

COGNITIVE-MOTOR INTERACTION DURING WHEELCHAIR PROPULSION

BY

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DISSERTATION

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ABSTRACT

Cognitive-motor interaction (CMI) research has exclusively investigated ambulatory adults, however, there is reason to believe that individuals who use manual wheelchairs may also be susceptible to this phenomenon. **PURPOSE:** This investigation seeks to determine: 1) the kinesthetic contributions mediating the attentional demands of wheelchair propulsion, 2) if wheelchair users experience CMI during wheelchair propulsion in a stable environment, and 3) if increased environmental complexity impacts the CMI of wheelchair propulsion. **METHODS:** Fourteen healthy individuals who use a manual wheelchair (age: 37.8 ± 16.3 ; sex: 8 males, 6 females) completed a series of single- and dual-task trials. Serial-7 Subtraction was used throughout testing to determine changes in cognitive function. Changes in motor function were determined through the performance of four, 30-second motor tasks: Static Sitting, Short Leans, Maximal Leans, and Stationary Propulsion, and four distinct 35-foot pathways, or Environments, varying in complexity. All dual-tasking trials required the simultaneous completion of Serial-7 Subtraction and a motor task/Environment. Two single- and dual-task trials were completed for each task, and average single and dual-task performance was calculated. Differences in average single- and dual-task performance were determined through paired samples *t*-tests, and percent changes (i.e., dual-task costs [DTCs]) were calculated to quantify CMI. Within-subjects, repeated-measures ANOVAs were conducted to determine significant differences between the DTCs of each outcome variable across the four motor tasks and Environments, respectively. IBM Statistical Package for the Social Sciences (SPSS) for Windows, version 28, was used to perform all statistical analyses on recorded data with statistical significance set at $\alpha=0.05$. **RESULTS:** Single- to dual-task cognitive function was maintained during all motor tasks

(DTC $\leq$ 13%; $p=0.12-0.74$; $d=0.09-0.44$) at the expense of impaired motor function during three motor tasks (DTC $\leq$ 43%; $p<0.01-0.03$; $d=0.67-1.21$). Motor function was uniquely maintained during Maximal Leans (DTC $\leq$ 0.5%; $p=0.12-0.93$; $d=0.02-0.45$), which required more cognitive resources than the other tasks, as indicated by significantly lower dual-task cognitive function ($p<0.001$; $\eta_p^2=0.44$). Likewise, cognitive function was maintained from the single- to dual-task trial in all Environments ($p\geq 0.16$; $d\leq 0.40$) and yielded similar DTCs across Environments ($p=0.80$; $\eta_p^2=0.03$). Compromised motor function was observed in all Environments ($p\leq 0.03$; $d\geq 0.67$) and yielded similar DTCs across Environments ($p\geq 0.37$, $\eta_p^2\geq 0.04$). **CONCLUSION:** Wheelchair propulsion is attentionally demanding for individuals who use manual wheelchairs. These demands likely stem from the task's seated balance requirements and are stable regardless of environmental complexity. When dual-tasking under these demands, participants most often experienced a decline in motor function to preserve cognitive function, demonstrating a posture-second approach.

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CHAPTER 1: INTRODUCTION

Many activities of daily living require the simultaneous completion of motor and cognitive tasks while navigating complex environments. Injury or disease can negatively impact the necessary systems to support the safe and successful completion of these activities. One outcome is an increase in the attentional resources to perform regular tasks (e.g., walking). As a result, ambulatory clinical populations commonly experience significant decrements in the performance of one or both tasks (i.e., motor and cognitive) when dual-tasking¹⁻⁷ and are further compromised as environmental complexity increases.^{8,9} This decrease in performance is called cognitive-motor interaction (CMI)² and is most commonly operationalized through dual-task costs (DTCs)¹, measured by the percent change in motor and cognitive function when completed together.

A common theoretical framework used to explain CMI is the attentional capacity model.¹⁰ This model suggests that each individual is limited in their attentional capacity and the successful completion of motor and cognitive tasks requires a given amount of attentional resources. When the tasks are simultaneously completed but do not exceed the individual's attentional capacity (each task has low attentional demands), the performance of both are maintained. It is theorized that clinical populations, or a group of individuals that are experiencing the same form of disability or health condition (e.g., stroke survivors), may require more attention resources when completing motor tasks, resulting in prioritization of its performance over cognitive performance⁸ and a heightened CMI.¹¹

The phenomenon of CMI holds clinical importance due to its association with health outcomes in ambulatory adults, such as decreased activity levels¹² and increased fall risk.^{3,13-15}

Fortunately, the development of CMI interventions has shown promise in improving dynamic balance and gait variables, such as decreased stride time variability and increased walking speed, across various ambulatory clinical populations.^{6,9,16–18}

There is reason to believe that individuals who use manual wheelchairs may be equally susceptible to CMI, but scientific evidence is lacking. Take, for instance, the fact that the automaticity of walking allows for the motor task to have low attentional demands.^{19,20} As it is understood today, wheelchair propulsion lacks the neural circuitry to support automaticity.²¹ Dedicated practice to a motor pattern can increase its automaticity²², but likely not to the same degree as reflexive movement.¹⁹ Wheelchair propulsion also requires adequate seated balance, which many users have significant difficulty maintaining. Previous research has demonstrated that as the stability requirements for the task increase, so do its attentional demands.^{23,24} Lastly, individuals who use manual wheelchairs experience additional difficulties with accessibility when navigating diverse environments. Although the Americans with Disabilities Act and efforts following²⁵ have improved accessibility for these individuals, constraints remain. Considering this, it is of little surprise that falls due to environmental hazards often occur in complex settings when individuals who use manual wheelchairs are distracted or multitasking.²⁶ The summation of these factors will likely lead to wheelchair propulsion having high attentional demands and individuals who use manual wheelchairs experiencing CMI when dual-tasking.

Determining the attentional demand of wheelchair propulsion and the influence of environmental complexity could expand the understanding and application of CMI theoretical models and inform rehabilitative interventions.²⁷ Consequently, the current investigation aims to understand the attentional-demanding elements of wheelchair propulsion and if individuals who use manual wheelchairs experience CMI during wheelchair propulsion in stable and increasingly

complex environments. Three simultaneous experiments were performed to achieve this objective. Individuals who enrolled in the investigation completed three experimental aims described below. *Please refer to Figure 1.1 for the study schematic.*

The first experimental aim (*see Chapter 3*) sought to determine the kinesthetic contributions mediating the attentional demands of wheelchair propulsion. This research focused on measuring participants' single-task motor and cognitive function followed by their simultaneous completion. DTCs were determined across four distinct propulsion-related motor tasks, varying in static and dynamic balance requirements: Static Sitting (**Figure 3.1A**), Short Leans (**Figure 3.1B**), Maximal Leans (**Figure 3.1C**), and Stationary Propulsion (**Figure 3.1D**). We hypothesized that arm action during stationary propulsion and seated balance would be attentionally demanding and that the highest attentional demands would occur during the motor task with the greatest stability requirements (Maximal Leans).

The second experimental aim (*see Chapter 4*) sought to determine if individuals who use manual wheelchairs experience CMI during wheelchair propulsion in a stable environment. Since there is no formal dual-tasking assessment for non-ambulatory adults, the current methodology was informