ± 5.93
DT Post	2.06 ± 2.75	3.83 ± 4.37	2.55 ± 5.42	0.92 ± 3.37	3.15 ± 5.01	1.15 ± 4.67
	Narrow Width Walkway					
	No Obstacles			Obstacles		
	Control	MS	PD	Control	MS	PD
ST Pre	0.48 ± 2.67	-1.79 ± 6.32	0.65 ± 3.54	0.05 ± 2.49	-2.40 ± 8.12	-1.36 ± 3.75
ST Post	0.14 ± 2.06	-2.56 ± 6.67	-0.91 ± 2.27	-0.65 ± 1.86	-2.88 ± 6.65	-1.73 ± 2.04
DT Pre	3.34 ± 4.42	4.74 ± 9.07	4.81 ± 7.99	4.73 ± 5.81	4.88 ± 11.07	6.34 ± 9.39
DT Post	1.78 ± 3.18	3.55 ± 9.50	1.90 ± 4.79	1.28 ± 3.12	0.40 ± 6.85	0.25 ± 4.65

Note: Values are mean ± std. deviation of (Imagined Walk Times – Actual Walk Times); Units are seconds

3.3.6 Correlates of DTCs of Gait and Cognition

A separate correlation analysis examined the relationships between DTCs of gait and cognition (during actual performance) with measures of cognition (SDMT and TMT), physiological fall risk (PPA) and self-reported balance confidence (FES-I). This analysis permitted an investigation into the proposed constructs of hazard estimate and postural reserve, which are theorized to influence prioritization strategy (Yogev-Seligmann, Hausdorff et al. 2012). The results of this analysis determined that none of these measures correlated with DTCs of gait for any of the walking conditions. In comparison, SDMT scores, PPA and FES-I were related to the observed DTCs of cognition. Better performance on the SDMT was associated with lower DTCs of cognition in the standard obstacles ($\rho = -0.251$) and narrow obstacle conditions ($\rho = -0.286$). Greater physiological fall risk was associated to elevated DTCs of cognition in the narrow ($\rho = 0.370$) and narrow obstacles ($\rho = 0.403$) conditions. Finally, FES-I was correlated to cognitive DTCs during the narrow (ρ = 0.255) and narrow obstacle (ρ = 0.401) conditions.

3.4 Discussion

The current analysis examined the effect of motor task difficulty on DTCs of gait and cognition as a function of health and neurological impairment. Four different walking challenges were completed by participants that ranged in difficulty by including obstacles and or adjusting the boundary width of the walking course. Originally, it was hypothesized that DTCs would increase as the difficulty of the task increased. Based on the attentional capacity model of dual tasking, it was assumed that those tasks including obstacles and/or walking on a narrow surface would require greater sensory processing, thus leading to heightened attentional demands (Kahneman 1973). Interestingly, the hypothesis was only partially confirmed. That is DTCs of walking were not statistically different across tasks whereas the DTCs of cognition increased as task difficulty increased. Consequently, these results provide some of the first direct evidence towards the efficacy of a behavioral prioritization model being an appropriate descriptor of CMI during walking and talking.

The current results are indicative of a prioritization model in multiple ways. First, examining the main effects of group and task on the DTCs of gait and cognition reveals that the motor task is being prioritized as task difficulty increases. That is, despite task difficulty increasing, individuals are maintaining a fixed DTC of gait across the trials. This is coupled with the observed increase in DTC of cognition across the conditions. These results suggest that as the task difficulty increases, resources are shifted away from the cognitive task performance to prevent large declines in gait performance. These findings align themselves directly with the theorized changes (see Figure 6) proposed by Yogev-Seligmann and colleagues in the self-awareness prioritization framework (Yogev-Seligmann, Hausdorff et al. 2012).

The correspondence with the prioritization framework is also evident when looking at the CMI characterizations in Table 1. These results showed that predominantly in the simplest task participants selected a posture second strategy based on cognitive prioritization. That is, DTCs of gait were indicative of slowing down from single task performance compared to DTCs of cognition, which were indicative of improvements or no changes on serial 7s subtraction compared to when that task was performed in isolation. As task difficulty increases, however, these CMI distributions also begin to shift. For tasks with obstacles and/or narrow paths a greater proportion of individuals exhibiting mutual interference or gait prioritization are observed. Thus, these findings bolster those of the main analysis by showing that not only are DTCs of cognition changing as motor task difficulty changes but, they are switching from a state of facilitation to interference. These results follow closely with the theorized tendencies outlined in Figure 6. The current sample adapts their performance on the cognitive task in the presence of increasing perceived fall risk based on task difficulty.

Also following along in this trend were the results examining error rates and obstacle collisions. These error rates are important as the tasks aimed to simulate outcomes that may be experienced in the community setting. For instance, the obstacles could represent uneven sidewalks and/or curbs and the walkway width could simulate walking in a busy or narrow corridor. These are all situations that could lead to an increased risk of trips and/or falls, especially under distracted conditions. For the simplest task with no obstacles and the wide boundary, no boundary errors were made in either the single or dual task trials. As the task constraints became more difficult, the proportion of minor and critical errors increased accordingly (see Table 2). Interestingly, the addition of the concurrent cognitive task had no effect on the number of error trials compared to single task outcomes. This once again points to the flexibility of participants to shift attention towards the motor task in order to try to minimize the risks associated with loss of balance. In the context of hazard estimate, this strategy potentially represents an inherent prioritization of safety over performance of the serial subtraction task.

The motor imagery task results provide valuable insight into the hazard estimate construct of the self-awareness prioritization model. Examining the mental chronometry times recorded prior to physical performance, it is evident that all groups tend to underestimate their ability to dual task. Interestingly, following performance it could be expected that this underestimation would be updated, but these updates only occurred in the control group. This finding suggests that the control subjects are more likely to have a better understanding of their limits on a task after limited practice, especially considering advanced tasks such as walking and thinking.. Conversely, the results suggest that clinical populations are more likely to stick with a conservative approach to movement planning and are unable or choose not to update their internal model of an action following its completion. This could possibly be viewed as a compensatory strategy to maintain safety when confronted with difficult environmental challenges. Further work is warranted to investigate the relevance of this strategy in regards to outcomes such as falls, fall risk, community ambulation and other motor tasks.

Finally, the notion of a self-awareness prioritization can also be interpreted from the results of the correlation analysis. It is important to recall, that the theorized model of prioritization by Yogev-Seligmann hinged on two factors, postural reserve and hazard estimate. These constructs are stated as the balance or physiological ability of the individual for postural reserve and the cognitive or awareness ability of the individual for hazard estimate. Utilizing the PPA and FES-I as surrogates for these constructs shows how an individual with deficits in either of these areas may change their performance to a greater extent than an individual with less impairment. Indeed, when looking at PPA, those individuals at greatest physiological risk for falls tended to display greater DTCs of cognition in the difficult conditions compared to participants with greater physiological performance. Similarly, those individuals who had decreased balance confidence also tended to display worsened performance on the serial 7 subtractions during the more challenging walking conditions. It is important to note that the observed correlations with PPA and FES-I were only observed for DTCs of cognition. This indicates that due to environmental stressors, participants are predominantly modulating cognitive performance.

This study is not without limitations. The unequal sample size may have limited the power of some statistical analyses. In general, however, the observed p values were generally strong whether in support of maintaining or rejecting the null hypothesis. Additionally, many comparisons were made, which could have led to possible Type I errors. This was managed by utilizing adjusted probability thresholds where necessary. Next, the current experiment utilized a subtraction task as the concurrent cognitive stressor. It could be argued that the task limits the relation of these findings to performance in the community where this subtraction task has limited ecological context. The choice of sevens, however, allowed for a consistent testing difficulty within and between tasks, which made it optimal for the repeated testing methodology utilized here. Finally, the use of standard obstacle placements may have led to variable difficulty on those tasks based on the respective leg lengths of the individual participants. This was accounted for by performing the main analyses on the DTCs of gait rather than simply using walking speeds. The use of DTC provides a within subject normalization of performance.

3.5 Conclusions

Overall, this study utilized a manipulation of environmental demands in order to investigate proposed theories of cognitive-motor interaction. Specifically, the analysis permitted an intricate view into possible prioritization strategies of individuals confronted with increasingly difficult walking conditions. The results suggest that when confronted with challenges in the motor domain, participants regardless of neurological status tend to reduce performance on the cognitive task to limit the effects on walking performance. This tendency was observed through multiple outcomes including the primary results of DTCs of gait and cognition, observed error rates, CMI outcome tendencies and associations between fall risk, balance confidence and DTCs.

To conclude, the results of the current study show that CMI may be influenced by the individual at levels above those described by the more mechanistic theories of attention such as the capacity and bottleneck models. Researchers should keep this in mind when developing future studies in order to avoid possible biases that could occur based on methodology. Specifically, the use of tasks that provide variable difficulty and instructions that don’t place limitations on performance are imperative.

Chapter 4: Attentional Cost of Movement

4.1 Introduction

4.1.1 Automaticity of Gait and Posture

The maintenance of upright stance and gait represent some of the most commonly performed and practiced human movements. In general, these movements are considered to be automatic, thus requiring little input from higher-level control systems. This concept of automaticity of movement is largely based on two conventions: The first maintains that walking and stance are highly practiced and therefore require minimal attention. The second states rhythmic movements such as walking can be controlled mainly through spinally mediated processes termed central pattern generators (CPGs). CPGs produce rhythmic movement patterns in the absence of supraspinal inputs (Grillner 1996).

However, locomotion is rarely performed in situations where there is no need for monitoring or adjustment. That is, in the complex environment humans constantly process sensory feedback as well as incorporate specific task-goals related to moving from one location to another or maintaining an upright posture. Indeed, afferent feedback is generally available and interpreted during the performance of each movement requiring at a minimum some attentional resources (Lajoie, Teasdale et al. 1993). This feedback includes visual, proprioceptive, and vestibular monitoring of the state of the body as well as the environment around it (Hausdorff, Yogev et al. 2005). Based on the realizations that not all processes associated with stance and gait are purely automatic, recent research has suggested that these motor functions do in fact require some higher level attentional processing (Woollacott and Shumway-Cook 2002). Predominantly, studies investigating the interplay of attention and movement employ a dual task testing strategy in order to examine how concurrent performance of cognitive and gait tasks lead to changes in one or both of the tasks compared to single task performance.

4.1.2 Stability and Dual Tasking

From the standpoint of stability, gait and balance are related through the necessity to control the position of one's center of mass (COM). Fundamentally, the tasks differ as this control is under static conditions for upright stance and dynamic conditions during gait (Lajoie, Teasdale et al. 1993). That is, the COM is constantly maintained in the base of support (BOS) during standing and continuously moved towards and within the BOS during walking. Based on the necessity to process sensory information and update body position, it is reasonable to expect that despite being highly learned, these movement tasks do indeed require attentional resources. Under this assumption it can be hypothesized that those actions requiring a greater amount of attention will ultimately lead to greater dual task costs (DTCs) when performed concurrently with a cognitive distractor. This assumption falls in line with Kahneman's proposed theory of attentional capacity (Kahneman 1973) that presumes individuals have a fixed capacity of available attentional resources (see Figure 9). These resources are utilized during the performance of our daily activities. If two concurrently performed tasks exceed the available capacity, then the performance of one or both will suffer. Therefore, movements with increased attentional costs will in turn take up more of the available resources that could be dedicated to the performance of a simultaneous dual task. In turn, it would therefore be more likely to observe greater dual task costs for multitasking situations utilizing high attention movements. In order to examine this relationship, however, one must first identify a measure to quantify the attentional cost of various movements.

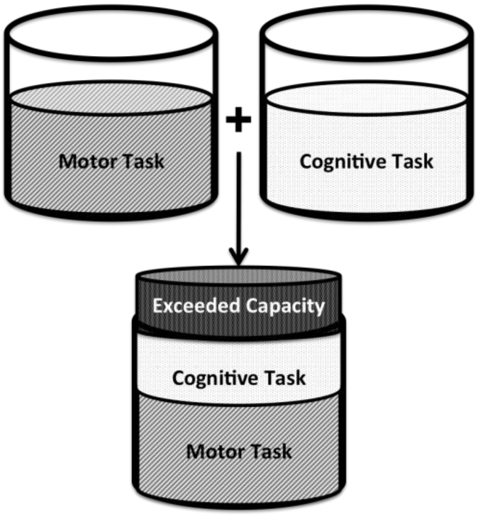


Figure 9: Graphical Representation of the Attentional Capacity Model

Previously, studies have examined attention and movement by focusing on the influence of stability maintenance on attentional resources in both young and old adults (Lajoie, Teasdale et al. 1996; Mazaheri, Roerdink et al. 2014) as well as patients with cerebral damage (Regnaux, David et al. 2005). These studies have commonly utilized a probe reaction dual task in order to measure attentional costs via reaction time while maintaining prescribed postures or movements. This probe reaction time serves two purposes as it can easily be obtained through a participant's response to a random auditory cue (i.e. simple reaction time) and is easily measured without interfering across many conditions of stability and locomotion (e.g. auditory probe with vocal response). Moreover, probe reaction time has been recommended as an indicator that mirrors the attentional demands of the primary task, with greater reaction times signifying greater attentional costs of the motor task. Therefore, the foundation for this approach aligns with the previously outlined capacity theory of dual tasking (Kahneman 1973). Thus, the use of a simple probe reaction task in combination with a postural/mobility task requires the individual to attend to movement stability as well as the stimulus cue. From a cognitive standpoint, the simple probe reaction time should place a relatively low demand on attentional resources and eliminate the recruitment of more complex cognitive processes such as executive function while also permitting full attention to the primary task.

A general methodological structure for examining the attentional demand of gait and balance is a within subject design utilizing the same probe reaction time task across trials of sitting, standing and walking. Sitting serves as the control condition as there are minimal requirements for stability and no movement requirements. Theoretically, standing should require greater attentional resources than sitting based on the added component of attending to sensory feedback to maintain the COP within the BOS. Finally, walking should represent the most attentionally demanding of the three motor conditions as the BOS is variable and the COM path is consistently updated to provide dynamic balance.

Indeed, previous studies utilizing this methodology have observed that increasing stability demands places a greater burden on higher-level systems. That is, the attentional demands for walking (i.e. PRTs) were greater than those for standing and sitting (Lajoie, Teasdale et al. 1993). Furthermore, attentional demands within these common motor tasks have been shown to scale with respective subtasks. During standing, probe reaction times have been shown to be greater when the BOS is narrowed from the participant’s self-selected comfortable stance (Lajoie, Teasdale et al. 1993). Similarly, reaction times are greater during walking when the subject is in the less stable single support phase compared to double support. Additional evidence supports an alteration of attentional demands with regards to speed in walking tasks as well. Specifically, the attentional demands of walking may be increased when individuals are forced to walk at speeds both below and above self-selected pace due to alterations in stability and energetic cost (Abernethy, Hanna et al. 2002). It should be noted, however, that the results pertaining to increased attentional costs of walking are particularly ambiguous. This is the result of walking consisting of two primary functions including dynamic control of the COM and propulsion of the body. To date, no study has directly examined if the rhythmic movement component or the dynamic stability component is the primary driver of elevated attentional costs.

4.1.3 Influence of Aging and CNS Damage on Attentional Costs of Gait and Balance

As previously mentioned, studies aimed at investigating the attentional cost of gait and posture commonly examine the effect of age on observed reaction times. The results of these studies have consistently shown an increase in attentional demands as measured with probe RT in older adults compared to younger adults as well as an increase in RTs during standing and walking for older adults (Lajoie, Teasdale et al. 1996; Mazaheri, Roerdink et al. 2014). Additionally, some studies have investigated the effect of neurological damage due to suffering a stroke (Regnaux, David et al. 2005). This study observed that probe reaction times were not significantly different between sitting, standing and treadmill walking in healthy controls (Age Range: 25-55 yrs); however, a significant increase in reaction time during walking was observed in the stroke group (Age Range:29-74 yrs, Time since injury: 13.6 months). These results suggest that the impairments to the CNS caused by stroke or the associated motor impairments may increase the attentional demand of steady state walking for patients.

The stroke research further suggests that similarly increased attentional costs of movement may be expected in other neurological populations as well. Indeed, individuals with MS, PD and stroke commonly exhibit alterations to motor performance when standing and walking with a concurrent dual task (Kelly, Eusterbrock et al. 2011; Plummer, Eskes et al. 2013; Wajda and Sosnoff 2015). It is often suggested that the decline in dual task performance in these clinical populations is due to increases in attentional demand of movement. However, the absence of probe reaction time tasks within the current literature in these populations limits a true analysis of the attentional cost of balance and walking. It is further confounded by the variable attentional demands related to the various utilized cognitive tasks. It is within reason to assume that the common motor and cognitive impairments observed in MS and PD lead to increased attention being placed on gait and posture compared to healthy subjects in an effort to maintain safety. An additional factor requiring greater attention for gait and posture in these populations is the possible impacts of disease on sensory feedback/processing, which may increase demands on attention through signal clarification processes. Sensorimotor issues are common in MS (Cattaneo, Jonsdottir et al. 2007) and PD (Jacobs and Horak 2006) and can lead to difficulties with processing feedback and making necessary postural adjustments.

4.1.4 Purpose

Limited empirical data exist regarding the attentional cost of movement in individuals with neurological disease/damage. The aim of this study was to analyze probe reaction time in individuals with MS, PD, stroke and healthy controls during five conditions requiring varying levels of stability and/or movement. These tasks included sitting, standing, leaning to the stability boundary, stationary cycling, and over ground walking. It was first hypothesized that attentional costs would increase in all groups as the dynamic stability and locomotion demands of the task were increased. That is, walking would have the largest attentional cost based on its dynamic stability and propulsion requirements. A secondary hypothesis was that the individuals in the patient groups would exhibit greater attentional demands of movement than the healthy control subjects. Examining this further, it was thought that the individuals with PD would have the greatest attentional costs based on possible delays in response initiation attributed to bradykinesia (Jankovic 2008). Previous studies have assumed that attentional costs of movement in neurological populations are elevated based on accrued impairments and thus the results of this study could be used to provide direct evidence of how the effects of sensorimotor damage impact the burden of performing common motor activities in these individuals. Finally, the study permitted a direct investigation of the attentional capacity model through examining the relation of probe reaction times during walking with DTCs from a walking while subtracting task. It was hypothesized that those individuals with the greatest probe reaction times would also have the largest DTCs during the complex dual task.

4.2 Methods

4.2.1 Design

The study was performed as a cross-sectional investigation. Participants were asked to come to the laboratory for a single one-hour assessment. In addition to the probe reaction time task, demographic information and measures of mobility, cognition and fall risk were also completed.

4.2.2 Participants

Overall, the sample included 61 individuals. The sample consisted of 26 healthy controls, 20 individuals with MS, 10 individuals with PD and 5 stroke survivors. Recruitment was accomplished by utilizing existing participant contacts, online and print advertisements and attending clinical population support group meetings.

Inclusion criteria for the patient groups included a physician’s confirmed diagnosis; the ability to walk without bilateral support; self-reported gait impairment and self-report of attentional/multi-tasking difficulties. Patient groups were matched based on scores from the upper and lower limb disability subsections of the Guy’s neurological disability scale (Sharrack and Hughes 1999). Guy's neurological disability scale was originally developed for use in individuals with MS but permits an accurate and simple analysis of function (e.g. assistive device use), which is applicable to the included neurological populations. Inclusion criteria for the control group was having no diagnosis of a neurological disease and no walking issues (e.g. orthopedic problems). Control participants were chosen such that their ages fell within the ranges of the recruited patient samples. Additionally, all participants (i.e. controls and clinical populations) were required to score above a set cutoff point of 20 on the modified telephone interview for cognitive status TICS-M (de Jager, Budge et al. 2003). Finally, participants were asked if they had normal to corrected normal hearing in order to complete the auditory probe reaction testing.

4.2.3 Procedures

Participants completed the probe reaction time test during five distinct conditions. These conditions included sitting, standing, leaning to the limits of stability, stationary cycling, and walking. During the performance of these tasks, participants were outfitted with a wireless headset and microphone for the presentation of auditory cues and recording of verbal responses. The participants were given the following instructions: "During each trial you will hear a series of beeps presented at random intervals. Any time you hear a beep please respond as quickly as possible by saying the word 'Pop' out loud. Please try to maintain a constant performance on the task you are performing, for example don't stop pedaling in order to respond to the cues." Instructions for the performance of each motor task were also given. Participants were asked to sit with their backs resting on the chair during the seated trial, utilize their normal comfortable stance during the standing trial, and continuously rotate their bodies in a circle by leaning as far in each direction without having to take a step for the limits of stability trial. For the task with greater movement requirements (i.e. cycling and walking), the participants were asked to pick a normal comfortable pace that they believed could be maintained throughout the duration of the probe reaction trial.

Auditory signal presentation and voice recording was handled with digital recording software (Audacity®). This software facilitated the development of unique stimulus tracks for each of the five motor tasks. These tracks consisted of twenty 500ms auditory cues (1000Hz sinusoidal signal) separated by random inter-stimulus intervals (ISIs) of 2000ms to 4500ms. Each audio track lasted approximately 70 seconds. The five motor tasks each had its own distinctive audio track, which was utilized for all participants.

4.2.4 Outcome Measures

The primary outcome measure for the experiment was the average time to respond to the presented auditory stimuli during each motor task. Participant responses were recorded through the microphone at a sampling rate of 44,100Hz. Reaction times were calculated as the time elapsed from stimulus presentation to the beginning of the participant's 'Pop' response (i.e. PRT = Response onset – Stimulus onset, see figure 10). In addition to average response times, variability measures including standard deviation (SD) and coefficient of variation (CV) were calculated for every individual's reaction times during each task condition. Secondary outcome measures include COP metrics during the standing trials, self-selected cadence during cycling trials, and spatiotemporal gait parameters during the walking trials.

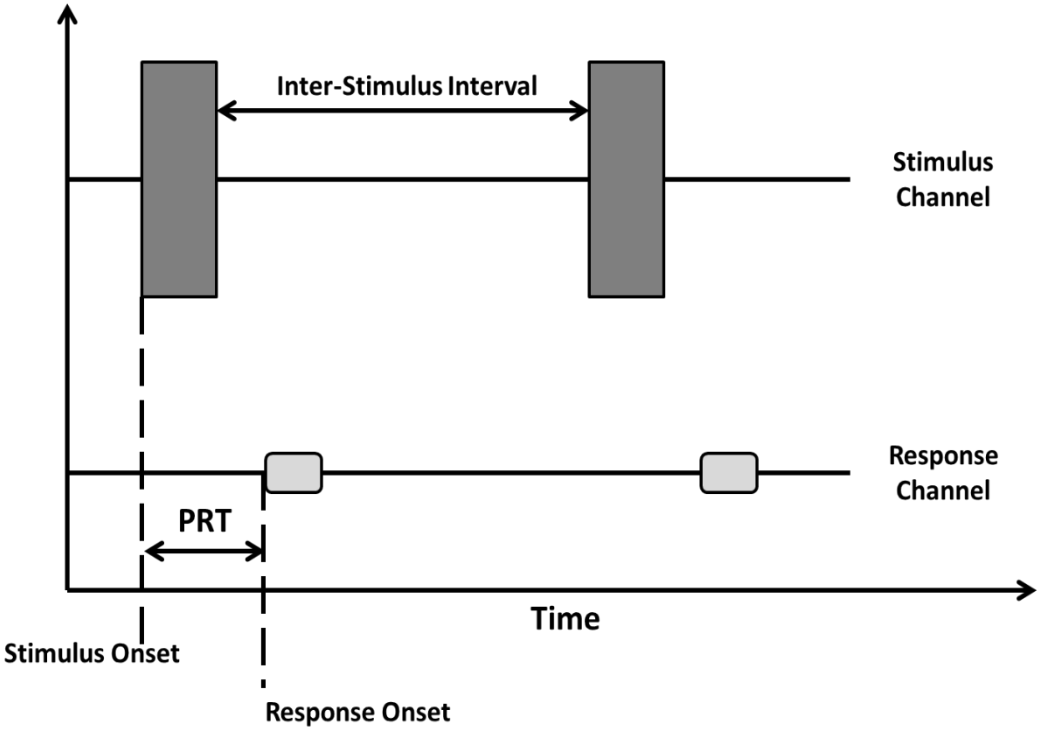


Figure 10 Representation of PRT audio data and subsequent outcome calculation.

Secondary outcomes included measures of movement, cognition, fall risk, demographics, and balance confidence. The movement measures consisted of two components. The first set of measures was collected during the various probe reaction trials. These included sway velocity during the standing and limits of stability trials, cadence during cycling and gait velocity during walking. Sway metrics were collected utilizing a Bertec (Bertec Inc., Columbus OH) force platform sampling at 1000Hz and COP measurements were calculated post hoc utilizing a custom MATLAB (Mathworks Inc., Natick MA) script. Cycling cadence was determined from accelerometry data collected from a sensor attached to the pedal of the stationary cycle. Gait velocity was calculated through the use of a pressure sensitive instrumented Zeno walkway (Protokinetics Inc., Haverton PA). The mat digitally recorded footfall data, which was then utilized to calculate the spatiotemporal parameters of gait. The second set of movement outcomes were collected separately during the complex dual task scenario of walking while subtracting 7s from a given number. Participants completed two walking trials at their normal comfortable pace and two trials of walking and thinking. DTCs were quantified by calculating the percentage change in walking times from single task to dual task performance.

Cognitive outcomes included the symbol digit modalities test (SDMT) and the trail making test (TMT) parts A and B. The SDMT requires participants to match numbers to a provided set of symbols based on their pairing in a response key. The scoring for the test is represented as the total number of correct responses given during a 90s trial. The SDMT has been suggested as a measure of cognitive processing speed (Sheridan, Fitzgerald et al. 2006). Further, it has been utilized in both healthy and clinical populations. The TMT is a neurocognitive test of visual attention and task switching (Tombaugh 2004). It consists of two parts, which require participants to connect dots of numbers and/or letters in a specific order as accurately and fast as possible. For part A of the TMT, participants connect numbered circles in order from 1-25. Part B of the TMT has participants alternate connecting numbers and letters sequentially (i.e. 1-A-2-B-3…). The difference in time between the two trials (i.e. TMT B – TMT A) represents the primary outcome of the TMT. Lower difference scores between conditions A and B are indicative of increased cognitive flexibility, divided attention ability, and processing (Tombaugh 2004).

Physiological fall risk was determined by the short form of the physiological profile assessment (PPA). The PPA is a validated tool to assess physiological function related to fall risk by combining measures of vision, proprioception, lower-limb strength, postural sway, and cognitive function (Lord, Menz et al. 2003). It is utilized as a global score of motor impairment and is predictive of future fall risk in persons with MS, PD and stroke (Lord, Delbaere et al. 2015). The vision task has participants identify shapes with varying levels of contrast. The reaction time task requires participants to press a button as quickly as possible following a visual stimulus (i.e. a light turning on). During the proprioception task, participants will be asked to match the knee extension positions of each leg with their eyes closed while seated. The leg strength test requires participants to push out against a strap placed around the ankle while seated. The strap is connected to a simple force gauge. Finally, participants will complete a balance test standing on a piece of foam (i.e. a compliant surface) with eyes open for 30s.

All participants completed a series of questionnaires. These included information regarding age, gender, education, disease/injury type and disease duration. Participants also completed the Falls Efficacy Scale International (FES-I), which provides insight into an individual's perception of balance ability during various activities of daily life (Yardley, Beyer et al. 2005).

4.2.5 Data Analysis

All statistics were performed in SPSS version 22.0 (IBM, Inc., Armonk, NY). Descriptive statistics (mean ± standard deviation) were calculated for all of the demographic and spatiotemporal gait parameters of interest. One-way analysis of variance tests were used to compare the average age and physiological fall risk of the groups.

Additionally, a 3 x 5 repeated-measures analysis of variance (ANOVA) with group (MS vs. PD vs. Control) and motor task (sitting vs. standing vs. limits of stability vs. cycling vs. walking) as the factors was used to analyze performance on the PRT task. The level of significance was set at $p \leq 0.05$ and Sidak corrections were utilized for multiple comparisons.

In order to investigate the relationship between PRTs, motor task performance, cognition, and physiological fall risk a series of correlation analyses were performed. Spearman correlations were utilized to minimize the influence of mild outliers or non-linearity in the data. Additionally, as a means to test the relationship to the attentional capacity an additional analysis was carried out examining the correlation between PRTs during walking and the change in gait speed during a complex dual task (i.e. DTCs of walking and subtracting).

Based on the low sample size and high variability within the outcomes, the stroke group was excluded from the main analyses of this experiment. Data relative to their performance is presented as a pilot analysis separately in Appendix B.

4.3 Results

4.3.1 Participant Characteristics

The mean age of participants was 61.6 ± 9.0yrs for the controls, 56.4 ± 11.0yrs for the MS group and 62.4 ± 8.5yrs for the PD group. A one-way ANOVA revealed no significant difference in age between groups ($F = 2.0$, $p = .14$). The control sample consisted of 18 females and 9 males compared to 12F/8M for the MS group and 5F/5M for the PD group. Physiological fall risk scores for the group averaged 0.37 ± 0.70 for the control group, 1.83 ± 1.21 for the MS group and 1.73 ± 1.16 for the PD group. The comparison of means showed that the MS and PD group did not differ ($p = 0.86$) from each other in terms of fall risk and both groups had significantly ($p < .001$ and $p = .001$ respectively) elevated fall risks compared to the control participants. The SDMT scores were 56.4 ± 6.68 for the controls, 56.4 ± 14.1 for the MS group and 46.5 ± 10.9 for the PD group. TMT scores were 24.2 ± 10.5s for the controls, 24.9 ± 11.2s for MS and 34.5 ± 22.1s for PD. An analysis of cognitive processing speed showed that the control participants had significantly greater scores on the SDMT compared to the PD group ($p = 0.48$). No differences were observed between the MS and control subjects ($p = 0.99$) or MS and

PD participants (*p* = 0.06). Both the control and MS groups had significantly less differences in TMT B-A performance compared to the PD group indicating greater cognitive flexibility.

In regards to the clinical populations, average disease duration was 16.8 ± 8.8yrs for the MS group and 6.8 ± 5.7yrs for the PD group. For MS specifically, the self-reported expanded disability status scale score had a median score of 3.5 and interquartile range of 2.6-5.4. None of the PD participants utilized assistive devices while 6 of the MS participants utilized unilateral support.

4.3.2 Probe Reaction Time Results

Table 4 displays the mean ± standard deviation of probe reaction times for each group across the 5 motor tasks. These values are also shown visually in Figure 11. The 5x2 ANOVA revealed a significant effect of group (*F* = 6.5, *p* = 0.003) and task (*F* = 40.9, *p* <0.001). No significant group by task interaction was observed (*F* = 1.5, *p* = 0.16). Examining the effect of group further with post hoc analyses, it was revealed that the MS and PD participants had significantly greater reaction times compared to control participants. No differences were observed between the MS and PD groups in PRT.

Table 4: PRT values by condition and group

Group	Sitting	Standing	Cycling	Limits	Walking	Group Mean
Control	333.9 (17.0)	334.0 (18.9)	355.3 (16.3)	399.6 (24.5)	394.0 (17.7)	363.4 (17.0)
MS	405.6 (19.4)	397.7 (21.6)	432.9 (18.6)	518.8 (27.9)	504.2 (20.1)	**451.8 (19.3)***
PD	388.0 (27.4)	384.4 (30.5)	419.3 (26.2)	485.5 (39.5)	489.8 (28.5)	**433.4 (27.3)***

Note: * Significantly greater than control group, $p \leq .05$, Values are Mean (Std Error); Units are milliseconds

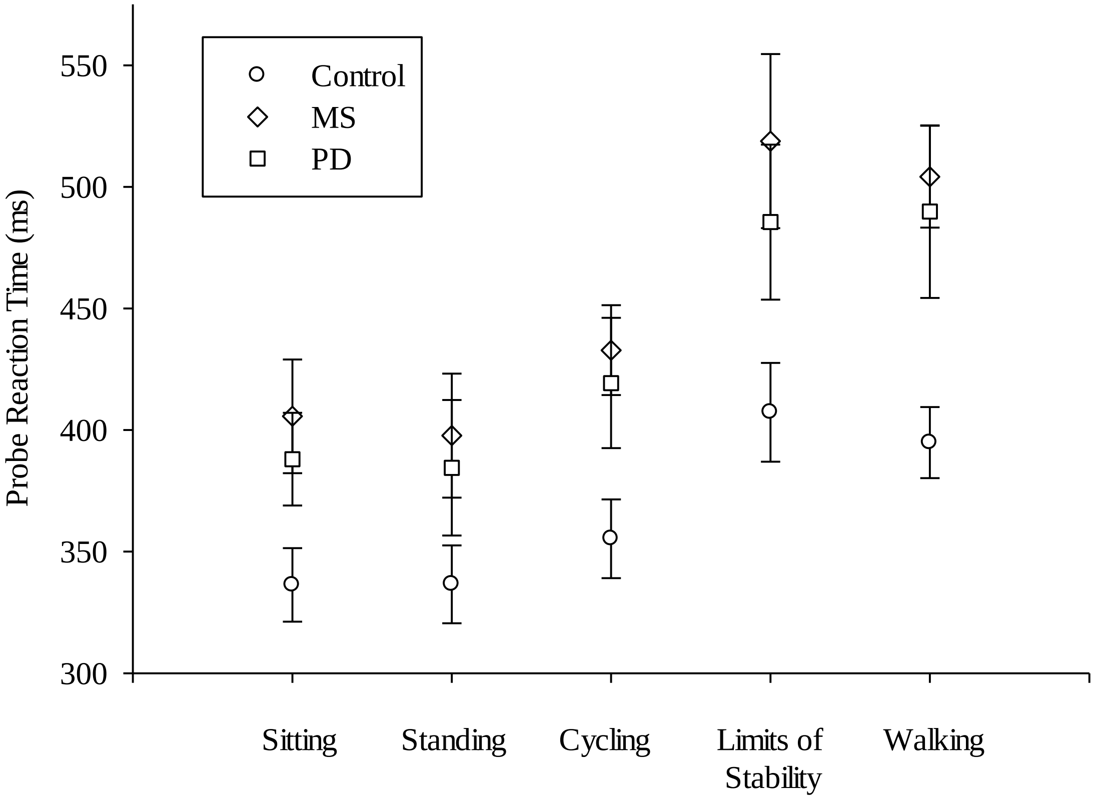


Figure 11: PRTs across group and task

A breakdown of the PRT values averaged across group is displayed in Figure 12. Post hoc analyses of the task effect showed that across all groups, there were no differences in PRTs between the sitting and standing conditions. PRTs during cycling were significantly greater than those observed for sitting and standing and significantly lower than those observed during the limits of stability and walking trials. PRTs did not differ between the limits of stability and walking trials; however, they were significantly greater than the other three conditions.

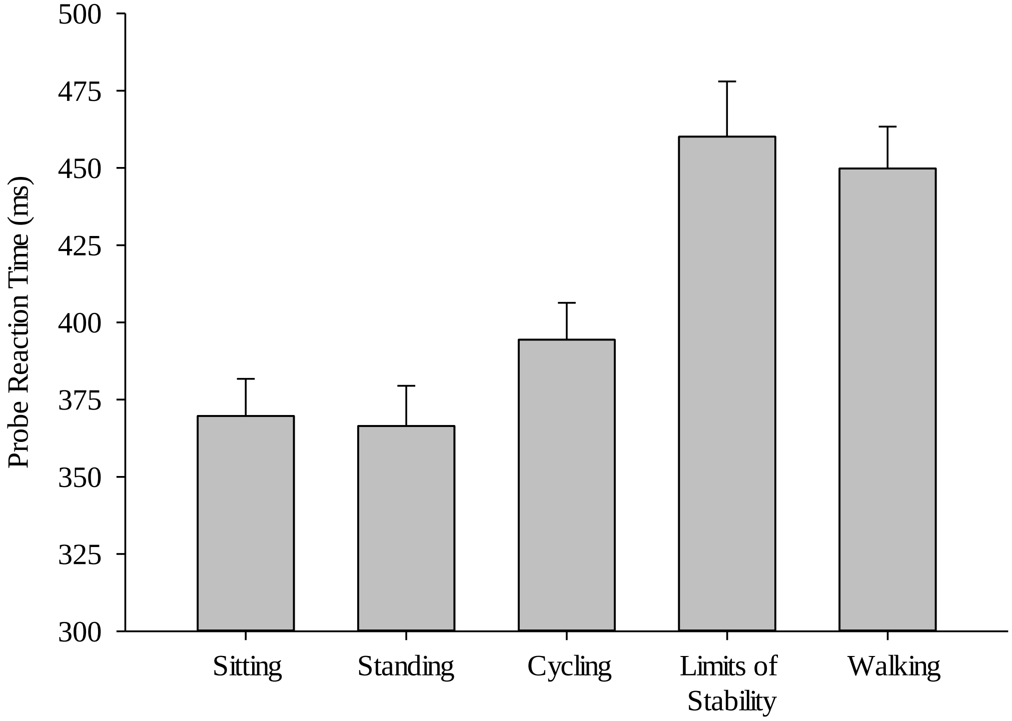


Figure 12 PRT averages across condition

4.3.3 Motor Performance, Cognition, Balance Confidence and Attentional Costs

Table 5 displays the correlation coefficients between the PRTs and the respective movement quantifications for the sitting, cycling, limits of stability and walking conditions. The aim of these correlations was to determine if differences in movement performance were related to differences in probe reaction times for each condition. The movement outcomes considered were mean radial COP velocity for sitting and limits of stability, cadence for cycling, and average gait speed for walking. Overall, no significant correlations were observed between performance of the movement tasks and corresponding mean reaction times for standing, cycling and limits of stability. A weak correlation was observed between self-selected walking speed and observed PRTs during the walking condition.

Table 5: Spearman Correlations between PRTs and motor performance

	Standing PRT	Cycling PRT	Limits PRT	Walking PRT
COP Velocity Standing	0.200	--	--	--
Cadence	--	-0.199	--	--
COP Velocity Limits	--	--	-0.076	--
Walking Velocity	--	--	--	-0.293*

Note: * Correlation is significant at the $p \leq 0.05$ level

Table 6 contains the results of the correlation analysis between the PRT trials, the global measures of physiological fall risk, and cognition as well as self-reported balance confidence. Of these items, the measures of cognitive processing speed and executive function were not related to performance on the PRT task. Physiological fall risk showed the greatest correlation across all conditions of PRT. Finally, self-reported balance confidence was significantly correlated with observed PRTs.

Table 6: Correlation coefficients for PRTs, cognition, physiological fall risk and balance confidence

	Sitting PRT	Standing PRT	Cycling PRT	Limits PRT	Walking PRT
SDMT	-0.249	-0.203	-0.231	-0.150	-0.128
TMT	0.031	-0.023	-0.076	-0.057	-0.075
PPA	**0.352***	**0.319***	**0.364***	**0.296***	**0.362***
FES-I	**0.371***	**0.258***	**0.378***	**0.299***	**0.283***

Note: * Correlation is significant at the $p \leq 0.05$ level

4.3.4 Attentional Costs and Complex Dual Tasking

The average comfortable gait speed for control subjects was 129.2 ± 18.9cm/s compared to 108.7 ± 34.7cm/s for the MS group and 105.8 ± 17.0cm/s for the PD participants. These gait speeds decreased to 114.7 ± 21.5cm/s, 95.4 ± 37.1cm/s and 96.5 ± 37.1cm/s respectively during the complex dual task of walking while subtracting 7s from a given number. Within subjects the average DTC of gait was 14.6 ± 18.5% for control participants, 16.0 ± 16.0% for individuals with MS and 10.7 ± 8.5% for individuals with PD. These values indicate that participants decreased their walk speed when given a concurrent cognitive challenge. The average DTC of cognition was -38.0 ± 53.7 for controls, -22.0 ± 58.0% for MS and -25.9 ± 48.3% for PD. These values indicate the participants increased their correct utterances per second when walking and thinking compared to doing the subtraction task while seated. Examining the correlation between complex DTCs of gait and cognition with PRTs during walking revealed no significant relationship between the outcomes (DTC gait: $\rho = -0.023$, $p = 0.87$, DTC cognition: $\rho = 0.118$, $p = 0.40$).

4.4 Discussion

This study investigated the relationship between movement, dynamic stability, and attentional cost in healthy participants, individuals with MS, and individuals with PD. Importantly, this study permitted a direct analysis of the commonly cited attentional capacity model of dual tasking (Kahneman 1973). We first hypothesized that tasks with greater stability requirements would induce longer reaction times and this effect would be exaggerated in the clinical populations. The observations from the main analysis of the study confirmed this hypothesis, showing tasks requiring dynamic stability (i.e. leaning to the limits of stability and walking) had significantly greater PRTs. Additionally, individuals with MS and PD displayed significantly longer PRTs across all tasks compared to the healthy control participants. Interestingly the PRTs on each movement task were not related to the individual's performance on the specific motor task. For example, gait velocity during the walking PRT trial was not significantly correlated to average auditory reaction times during the trial. Finally, and perhaps of most import, it was determined that the PRTs during walking were not related to the levels of

DTCs of gait and cognition observed during a complex walking and subtracting scenario. This result suggests that the attentional capacity model itself may not account for the changes that occur due to CMI. This is due to a lack of understanding in regards to attention allocation that can be garnered from the attentional capacity model alone.

Examining the task effect from the model revealed consistent results compared to prior movement and attentional cost literature (Lajoie, Teasdale et al. 1996). Lajoie and colleagues showed that older adults displayed greater PRTs during walking compared to sitting and standing. The assumption regarding this result was that walking was a more challenging stability task that required a greater amount of sensory feedback. However, this assumption could not be tested with the methodology utilized in their protocol. The results of the current study offer a unique investigation of the relation between movement and stability to attentional costs of motor performance. That is, two additional tasks were included that directly required rhythmic movement in the absence of high stability demands (i.e. cycling) and a task that taxed dynamic stability with reduced movement demands (i.e. leaning to the limits of stability). Examining the mean PRTs of these tasks, it appears that the dynamic stability component has a greater influence on response speed compared to rhythmic movement. It should be noted that the cycling task did have greater PRTs than sitting and standing as well indicating that movement does have a marginal influence on recruiting additional attentional resources. It is possible that the largest PRTs are observed for stability tasks based on a greater need to synthesize sensory information from multiple systems. In summary, these results suggest that dynamic plays a greater role in slowed reactions than simple balance and rhythmic movement.

It was originally hypothesized that the PD group would display the largest PRTs due to the common symptom of bradykinesia being associated with that disorder. Interestingly, the results did not confirm this hypothesis. Post hoc analysis of the ANOVA showed that PRTs of the neurological disorders included in the model (MS and PD) were not significantly different. PRTs for the clinical groups were, however, significantly greater than healthy controls. The implication of this finding points to a more generalized understanding of attentional costs where impairment may be the main driver rather than the specific mechanism causing the deficits.

The possible effects of cognitive, physiological, and behavioral factors on observed PRTs were further examined through a correlation analysis. The initial focus of this analysis was to investigate within subjects' differences on reaction times. That is, did variances in performance on the motor task manifest themselves in observed PRT values. The results of this analysis primarily showed no significant correlations between the characteristic measures of each motor task and PRTs during those motor tasks. There was a weak correlation between self-selected walking speed and PRTs during walking suggesting that those individuals who walk faster have higher reaction times. This could suggest that some individuals were trying to walk at a greater pace to the detriment of their reaction time. In general, these findings have an impact on the possible generalizability of the current results. Once again, it points to a different factor than simple motor output being the main driver of attentional costs rather than specific clinical impairments.

In the absence of motor performance primarily influencing observed PRTs, it was assumed that basic cognitive measures such as processing speed or executive functions may account for performance differences. Further investigation of these factors found no relation between cognitive processing speed (SDMT), cognitive flexibility (TMT), and PRTs. Finally, the influence of physiological fall risk, a broad measure of physiological function, and balance confidence was examined. Both the physiological function (PPA) and balance confidence (FES-

I) showed moderate correlation to PRTs in all conditions. This result in regards to physiological fall risk score and PRTs once again reinforced that a global measure of physiology rather than disease specific mechanisms may be of greater importance when considering the attentional costs of movement. Physiological fall risk has previously been shown to be related to dual task costs of walking in individuals with MS (Wajda, Motl et al. 2013). The finding of a correlation between PRTs and balance confidence lends itself to the argument that individuals with low balance confidence may be consciously shifting their attention towards balance maintenance and thus allowing/forcing secondary task performance to suffer. Indeed, previous studies in older adult women (Liu-Ambrose, Katarynych et al. 2009) and MS (Wajda, Roeing et al. 2015) have presented a link between balance confidence and dual task costs during a complex multitasking scenario.

The final hypothesis for the current experiment involved the ability of the utilized experimental framework to directly investigate the attentional capacity model (Kahneman 1973). It was hypothesized that those individuals displaying the greatest PRTs during walking would also have the largest DTCs during a complex walking and subtracting task. This hypothesis was not confirmed, as there was no relationship between PRTs and DTCs of walking or cognition within the total sample. These results suggest that the attentional capacity model is inadequate in predicting the motor behavior changes observed from single to dual task walking scenarios. This has important implications for future studies examining the underlying mechanisms of CMI in both healthy and clinical populations. The implication is that the assumed attentional cost of a movement (e.g. based on PRTs) does not have an express bearing on dual task performance of that movement with a concurrent cognitive challenge. All in all the lack of a direct relation with the attentional capacity model could be a result of an inability to determine allocation policy on a within subjects basis. Overall, the finding further suggests that CMI outcomes cannot be explained simply through this capacity framework and more rigorous prioritization models should be examined.

The current study is not without limitations. First, the sample sizes for the PD and stroke groups were significantly less than those of the MS and control groups. This was managed by excluding the stroke group from the main analysis as well as making the proper statistical adjustments for unequal sample sizes. As such, the observed statistical power for the main effects of task and group were within acceptable ranges. Second, the sample consisted primarily of individuals utilizing no assistance or unilateral walking aids. Therefore, it is possible that the results are not generalizable to individuals in the clinical populations who are at more advanced stages of their respective diseases.

4.5 Conclusions

Overall, it was observed that tasks requiring greater amounts of dynamic stability also had greater associated attentional costs. This experiment was novel in that it considered both rhythmic movement and dynamic stability in relative isolation (e.g. cycling and leaning) as well as in combination (e.g. walking). The clinical population samples displayed greater average PRTs compared to healthy controls. Interestingly, across all participants, the greatest predictors of PRTs were physiological fall risk and self-reported balance confidence. These findings are of great import to the field of cognitive-motor research as they suggest that overall physiological function and perceived abilities, rather than disease specific mechanisms, are contributing to the attentional costs associated with movement. Moreover, this investigation was one of the first to directly test the application of the attention capacity model to CMI related tasks. The findings point towards this model being insufficient at describing complex DTCs.

Chapter 5: Task Prioritization and Cognitive-Motor Interaction

5.1 Introduction

5.1.1 Instructional Constraints and Dual Tasking

Often overlooked in cognitive-motor interference (CMI) research is the influence that task instructions may have on participant performance. For example, offering vague instructions such as "walk and complete a given cognitive task" with no indication as to which task to prioritize may provide a more ecologically valid performance of simultaneous tasks. This is compared to testing instructions which may provide participant with a directed task focus such as asking participants to walk "as quickly as possible" or "respond as accurately as possible" during dual task conditions. These instructions where some prioritization is implied may cause an atypical modification of task completion that would not have been observed without the detailed task parameters.

As outlined by Plummer and colleagues there are a total of nine possible performance outcomes when examining dual task situations (Table 7) (Plummer, Eskes et al. 2013). These outcomes include facilitations and/or declines in one or both of the tested domains as well as no changes in performance from single task to dual task scenarios. Allowing participants to organically complete dual task trials without rigid task constraints thus permits for an accurate placement of each individual on the dual task outcome spectrum. Following these placements onto the performance spectrum, researchers could then gain insight into the factors that led an individual to complete the tasks in the manner they did. One such method to gain a deeper understanding of dual tasking is to utilize task constraint influences in an attempt to influence participants to behave in a certain way and then compare those results to the participants' self-selected performance. Consequently, researchers could then make improved inferences on the mechanisms behind observed behaviors and more accurately hypothesize on the extension of observations from the lab setting to the real world.

Table 7: Dual Task Outcome Spectrum

	Cognitive Performance		
Motor Performance	No Change	Improved	Worsened
No Change	No DTC	Cognitive Facilitation	Motor-related cognitive interference
Improved	Motor Facilitation	Mutual Facilitation	Motor-priority trade-off
Worsened	Cognitive-related motor interference	Cognitive priority trade-off	Mutual Interference

Note: Table adapted from Plummer et al 2013

5.1.2 Utilizing Explicit Prioritization

Despite being a possible confounder of CMI studies, relatively few articles have specifically examined the possible effect of prioritization bias on observed results. As previously stated, this is imperative if opinions and recommendations are to be drawn from data that do not contain predispositions to task instruction. One method from which to analyze prioritization is through the utilization of very specific task instructions and a randomization of conditions. That is, asking participants to complete the tasks first in isolation to obtain a measure of baseline performance. Following that, participants complete the tasks concurrently with no indication as to which should be prioritized. Then, in a randomized fashion subjects can be asked to dual task while focusing on (i.e. trying to perform at baseline levels) either the motor or cognitive task. This design enables an analysis to determine if the no prioritization condition more closely mimics a strategy that emphasizes gait or cognitive maintenance or possibly one of mutual decline or facilitation.

Two studies have utilized this method of forced prioritization during walking with a concurrent cognitive challenge as a function of aging (Verghese, Kuslansky et al. 2007; Yogev-Seligmann, Rotem-Galili et al. 2010). Both studies found significant effects of altering prioritization including a more prominent effect on walking compared to cognition. Verghese et al observed that older adults slowed down more when asked to focus primarily on the cognitive task compared to when asked to dedicate equal attention to the tasks (Verghese, Kuslansky et al. 2007). This result suggests that in the standard dual task situations these participants dedicated more resources to maintaining normal gait compared to the cognitive prioritization condition where gait speed was further reduced to complete the cognitive task. Yogev-Seligmann and colleagues found similar results (Yogev-Seligmann, Rotem-Galili et al. 2010). In a sample of both young and old adults it was observed that younger adults possessed more flexibility to adjust gait speed to the given prioritization instructions compared to older individuals. Moreover, when compared to the prioritization conditions, gait speeds in the non-prioritized condition more closely represented those observed during cognitive priority conditions in both groups.

Multiple inferences can be drawn from these observations. Firstly, there is a potential reduction of mental flexibility associated with the aging process that accounts for differences observed between young and old adults to change gait under specific instruction. Second, the results suggest that individuals without neurological impairments may be more likely to prioritize the cognitive task when not given explicit instructions for completing a dual task.

To date, few studies have looked directly at the effect of rigid task constraints on dual tasking in populations with neurological dysfunction such as MS, PD and stroke. Predominantly the prioritization work in individuals with neurological pathologies has been completed in individuals with PD and yielded mixed results. In one such study, Kelly and colleagues observed that individuals with PD were able to manipulate their gait speed to match prioritization instructions (Kelly, Eusterbrock et al. 2012). Contrarily, inferences have been made regarding the strategies in these populations from general CMI studies. For example, based on previous reports Yogev-Seligmann and colleagues as well as Bloem and colleagues proposed that individuals with PD commonly instituted a posture second strategy based on DTCs being lower in the cognitive domain compared to the motor domain (Bloem, Grimbergen et al. 2006; Yogev-Seligmann, Hausdorff et al. 2012).

There are pitfalls, however, associated with the analysis of CMI studies that didn’t include different prioritization strategies as they commonly utilize a wide range of instructions and/or concurrent cognitive tasks. Thus, it is possible that the interpretation of reduced DTCs in one domain may be related to the difficulty of the two tasks being performed and not indicative of a distinct prioritization strategy.

5.1.3 Prioritization Strategies and Theoretical Frameworks

The common theoretical frameworks utilized to describe CMI are the attentional capacity model, bottleneck model, and the self-awareness framework. In regards to prioritization, each model could technically account for explicit prioritization by the individual however each would do so through a distinct mechanism. Under the attentional capacity and bottleneck models it would be assumed that participants would achieve prioritization by having the cognitive flexibility to either dedicate more available resources to one task compared to the other or prioritize the processing of a particular task respectively. It has been previously suggested that cognitive flexibility is fundamental to determining which task is given priority. That is, in a sample of older adults performance on the trail making test (TMT) was related to the outcomes of a complex dual tasking scenario (walking while performing serial 7s) (Hobert, Niebler et al. 2011). Results of the study displayed that individuals with reduced TMT scores prioritized the cognitive task at the expense of the walking task. These results are of interest as it has previously been shown that older fallers and individuals with PD also tend to prioritize performance of the cognitive task over the gait task (Yogev-Seligmann, Hausdorff et al. 2012). These results are commonly attributed to cognitive deficits in these samples leading to an inappropriate allocation of attention. Having a tendency to provide more focus towards the cognitive domain while dual tasking has been labeled as the posture second approach. When comparing dual task costs (DTCs), a posture second approach is indicated by the DTCs of cognition being less than the DTCs of the motor task. The counter to the posture second approach is one in which DTCs of the motor domain are less than those of the cognitive domain and is termed posture first.

An alternative to the cognitive resource frameworks of dual tasking is the self-awareness framework (Yogev-Seligmann, Hausdorff et al. 2012). This framework suggests that an individual prioritizes tasks based on the assessment of their own ability as well as task and environmental constraints. This is often described through two parameters: postural reserve and hazard estimation. Postural reserve is indicative of an individuals’ ability to maintain balance in response to postural threats. From a motor behavior perspective, these can be thought of as a range of parameters from muscle strength and coordination to sensory feedback integration. The second parameter highlighted in the self-awareness framework is hazard estimation. Hazard estimation encompasses an individual's ability to both process the risks associated with a task as well as choose a prioritization based on an assessment of their own abilities. It stands then that differences in hazard estimate are primarily suggested as a manifestation of variances in cognitive function. Based on these two functional categories arguments for prioritization of one task over the other under the self-awareness framework can become much more nuanced than simple cognitive flexibility. That is participants may wish to prioritize a particular task while dual tasking but lack the postural reserve and/or hazard estimate to properly carry out the prioritization. This has implications for safety when it leads to incorrect prioritization during performance in varied environmental conditions based on an inaccurate assessment of one's own ability.

5.1.4 Purpose

The purpose of this experiment was twofold. First, it aimed to look at how differences in the individual (e.g. healthy vs. clinical populations) affected dual task performance under specific task instructions. Additionally, we aimed to determine if cognitive and/or motor function are related to the choice of a particular prioritization strategy. Based on previous results it was hypothesized that individuals with neurological dysfunction would adopt a posture second strategy based on the common cognitive and motor declines associated with these ailments. Furthermore, it was hypothesized that the observed placement and indicative prioritization strategy of individuals on the dual task spectrum would be related to measures of mobility, cognition, and self-awareness (e.g. balance confidence). Overall, the results of this experiment provide an analysis of the applicability of the behavioral prioritization framework in regards to explaining DTCs of walking.

5.2 Methods

5.2.1 Design

The study was performed as a cross-sectional investigation. Participants were asked to come to the laboratory for a single one-hour assessment. In addition to walking while thinking tasks, measures of demographics, mobility, and cognition were also collected.

5.2.2 Participants

A total of 70 participants, took part in this study. This included 20 individuals with MS, 10 with PD, 6 with chronic stroke (i.e. >6 months since injury) and 34 healthy controls. Recruitment took place through a combination of informational flyers, online advertisements and local newsletters. Additionally, we recruited individuals from the Motor Control Research Laboratory participant database. Finally, PD and stroke participants were also recruited through informational visits to local support groups (4 PD and 1 Stroke).

Inclusion criteria for the patient groups included the following aspects: physician's confirmed diagnosis; the ability to walk without bilateral support; self-reported gait impairment and; self-report of attentional/multi-tasking difficulties. Patient groups were matched based on scores from the upper and lower limb disability subsections of the Guy's neurological disability scale (Sharrack and Hughes 1999). Guy's neurological disability scale was originally developed for use in individuals with MS but permits an accurate and simple analysis of function (e.g. assistive device use), which is applicable to the included neurological populations. Inclusion criteria for the control group was having no diagnosis of a neurological disease and no self-reported walking issues (e.g. orthopedic problems). Control participants were recruited such that their ages fell within the ranges of the recruited patient samples. Additionally, all participants (i.e. controls and clinical populations) were required to score above a set cutoff point of 20 on the modified telephone interview for cognitive status TICS-M (de Jager, Budge et al. 2003).

5.2.3 Procedures

All procedures were approved by the University of Illinois Institutional Review Board and participants completed written informed consent upon arrival to the research laboratory. Before completing the walking tasks, participants provided demographic information (e.g. age, gender, disease duration) and completed cognitive testing. The cognitive tests consisted of a two global measures of cognition. These included the trail making test (Reitan 1958) and the symbol digit modalities test (Smith 2002).

The trail making test (TMT) is a neurocognitive test of visual attention and task switching (Tombaugh 2004). It consists of two parts (A & B) which require participants to connect dots of sequential numbers and/or letters in a specific order as fast as possible. The SDMT requires participants to match numbers to a provided set of symbols based on their pairing in a response key. The SDMT has been suggested as a measure of cognitive processing speed (Sheridan, Fitzgerald et al. 2006). Further, it has been utilized in both healthy and clinical populations.

A serial 7 subtraction task was chosen as the cognitive test to be utilized during dual tasking. Before any of the walking and talking trials were conducted, the subtraction task was performed in isolation with the participant seated in a chair. They were read the following standardized instructions: “For this task we are going to ask you to perform some subtractions. I will give you a number and we want you to start by repeating that number and then subtract 7 from it. Continue to subtract 7 from your response and tell us your answers out loud.” An example of the task was given by the administrator and then participants completed two practice trials themselves. After the practice trials, participants were provided with a new number and performed the serial subtraction task for ten seconds. Serial 7s were chosen as the task difficulty remains relatively constant both within and between trials.

For the walking task, participants completed 8 walking trials over a 25ft course (See Table 8). For the first two trials, participants were asked to walk at their "normal, comfortable pace." These two walking trials served as the baseline (single task) condition of walking for use in the calculation of dual task costs. Following the initial walks performed in the absence of a cognitive challenge, participants were asked to walk and think under three sets of specific task instructions. These task instructions emphasized equal prioritization, gait prioritization and cognitive prioritization respectively.

Table 8: Walking conditions and testing orders.

Testing Condition:	Normal Pace	No Prioritization Dual Task	Gait Prioritization Dual Task	Cognitive Prioritization Dual Task
Completion Order:	First	Second	Randomized	

Note: Each testing condition consisted of two successive walking trials.

For the no prioritization dual task trials, participants were simply instructed to "walk and perform the serial subtraction task from the given number." For gait prioritization trials, participants were instructed to "walk and perform the subtraction task with your primary focus on maintaining your normal walking pace." Finally, for the cognitive prioritization task participants were instructed to "walk and subtract with your primary focus on getting all of your subtractions correct." These instructions varied from those previously utilized to examine task prioritization in dual task situations (Verghese, Kuslansky et al. 2007; Kelly, Janke et al. 2010; Yogev-Seligmann, Rotem-Galili et al. 2010). That is, rather than ask participants to focus on a task as if they were doing it alone (possibly negating the importance of still attempting to perform both tasks) the current instructions emphasized the necessity to dual task with shifted focus. The ordering for the 6 dual task trials consisted of the two no prioritization trials being performed immediately after single task walking and then followed by the trials for the prioritized conditions being performed in a randomized sequence.

5.2.4 Outcome Measures

The primary outcomes for the experiment were DTCs of gait and cognition across the three dual tasking conditions. DTC of gait was calculated as the percentage change of walking time from single task to dual task conditions. In this computation, positive DTCs are indicative of reducing gait speed and therefore requiring longer to cover the 25ft. compared to single task performance. DTCs of cognition were calculated as percentage changes in correct subtraction response frequency from single task (seated) trials to dual task trials. Correct response rate provides a measure that encompasses both speed and accuracy of the cognitive task (Etemadi 2016). Once again, calculations were structured such that positive DTCs of cognition represented a decrease in correct response rate on the subtraction task during dual tasking. The use of DTCs serves to normalize the data by limiting the influence of baseline performance differences in walking and cognitive abilities between participants.

Secondary measures included those of cognition, fall risk (e.g. physiological function), demographics and balance confidence. The difference in time to complete part B (alternate connecting numbers and letters) and part A (connecting numbers) represented the primary outcome score for the TMT. This method of scoring the TMT decreases the influence of variability between participants (e.g. upper limb function) by having subjects act as their own controls under the testing design assumption that part B represents a more difficult cognitive challenge (Drane, Yuspeh et al. 2002). Performance on the TMT has previously been linked to dual task performance in a sample of older adults (Hobert, Niebler et al. 2011); however, the relations between TMT and dual task performance are unclear in individuals with neurological impairment. Performance on the SDMT was quantified as the total number of correct responses over the 90 second trial.

Physiological fall risk was determined by the short form of the physiological profile assessment (PPA). The PPA is a validated tool to assess physiological function related to fall risk by combining measures of vision, proprioception, lower-limb strength, postural sway, and cognitive function (Lord, Menz et al. 2003). It is utilized as a global score of motor impairment and is predictive of future fall risk in persons with MS, PD and stroke (Lord, Delbaere et al. 2015). The vision task has participants identify shapes with varying levels of contrast. The reaction time task requires participants to press a button as quickly as possible following a visual stimulus (i.e. a light turning on). During the proprioception task, participants were asked to match the knee extension positions of each leg with their eyes closed while seated. The leg strength test required participants to push out against a strap placed around the ankle while seated. The strap was connected to a simple force gauge. Finally, participants completed a balance test standing on a piece of foam (i.e. a compliant surface) with eyes open for 30s.

All participants completed a series of questionnaires. These included information regarding age, gender, education, disease/injury type and disease duration. Participants also completed the Falls Efficacy Scale International (FES-I) (Yardley, Beyer et al. 2005). This measure provides insight into an individual’s perception of balance ability during various activities of daily life.

5.2.5 Data Analysis

All statistics were performed in SPSS version 22.0 (IBM, Inc., Armonk, NY). Descriptive statistics (mean ± standard deviation) were calculated for all of the demographic and spatiotemporal gait parameters of interest. One-way analysis of variance tests were used to compare the average age and physiological fall risk of the groups.

Two 3 x 3 repeated-measures analysis of variance tests were conducted to examine the effects of group (MS vs. PD vs. Control) and conditions (No Prioritization vs. Gait Prioritization vs. Cognitive Prioritization) on observed DTCs of gait and cognition. The level of significance was set at $p \leq 0.05$ and Sidak corrections were utilized for multiple comparisons.

To investigate prioritization strategies, the proportion of participants in each group were determined based on the dual task outcomes identified in Table 7. We then considered changes to these proportions across the three prioritization conditions. This permitted inferences to be drawn on natural prioritization tendencies (no prioritization condition) and the influence of task constraints on those tendencies (gait and cognitive prioritization conditions).

To examine if different prioritization strategies were related to differences in physiology, cognition and balance confidence a correlation analysis was performed. Spearman correlations were utilized in order to account for any mild outliers or non-linearity in the data. The primary outcomes included in this analysis were DTCs of gait and balance, TMT, SDMT, PPA and balance confidence as measured by the falls-efficacy scale international.

Based on the low sample size and high variability within the outcomes, the stroke group was excluded from the main analyses of this experiment. Data relative to their performance is presented as a pilot analysis separately in Appendix B.

5.3 Results

5.3.1 Participant Characteristics

Sixty-five participants were included in the primary analyses for the study. The average age of the healthy controls (N = 34) was 63.6 ± 8.2yrs compared to 58.1 ± 9.1yrs for the MS group (N=20) and 62.4 ± 8.5 for the PD group (N=10). A one-way analysis of variance revealed no significant difference in age across the groups ($F = 2.6$, $p = 0.08$). The gender breakdown was 20F/14M for the control group, 11F/9M for the MS group and 5F/5M for the PD group.

In regards to the clinical populations, average disease duration was 17.1 ± 8.2yrs for the MS group and 6.8 ± 5.7yrs for the PD group. For MS specifically, the self-reported expanded disability status scale score had a median value of 3.75 and interquartile range of 2.6-5.9. None of the PD participants utilized assistive devices while 6 of the MS participants utilized unilateral support.

Physiological fall risk scores for the group averaged 0.47 ± 0.83 for the control group, 1.97 ± 1.19 for the MS group and 1.73 ± 1.16 for the PD group. The comparison of means showed that the MS and PD group did not differ ($p = 0.99$) from each other in terms of fall risk and both groups had significantly ($p < .001$ and $p = .003$ respectively) elevated fall risks compared to the control participants. Additionally, the clinical groups had significantly reduced balance confidence compared to controls (MS v. Control $p = 0.001$, PD vs. Control $p < 0.001$) as evidenced by higher scores on the FES-I. No differences in self-reported balance confidence were observed between the MS and PD groups ($p = 0.69$).

One-way analyses of variance on the cognitive function variables revealed there were no group differences in either executive function as measured by the TMT ($p = 0.41$) or cognitive processing speed as measured by the SDMT (*p* = 0.06). TMT differences averaged 26.85 ± 17.57sec for the healthy controls, 26.60 ± 12.29 for the MS group and 34.54 ± 22.07 for the PD sample. Values for the controls, MS and PD groups on the SDMT were 55.4 ± 8.1, 55.2 ± 13.6 and 46.5 ± 10.9 respectively.

5.3.2 Dual Task Costs

Table 9 displays the mean ± standard deviation of DTCs of gait for the three groups for the three prioritization conditions. Additionally, Figure 13 presents these results visually. The 3x3 ANOVA looking at group and task effects revealed a significant effect of task instructions ($F = 23.0$, $p < 0.001$) and of group ($F = 4.3$, p = 0.017). No significant group by task interaction was observed ($F = 0.41$, $p = 0.765$). Post hoc analyses of group differences showed significantly lower DTCs of gait for the control group compared to the MS group ($p = 0.021$). No significant differences were observed between the PD group and controls ($p = 0.99$) or the PD group and MS group ($p = 0.12$).

Further examination of the task effect showed significant differences in DTCs of gait across all three tasks. DTCs were lowest in the gait prioritization task (6.6 ± 1.4%), followed by the no prioritization task (11.5 ± 1.3%) and then finally the cognitive prioritization task (20.1 ± 2.4%). These average DTCs of gait were significantly different between all three task conditions (p’s < 0.006).

Table 9: DTCs of Gait Across Group and Task

Group	No Prio	Gait Prio	Cognitive Prio
Control	8.6 (1.5)	4.6 (1.7)	17.7 (2.9)
MS	15.1 (2.0)	11.3 (2.2)	26.9 (3.9)
PD	10.7 (2.8)	3.9 (3.1)	15.8 (5.5)

Note: All values represent % decline in walking speed, Mean (Std, Error)

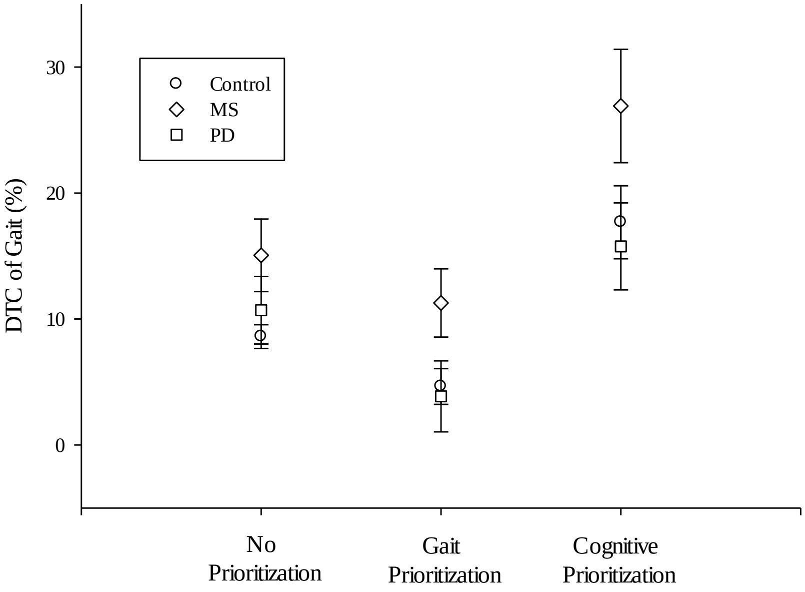


Figure 13: DTCs of Gait Across Group and Task

Table 10 and figure 14 outline the data regarding DTCs of cognition between the groups across the three dual tasking conditions. The 3x3 ANOVA for these measures identified only a significant effect of task (F = 8.0, p < 0.001) on observed DTCs of cognition. This task effect was based on the average DTCs of cognition being significantly lower during the no prioritization (Mean ± Std. Error: -26.9 ± 7.2%) and gait prioritization (-23.8 ± 5.6) conditions compared to the cognitive prioritization condition (-6.2 ± 5.0). These averages suggest that in all three conditions, cognitive facilitation was taking place with individuals having increased cognitive performance as indicated by correct responses per second during walking conditions compared to sitting.

Table 10: DTCs of Cognition Across Group and Task

Group	No Prioritization	Gait Prioritization	Cognitive Prioritization
Control	-26.7 (8.8)	-24.3 (6.8)	-6.6 (6.1)
MS	-28.1 (11.4)	-22.3 (8.8)	-4.2 (7.9)
PD	-25.9 (16.2)	-24.9 (12.5)	-7.9 (11.2)

Note: All values represent % decline in correct response rate, Mean (Std. Error)

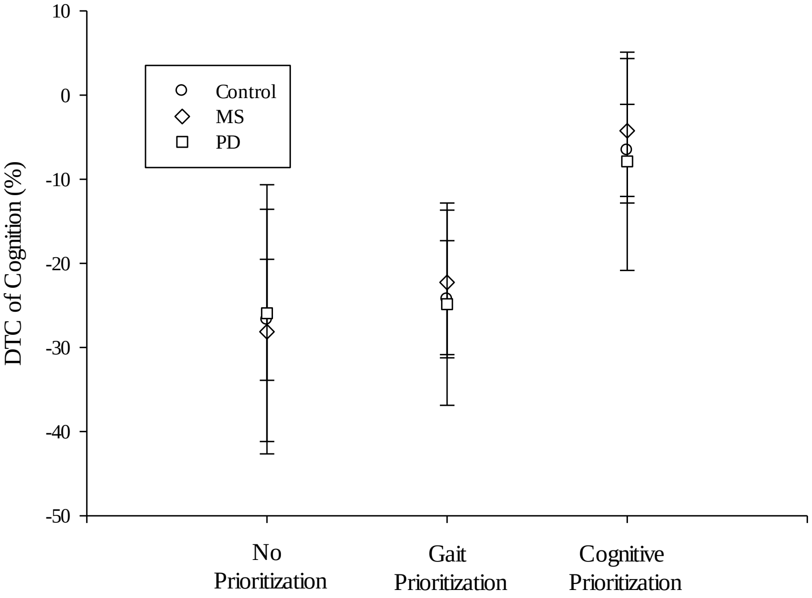


Figure 14: DTCs of Cognition Across Group and Task

5.3.3 CMI Spectrum Outcomes

Table 11 outlines participant performance on the three dual tasking conditions based on how the observed DTCs would fall on the CMI spectrum proposed by Plummer and colleagues (Plummer, Eskes et al. 2013). During the no prioritization condition, the most common outcome across groups was that of a cognitive priority tradeoff. That is, participants experienced slowing of gait while dual tasking accompanied by either no change on or improvement on the cognitive task. During the gait prioritization condition, an increase in participants experiencing mutual interference and mutual facilitation is observed. Finally, during the cognitive prioritization task, individuals predominantly shift back towards the mutual interference and cognitive priority tradeoff areas of the CMI spectrum.

For each prioritization condition, the relationship between group and CMI outcomes were examined using Fisher’s exact test. In no condition was there statistically significant evidence that the groups differed in regards to proportion of individuals in each of the CMI outcome categories.

Table 11: Dual Task Spectrum Values

	No Prioritization				Gait Prioritization				Cognitive Prioritization			
	MI	CP	GP	MF	MI	CP	GP	MF	MI	CP	GP	MF
Control	8 (23.5)	24 (70.6)	0 (0.0)	2 (5.9)	11 (32.4)	15 (44.1)	0 (0.0)	8 (23.5)	12 (35.3)	17 (50.0)	1 (2.9)	4 (11.8)
MS	7 (38.1)	10 (47.6)	1 (4.8)	2 (9.5)	8 (42.9)	10 (47.6)	1 (4.8)	1 (4.8)	10 (52.4)	10 (47.6)	0 (0.0)	0 (0.0)
PD	3 (30.0)	7 (70.0)	0 (0.0)	0 (0.0)	3 (30.0)	3 (30.0)	0 (0.0)	4 (40.0)	5 (50.0)	5 (50.0)	0 (0.0)	0 (0.0)

Note: All values are N (% of sample); MI: Mutual Interference, CP: Cognitive Priority Tradeoff, GP: Gait Priority Tradeoff, MF: Mutual Facilitation

5.3.4 Correlates of Dual Task Cost

In order to investigate the proposed mechanisms that may be related to observed DTC patterns during the no prioritization condition, a Spearman correlation analysis was performed. The primary variables were the DTCs of gait and cognition, PPA, TMT, SDMT and FES-I. Table 12 displays the resulting correlation coefficients. Four significant correlations were observed between the included parameters and DTCs during the no prioritization condition. These included relationships between FES-I and DTCs of walking and cognition as well as relationships between the DTCs of cognition with both PPA and SDMT scores. Additionally, balance confidence was also significantly correlated to DTC of cognition in the gait prioritization condition ($\rho = 0.316$, $p = 0.012$).

Table 12: Correlation Coefficients During the No Prioritization Condition

	NP DTC Gait	NP DTC Cognition
PPA	0.196	**0.329**
TMT	-0.026	0.187
SDMT	-0.096	**-0.348**
FES-I	**0.309**	**0.253**

Note: NP = No Prioritization Condition

5.4 Discussion

The primary goal of this investigation was to examine the impact of forced task prioritization on CMI tendencies in healthy participants and individuals with neurological disease/injury. It was hypothesized based on previous observational reports that the clinical populations would adapt a posture second approach (i.e. emphasizing cognitive task performance) and healthy controls would adopt a posture first approach (i.e. attempting to maintain gait performance at single task levels). This hypothesis was partially supported, as all groups predominantly adopted a posture second approach. The secondary hypothesis of this study was that factors such as overall physiological function, cognitive status, and self-perceived balance confidence would be related to observed DTCs. This hypothesis was confirmed as all three domains were related to DTCs of gait and/or cognition in the no prioritization condition. Overall, the results of this study provide valuable data for understanding prioritization strategies in a broad sample of individuals.

Perhaps the finding of most importance from the current analysis was evidence of the utilization of a posture second strategy throughout the total sample during the no prioritization condition. It was assumed that this dual tasking condition would provide the most unbiased view of dual tasking as it placed the minimum amount of task constraints on the participants. Adoption of the posture second strategy presumes that participants generally sacrificed gait performance (slowed down) in order to shift attention to maintaining or improving their cognitive performance. During the no prioritization condition 64% of the total sample (70.6% controls, 50.0% MS, 70% PD) adopted this strategy. Of the four CMI spectrum outcomes observed, focusing on the cognitive task represented the greatest proportion of individuals in each group. No differences in proportion were observed across groups ($p = 0.60$). This result has significant importance as it suggests that individuals with possible gait and balance issues naturally tend to select a strategy that further alters their gait. It is generally assumed that observing slowing of gait during dual task conditions represents a safety mechanism; however, further evidence is required to make firm conclusions on the accuracy of this assumption.

The inclusion of the two forced prioritization conditions enhanced the current analysis by permitting insight into the issue of cognitive flexibility. That is, we were able to see if participants have the capacity to alter their dual task performance when instructed or if there are mechanisms at play preventing this shifting of attention. In line with previous reports (Verghese, Kuslansky et al. 2007), the current sample displayed significantly different dual task costs under the various prioritization instructions. Specifically, participants had the lowest dual task costs during the gait prioritization conditions and the greatest DTCs during cognitive prioritization. For all groups, the DTCs observed during the no prioritization conditions fell on average between those observed for the forced prioritization conditions (see Figure 13). Overall, these results suggest that individuals with neurological impairment and healthy controls have the ability to alter their dual task performances when instructed.

Interestingly, the results for the DTCs of cognition do not follow the same trend as those observed for gait. In general, cognitive facilitation was maximized during the no prioritization conditions and this facilitation lessened during the cognitive prioritization conditions. Deeper analysis suggests this was an artifact of the instructions placing emphasis on subtraction accuracy. In doing this, participants significantly decreased response frequency in order to maximize accuracy, which translated into decreased correct utterance rates (see figure 14). None the less, the results still suggest that task flexibility existed in the cognitive domain as well. Taken together, these results indicate that dual task performance is not strictly mechanistic and can be influenced by task constraints or adapted based on the intention of the individual.

In an effort to analyze factors that may have influenced individuals to select a certain dual tasking strategy, a correlation analysis was carried out. This analysis included a measure of overall physiological function (PPA), two measures of cognition (TMT and SDMT) and a self-reported measure of balance confidence (FES-I). The results showed that balance confidence was related to both DTCs of gait and cognition. Individuals who reported having an increased fear of falling tended to slow down more during dual tasking as well as decrease their performance on the cognitive task. Looking solely at DTCs of cognition, both fall risk and cognitive processing speed were significantly correlated. Individuals with increased fall risk tended to decrease their performance on the cognitive task during dual task conditions. Individuals who had greater cognitive processing speed tended to have reduced DTCs of cognition (i.e. higher correct response rates while dual tasking).

Taken together, these results are congruent with the self-awareness prioritization model proposed by Yogev-Seligmann and colleagues (Yogev-Seligmann, Hausdorff et al. 2012). Physiological fall risk and balance confidence offer two particular mechanisms that could influence dual tasking behavior. Coincidently, these structures can be related to those postural reserve and hazard estimate included in the self-awareness model. If we interpret fall risk as an index of postural reserve and balance confidence as an index of hazard estimate, the current data suggest that individuals confronted with a dual task situation alter their behavior in accordance with these parameters. That is, those individuals who are aware of their balance deficits and physiological limitations tend to have worse performance in the cognitive domain during dual tasking. While a firm conclusion cannot be drawn from the current data, these results are indicative of a strategy where the individual is placing more emphasis on maintaining gait and balance rather than shifting attention to the added cognitive challenge.

The current study is not without limitation. It could be argued that limiting the instruction given for single task performance yielded inaccurate task performance during those outcomes. It should be noted that the methodology utilized to limit task bias during single task performance and the no prioritization condition was carefully chosen in an effort to prevent potential biases that may have confounded previous studies examining prioritization strategies. First, we avoided the inflation of single task performances by having participants perform the tasks absent of instructions such as “walk as quickly as possible” or “subtract as quickly as you can.” By doing this, there was a reduced likelihood that dual task performances would be skewed by possible ceiling or floor effects. For example, since single task performance of gait was conducted at self-selected pace rather than fastest pace, it is conceivable that individuals would still have the motor capacity to alter their gait in either direction during dual task conditions (i.e. walk faster or slower than the single task pace). It has previously been argued that possible ceiling effects on motor performance could negate the utility of interpreting DTCs during dual task scenarios (Wajda, Motl et al. 2014).

5.5 Conclusions

Overall, the results of this study offer valuable insights into the potential influence of a behavioral component on dual task performance. Interestingly, in the absence of any rigid task instructions participants generally adopted a posture second approach. It is possible, however, that this behavior is attenuated by the individual’s self-awareness of balance function and overall physiological function. Indeed, it was observed that those individuals who were most likely to perform poorly on the cognitive aspect of dual tasking were also those at the greatest risk of falling and with the lowest balance confidence.

These results could be potentially useful in future studies of CMI. Researchers should note the potential impact of physiological function as well as balance self-efficacy factors when designing their methodologies. Similar to the results presented in Chapter 4, it is possible that the current results suggest that analyzing the symptoms may be more important when it comes to dual tasking rather than the mechanisms that caused the symptoms (i.e. disease type). Finally, the observation that DTCs were flexible in response to specific task instructions could be beneficial for intervention programs. These highlight that possible training programs could utilize techniques such as variable prioritization to enhance dual task performance, and it would be expected that participants would have the ability to match the training demands.

Chapter 6: Conclusions

The current study leveraged a classic motor control theory in order to design three experiments aimed at determining the underlying mechanisms associated with cognitive-motor interaction. The three experiments utilized modulations of the individual (i.e. including clinical populations), task (e.g. altering motor requirements or task instructions) and environment (e.g. walking over obstacles) to gain a multifactorial view of a range of dual task outcomes. The primary result of the present work was a direct comparison of the attentional capacity model, a neuro-resource based framework of dual tasking, compared to the behaviorally based self-awareness prioritization model. Examining the results as a whole suggests that the capacity model in and of itself may not fully describe the changes to gait and balance during concurrent performance. Contrarily, measures similar to the hazard estimate and postural reserve constructs of the prioritization model commonly displayed congruence with the observed CMI outcomes. Additionally, these relationships were primarily present across all groups, healthy and clinical samples, indicating that the level of physiological and/or cognitive impairment in an individual may be more pertinent to dual task costs than the disease or injury that is the root of those impairments.

The current results have worthwhile clinical import. First, they suggest that studies of CMI should consider utilizing methodology that limits task bias in order to get the most valid understanding of prioritization as possible. Moreover, it was determined in the current analysis that in total, the participants tended to adopt a posture second approach for simple motor conditions and later shift this focus towards posture as task difficulty increased. This behavior suggests that cognitive flexibility is present in both the healthy and clinical populations and ultimately could be a target for intervention if possibly unsafe dual task strategies are observed.

Additionally, it is of note that overall measures of physiological fall risk, cognition and balance confidence were commonly related to observed DTCs. Future longitudinal work should address these factors and determine the possible mediating role they play in CMI. As these factors are modifiable, they are also potential rehabilitation targets for the improvement of dual task ability.

Ultimately, the current results serve to provide exciting new evidence in regards to the theoretical underpinnings of CMI. Future work is warranted to further confirm and extend these findings as dual tasking represents an inherent part of our daily lives. It is recommended that the research in this field continue to progress towards methodologies that more closely approximate the complex scenarios seen in the community to better predict adverse dual task outcomes such as falls.

REFERENCES

Abernethy, B., A. Hanna, et al. (2002). "The attentional demands of preferred and non-preferred gait patterns." Gait & posture **15**(3): 256-265.

Al-Yahya, E., H. Dawes, et al. (2011). "Cognitive motor interference while walking: a systematic review and meta-analysis." Neuroscience & Biobehavioral Reviews **35**(3): 715-728.

Allali, G., M. Laidet, et al. (2014). "Walking while talking in patients with multiple sclerosis: The impact of specific cognitive loads." Neurophysiologie Clinique/Clinical Neurophysiology **44**(1): 87-93.

Baddeley, A., S. Della Sala, et al. (1997). "Testing central executive functioning with a pencil-and-paper test." Methodology of frontal and executive function: 59.

Beauchet, O., V. Dubost, et al. (2005). "Dual-task-related gait changes in the elderly: does the type of cognitive task matter?" Journal of Motor Behavior **37**(4): 259.

Beer, R. D. (2009). Beyond control: The dynamics of brain-body-environment interaction in motor systems. Progress in Motor Control, Springer**:** 7-24.

Bernstein, N. A. (1967). "The co-ordination and regulation of movements." from http://books.google.com/books?id=F9dqAAAAMAAJ.

Bloem, B. R., Y. A. Grimbergen, et al. (2006). "The "posture second" strategy: a review of wrong priorities in Parkinson's disease." Journal of the Neurological Sciences **248**(1): 196-204.

Blumen, H. M., R. Holtzer, et al. (2014). "Behavioral and neural correlates of imagined walking and walking-while-talking in the elderly." Human Brain Mapping **35**(8): 4090-4104.

Camicioli, R., D. Howieson, et al. (1997). "Talking while walking: the effect of a dual task in aging and Alzheimer's disease." Neurology **48**(4): 955-958.

Cattaneo, D., J. Jonsdottir, et al. (2007). "Effects of balance exercises on people with multiple sclerosis: a pilot study." Clinincal Rehabilitation **21**(9): 771-781.

Cordo, P. and L. M. Nashner (1982). "Properties of postural adjustments associated with rapid arm movements." Journal of Neurophysiology **47**(2): 287-302.

de Jager, C. A., M. M. Budge, et al. (2003). "Utility of TICS-M for the assessment of cognitive function in older adults." International Journal of Geriatric Psychiatry **18**(4): 318-324.

Dennis, A., H. Dawes, et al. (2009). "Fast walking under cognitive-motor interference conditions in chronic stroke." Brain Research **1287**: 104-110.

Drane, D. L., R. L. Yuspeh, et al. (2002). "Demographic characteristics and normative observations for derived-trail making test indices." Cognitive and Behavioral Neurology **15**(1): 39-43.

Etemadi, Y. (2016). "Dual task cost of cognition is related to fall risk in patients with multiple sclerosis: A prospective study." Clinical Rehabilitation: 0269215516637201.

Grillner, S. (1996). "Neural networks for vertebrate locomotion." Scientific American **274**(1): 64-69.

Gunn, H., S. Creanor, et al. (2013). "Risk factors for falls in multiple sclerosis: an observational study." Multiple Sclerosis **19**(14): 1913-1922.

Hackney, M. E. and G. M. Earhart (2009). "The effects of a secondary task on forward and backward walking in Parkinson's disease." Neurorehabilitation and Neural Repair.

Hamilton, F., L. Rochester, et al. (2009). "Walking and talking: an investigation of cognitive—motor dual tasking in multiple sclerosis." Multiple Sclerosis **15**(10): 1215-1227.

Harley, C., R. M. Wilkie, et al. (2009). "Stepping over obstacles: attention demands and aging." Gait & Posture **29**(3): 428-432.

Hausdorff, J., G. Yogev, et al. (2005). "Walking is more like catching than tapping: gait in the elderly as a complex cognitive task." Experimental Brain Research **164**(4): 541-548.

Hoang, P. D., M. H. Cameron, et al. (2014). "Neuropsychological, balance, and mobility risk factors for falls in people with multiple sclerosis: a prospective cohort study." Archives of Physical Medicine and Rehabilitation **95**(3): 480-486.

Hobert, M. A., R. Niebler, et al. (2011). "Poor trail making test performance is directly associated with altered dual task prioritization in the elderly – baseline results from the TREND study." PloS One **6**(11): e27831.

Holtzer, R., J. R. Mahoney, et al. (2011). "fNIRS study of walking and walking while talking in young and old individuals." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences: glr068.

Holtzer, R., C. Wang, et al. (2014). "Performance variance on walking while talking tasks: theory, findings, and clinical implications." Age **36**(1): 373-381.

Jacobs, J. V. and F. B. Horak (2006). "Abnormal proprioceptive-motor integration contributes to hypometric postural responses of subjects with parkinson's disease." Neuroscience **141**(2): 999-1009.

Jankovic, J. (2008). "Parkinson's disease: clinical features and diagnosis." Journal of Neurology, Neurosurgery & Psychiatry **79**(4): 368-376.

Jeannerod, M. and V. Frak (1999). "Mental imaging of motor activity in humans." Current Opinion in Neurobiology **9**(6): 735-739.

Kahneman, D. (1973). Attention and effort. Englewood Cliffs, New Jersey, Prentice-Hall Inc.

Kandel, E. R., J. H. Schwartz, et al. (2000). Principles of neural science 4th ed, McGraw-Hill, New York.

Kelly, V. E., A. J. Eusterbrock, et al. (2011). "A review of dual-task walking deficits in people with Parkinson's disease: motor and cognitive contributions, mechanisms, and clinical implications." Parkinson's Disease **2012**.

Kelly, V. E., A. J. Eusterbrock, et al. (2012). "The effects of instructions on dual-task walking and cognitive task performance in people with Parkinson's disease." Parkinson's Disease **2012**.

Kelly, V. E., A. A. Janke, et al. (2010). "Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults." Experimental Brain Research **207**(1-2): 65-73.

Kelly, V. E., M. A. Schrager, et al. (2008). "Age-Associated Effects of a Concurrent Cognitive Task on Gait Speed and Stability During Narrow-Base Walking." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **63**(12): 1329-1334.

Kim, H.-D. and D. Brunt (2007). "The effect of a dual-task on obstacle crossing in healthy elderly and young adults." Archives of Physical Medicine and Rehabilitation **88**(10): 1309-1313.

Lafargue, G., M. Noël, et al. (2013). "In the elderly, failure to update internal models leads to over-optimistic predictions about upcoming actions." PloS One **8**(1): e51218.

Lajoie, Y., N. Teasdale, et al. (1993). "Attentional demands for static and dynamic equilibrium." Experimental Brain Research **97**(1): 139-144.

Lajoie, Y., N. Teasdale, et al. (1996). "Upright standing and gait: are there changes in attentional requirements related to normal aging?" Experimental Aging Research **22**(2): 185-198.

Learmonth, Y., L. Pilutti, et al. (2015). "Generalised cognitive motor interference in multiple sclerosis." Gait & Posture **42**(1): 96-100.

Learmonth, Y. C., B. M. Sandroff, et al. (2014). "Cognitive motor interference during walking in multiple sclerosis using an alternate letter alphabet task." Archives of Physical Medicine and Rehabilitation 95(8): 1498-1503.

Leone, C., F. Patti, et al. (2014). "Measuring the cost of cognitive-motor dual tasking during walking in multiple sclerosis." Multiple Sclerosis: 1352458514547408.

Liu-Ambrose, T., L. A. Katarynych, et al. (2009). "Dual-task gait performance among community-dwelling senior women: the role of balance confidence and executive functions." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences: glp063.

Lord, S., K. Delbaere, et al. (2015). "Use of a physiological profile to document motor impairment in ageing and in clinical groups." The Journal of Physiology.

Lord, S. R., H. B. Menz, et al. (2003). "A physiological profile approach to falls risk assessment and prevention." Physical Therapy **83**(3): 237-252.

Mazaheri, M., M. Roerdink, et al. (2014). "Attentional costs of visually guided walking: effects of age, executive function and stepping-task demands." Gait & Posture **40**(1): 182-186.

Merchant, H., W. Zarco, et al. (2009). Behavioral and neurophysiological aspects of target interception. Progress in Motor Control, Springer**:** 201-220.

Motl, R. W., J. J. Sosnoff, et al. (2014). "Walking and cognition, but not symptoms, correlate with dual task cost of walking in multiple sclerosis." Gait & Posture **39**(3): 870-874.

Neider, M. B., J. G. Gaspar, et al. (2011). "Walking and talking: dual-task effects on street crossing behavior in older adults." Psychology and Aging **26**(2): 260.

Newell, K. M. (1986). "Constraints on the development of coordination." Motor Development in Children: Aspects of Coordination and Control **34**: 341-360.

Pashler, H. (1994). "Graded capacity-sharing in dual-task interference?" Journal of Experimental Psychology. Human Perception and Performance **20**(2): 330-342.

Plotnik, M., N. Giladi, et al. (2011). "Postural instability and fall risk in Parkinson’s disease: impaired dual tasking, pacing, and bilateral coordination of gait during the “ON” medication state." Experimental Brain Research **210**(3-4): 529-538.

Plummer, P., S. Apple, et al. (2015). "Texting and walking: Effect of environmental setting and task prioritization on dual-task interference in healthy young adults." Gait & Posture **41**(1): 46-51.

Plummer, P., G. Eskes, et al. (2013). "Cognitive-motor interference during functional mobility after stroke: state of the science and implications for future research." Archives of Physical Medicine and Rehabilitation **94**(12): 2565-2574.e2566.

Priest, A. W., K. B. Salamon, et al. (2008). "Age-related differences in dual task walking: a cross sectional study." Journal of Neuroengineering and Rehabilitation **5**(1): 1.

Regnaux, J., D. David, et al. (2005). "Evidence for cognitive processes involved in the control of steady state of walking in healthy subjects and after cerebral damage." Neurorehabilitation and Neural Repair **19**(2): 125-132.

Reitan, R. M. (1958). "Validity of the trail making test as an indicator of organic brain damage." Perceptual and Motor Skills **8**(3): 271-276.

Roeing, K. L., D. A. Wajda, et al. (2015). "Gait termination in individuals with multiple sclerosis." Gait & Posture **42**(3): 335-339.

Ryckewaert, G., M. Luyat, et al. (2015). "Self-perceived and actual ability in the functional reach test in patients with Parkinson's disease." Neuroscience Letters **589**: 181-184.

Schaefer, S., M. Schellenbach, et al. (2015). "Walking in high-risk settings: do older adults still prioritize gait when distracted by a cognitive task?" Experimental Brain Research **233**(1): 79-88.

Schrodt, L. A., V. S. Mercer, et al. (2004). "Characteristics of stepping over an obstacle in community dwelling older adults under dual-task conditions." Gait & Posture **19**(3): 279-287.

Sharrack, B. and R. A. Hughes (1999). "The Guy's Neurological Disability Scale (GNDS): a new disability measure for multiple sclerosis." Multiple Sclerosis **5**(4): 223-233.

Sheridan, L. K., H. E. Fitzgerald, et al. (2006). "Normative symbol digit modalities test performance in a community-based sample." Archives of Clinical Neuropsychology **21**(1): 23-28.

Shumway-Cook, A., M. Woollacott, et al. (1997). "The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **52A**(4): M232-M240.

Shumway-Cook, A. and M. H. Woollacott (2007). Motor control: translating research into clinical practice, Lippincott Williams & Wilkins.

Smith, A. (2002). Symbol digit modalities test, Western Psychological Services.

Sosnoff, J., M. Socie, et al. (2013). "Mobility and cognitive correlates of dual task cost of walking in persons with multiple sclerosis." Disability & Rehabilitation(0): 1-5.

Springer, S., N. Giladi, et al. (2006). "Dual-tasking effects on gait variability: the role of aging, falls, and executive function." Movement Disorders **21**(7): 950-957.

Stelmach, G., H. N. Zelaznik, et al. (1990). "The influence of aging and attentional demands on recovery from postural instability." Aging Clinical and Experimental Research **2**(2): 155-161.

Tombaugh, T. N. (2004). "Trail making test A and B: normative data stratified by age and education." Archives of Clinical Neuropsychology **19**(2): 203-214.

Turvey, M. T. and S. Fonseca (2009). Nature of motor control: perspectives and issues. Progress in Motor Control, Springer**:** 93-123.

Verghese, J., G. Kuslansky, et al. (2007). "Walking while talking: effect of task prioritization in the elderly." Archives of Physical Medicine and Rehabilitation **88**(1): 50-53.

Wajda, D. A., Y. Moon, et al. (2015). "Preliminary investigation of gait initiation and falls in multiple sclerosis." Archives of Physical Medicine and Rehabilitation.

Wajda, D. A., R. W. Motl, et al. (2013). "Dual task cost of walking is related to fall risk in persons with multiple sclerosis." Journal of the Neurological Sciences **335**(1-2): 160-163.

Wajda, D. A., R. W. Motl, et al. (2014). "Correlates of dual task cost of standing balance in individuals with multiple sclerosis." Gait & Posture **40**(3): 352-356.

Wajda, D. A., K. L. Roeing, et al. (2015). "The relationship between balance confidence and cognitive motor interference in individuals with multiple sclerosis." Journal of Motor Behavior(ahead-of-print): 1-6.

Wajda, D. A., B. M. Sandroff, et al. (2013). "Effects of walking direction and cognitive challenges on gait in persons with multiple sclerosis." Multiple Sclerosis International **2013**.

Wajda, D. A. and J. J. Sosnoff (2015). "Cognitive-motor interference in multiple sclerosis: a systematic review of evidence, correlates, and consequences." Biomedical Research International **2015**: 8.

Wickens, C. D. (1991). "Processing resources and attention." Multiple-Task Performance: 3-34.

Woollacott, M. and A. Shumway-Cook (2002). "Attention and the control of posture and gait: a review of an emerging area of research." Gait & Posture **16**(1): 1-14.

Yardley, L., N. Beyer, et al. (2005). "Development and initial validation of the falls efficacy scale-international (FES-I)." Age and Ageing **34**(6): 614-619.

Yogev-Seligmann, G., Y. Rotem-Galili, et al. (2010). "How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability." Physical Therapy **90**(2): 177-186.

Yogev-Seligmann, G., J. M. Hausdorff, et al. (2012). "Do we always prioritize balance when walking? Towards an integrated model of task prioritization." Movement Disorders **27**(6): 765-770.

Appendix A: Participant Recruitment

To recruit for this study, several strategies were utilized. The MCRL's database was accessed to recruit individuals with multiple sclerosis. MCRL's project coordinator used the database list to call 28 people with MS. Of the 28 contacts, 24 people with MS were screened and scheduled. Of those 24, 23 were assessed. One dropped out before consenting as she was in a car accident. A portion of data for two participants was lost when a laptop was stolen from an MCRL researcher's personal vehicle.

Since MCRL has done little research for people with Parkinson's disease and stroke, extra measures were utilized to target these specific areas. An advertisement in the University of Illinois Eweek was placed for participants that had suffered a stroke and it yielded one contact. This contact passed the screen and was scheduled. Additionally, a newspaper advertisement was placed in the News Gazette to recruit stroke survivors. That yielded two contacts that were screened and both passed and were assessed. Facebook advertisements were also used. Stroke survivors within a 20 mile radius were targeted for this study. Unfortunately, no contacts were made. Additionally, MCRL reached out to local support groups for stroke survivors, but they did not yield any contacts. Finally, a family member from Cleveland, Ohio who had suffered a stroke was recruited and agreed to participate. In total 5 stroke survivors completed portions of the testing.

To obtain participants with Parkinson's disease, we went to three support groups in the area. From those, we received 15 contacts. Of those 15 contacts, only 9 passed the screener. Five failed to score above the inclusion level on the TICS-M and one contact tore his ACL prior to participating. Another family member from Cleveland. Ohio diagnosed with PD was recruited and agreed to participate. Her inclusion brought the PD sample up to a total of 10 individuals.

The control participants were obtained by accessing the MCRL database as well as using an UIUC Eweek advertisement. From these two avenues, 21 participants ages 45-65 and 23 participants ages 65 and older were contacted, screened and scheduled. Not all of these 44 individuals were included in each experiment as partial data for some of the controls was lost due to the stolen laptop. Exact n values for each experiment are provided in the methodology sections.

Appendix B: Chronic Stroke Pilot Data

Overall, recruitment of the chronic stroke group (i.e. >6 months since injury) yielded 6 participants. This sample included 3 males and 3 females. The average age of the stroke survivors was 61.7yrs. with a standard deviation of 8.5yrs. The time since injury ranged from 1 year to 16 years with an average (std. dev) of 8.0 (6.9) years. Performance on the SDMT was most comparable to the PD groups with an average of 44.3 (9.6) correct responses during the 90 second test. In regards to the trail making test, performance was in line with the control and MS subjects with TMT B-A differences having a mean of 25.2 (12.9) seconds. Finally, in regards to physiological fall risk the stroke group had an average PPA score of 1.02 (0.97) indicating a slightly increased risk for falling. This value fell between those observed for controls (~0.40) and the other clinical populations (~1.75).

Five of the six stroke survivors completed the environmental hazard and CMI study. One participant had opted out due to a fear of falling negotiating the obstacles and narrow walkway. Of the five completers, one individual was excluded from the mean calculations as their average DTCs were an order of magnitude greater than the other participants. Figure 15 A and B displays the DTCs of gait and DTCs of cognition across the environmental challenge conditions. Visual inspection of the data indicates accordance with the observed results from the other groups. That is, DTCs of gait remained generally constant across the four challenge conditions. For the DTCs of cognition, cognitive performance decreases as the task difficulty increases. These trends are also in line with the observed outcomes from the other groups and indicate a strategy where attention is shifted from the cognitive task to prevent any additional declines in motor performance as motor task difficulty increases.

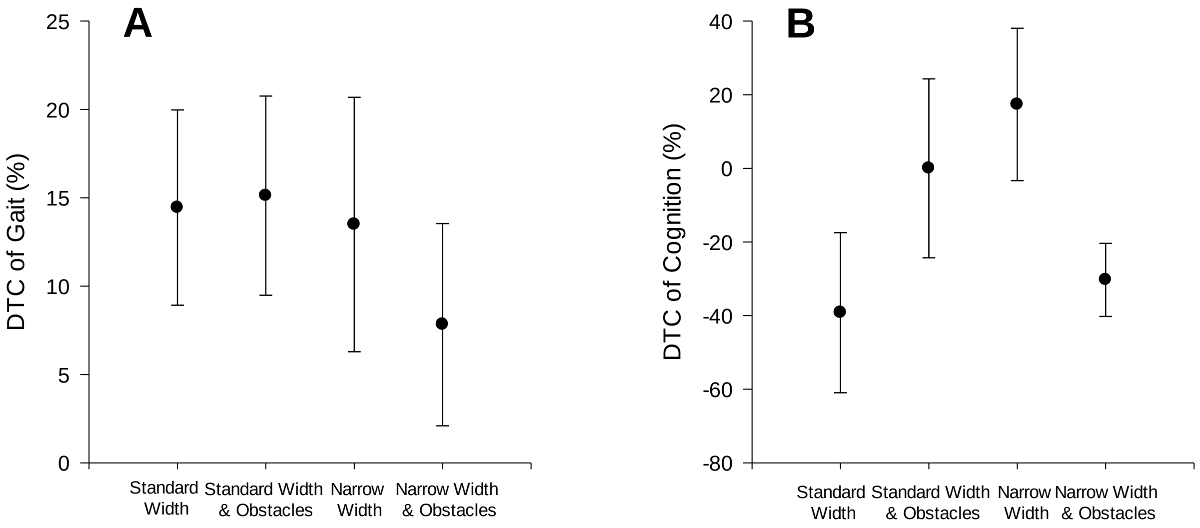


Figure 15: DTCs of Gait and Cognition across Environmental Challenge

Five of the six stroke survivors completed the probe reaction time experiment. For this study, individuals with chronic stroke had PRTs that were similar to those observed from healthy controls. These averages followed the same trend across task as displayed by all groups, that is the tasks requiring dynamic balance control had the greatest PRTs. Figure 16 displays the mean ± standard error for the stroke survivors across each task. The small sample size and high standard errors limited the ability to investigate the impact of PPA and FES-I on observed PRTs for the stroke participants.

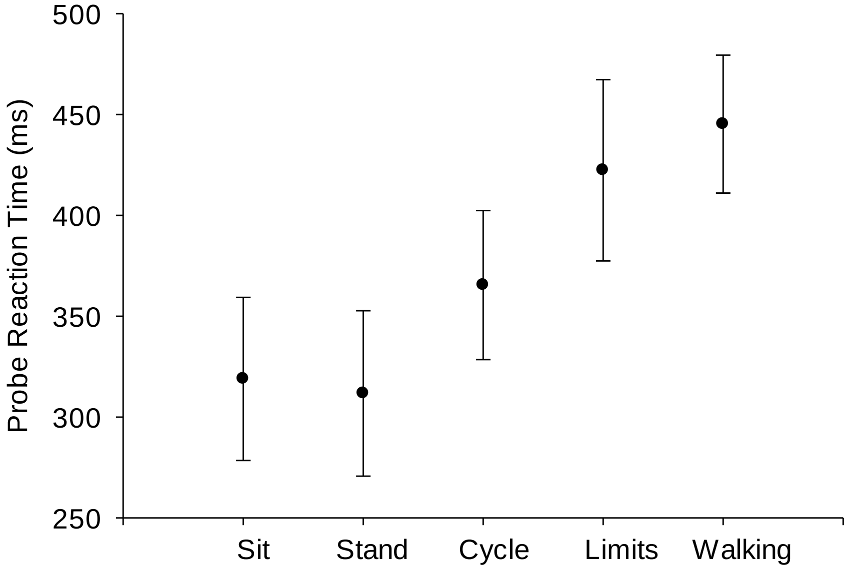


Figure 16: Probe Reaction Times Across Tasks

All six participants completed the explicit task prioritization study. Once again, one individual exhibited DTCs an order of magnitude greater so means were calculated from the remaining five participants. For the DTCs of gait, the average during the no prioritization was greater than the gait prioritization condition and less than the cognitive prioritization condition. These results are congruent with those observed for the other groups. For the DTCs of cognition, the stroke group tended to display elevated DTCS compared to the other groups across all conditions; however the large amount of variability limits any firm conclusions being drawn from this result. Figure 17 A and B display the DTCs across prioritization conditions.

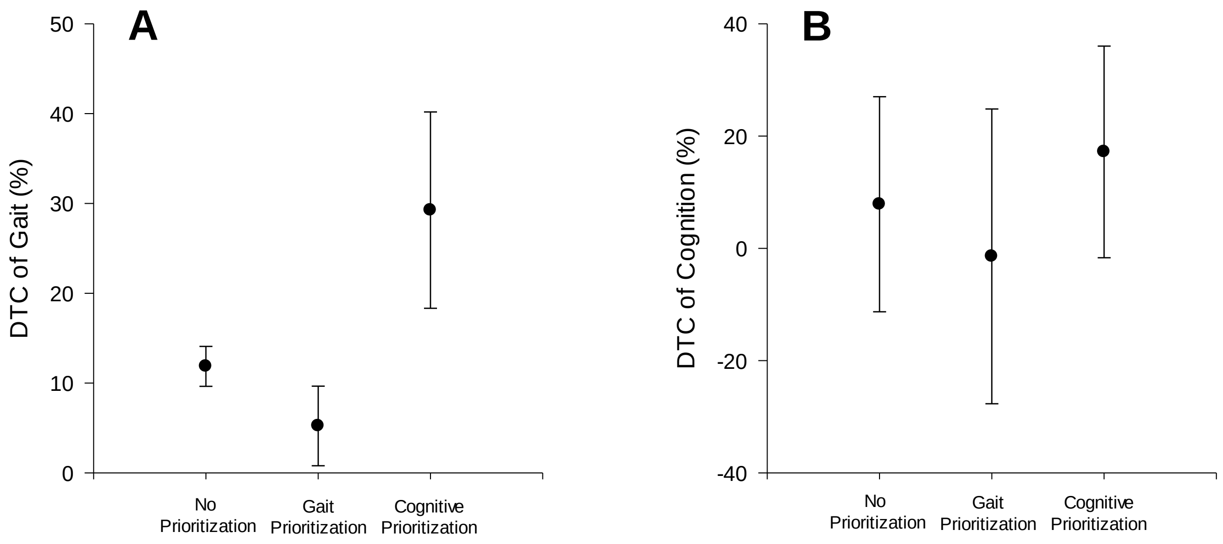
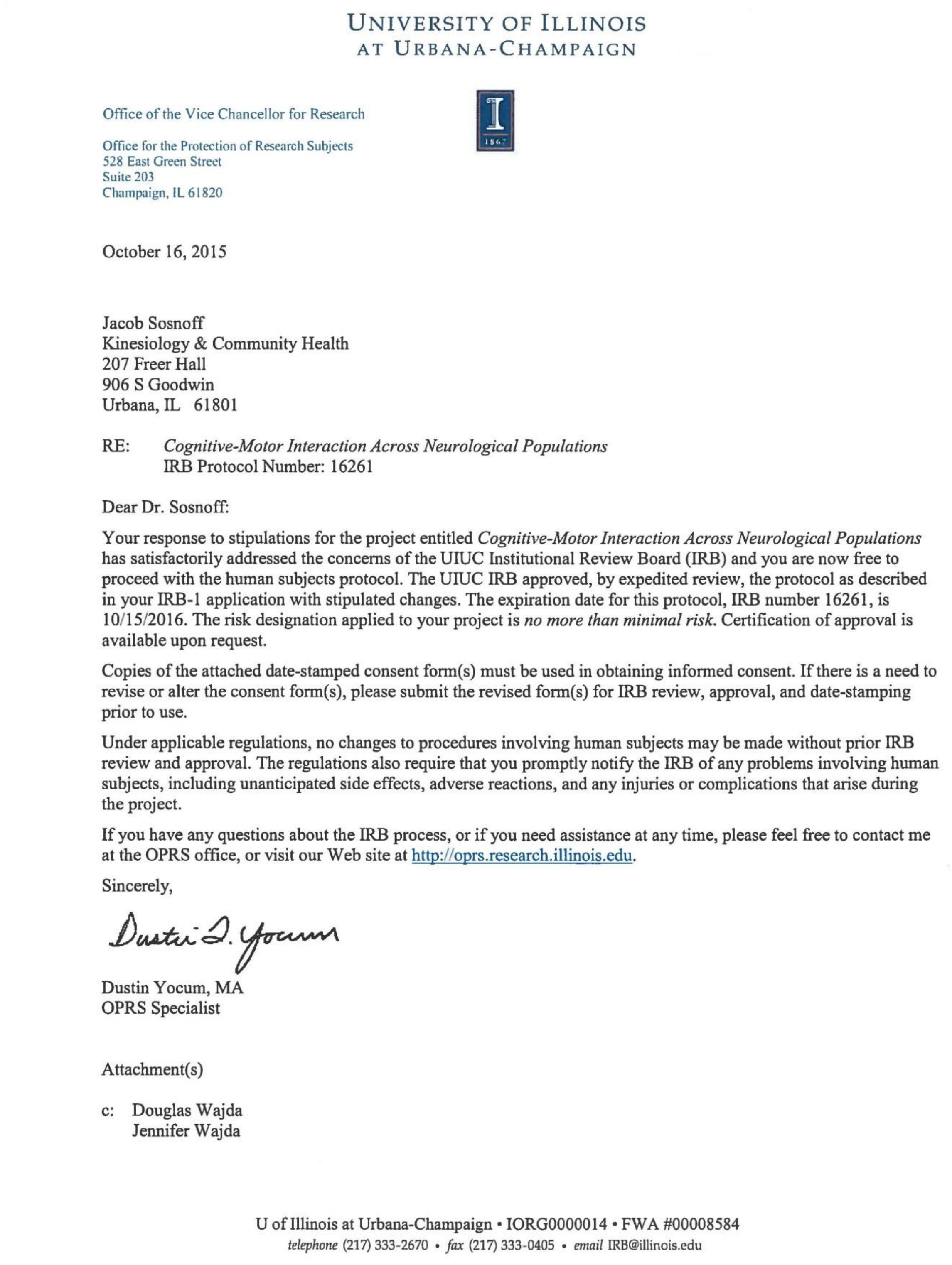


Figure 17: DTCs of Gait and Cognition across Prioritization Conditions

Overall, the results provide initial pilot data in regards to the theories of CMI and observed dual tasking results from chronic stroke participants. The observed trends from the environmental hazard study provide perhaps the strongest evidence that a behavioral prioritization model may also be applicable in these individuals. Future work utilizing a larger sample with perhaps more stringent inclusion with regards to the time since injury would be well served to consider both physiological and perceptual (e.g. balance confidence) outcomes when interpreting observed DTCs of movement and cognition to further confirm these preliminary results.

Appendix C: IRB Approval



UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

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528 East Green Street
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October 16, 2015

Jacob Sosnoff
Kinesiology & Community Health
207 Freer Hall
906 S Goodwin
Urbana, IL 61801

RE: *Cognitive-Motor Interaction Across Neurological Populations*
IRB Protocol Number: 16261

Dear Dr. Sosnoff:

Your response to stipulations for the project entitled *Cognitive-Motor Interaction Across Neurological Populations* has satisfactorily addressed the concerns of the UIUC Institutional Review Board (IRB) and you are now free to proceed with the human subjects protocol. The UIUC IRB approved, by expedited review, the protocol as described in your IRB-1 application with stipulated changes. The expiration date for this protocol, IRB number 16261, is 10/15/2016. The risk designation applied to your project is *no more than minimal risk.* Certification of approval is available upon request.

Copies of the attached date-stamped consent form(s) must be used in obtaining informed consent. If there is a need to revise or alter the consent form(s), please submit the revised form(s) for IRB review, approval, and date-stamping prior to use.

Under applicable regulations, no changes to procedures involving human subjects may be made without prior IRB review and approval. The regulations also require that you promptly notify the IRB of any problems involving human subjects, including unanticipated side effects, adverse reactions, and any injuries or complications that arise during the project.

If you have any questions about the IRB process, or if you need assistance at any time, please feel free to contact me at the OPRS office, or visit our Web site at http://oprs.research.illinois.edu.

Sincerely,

Dustin D. Yocum

Dustin Yocum, MA
OPRS Specialist

Attachment(s)

c: Douglas Wajda
Jennifer Wajda

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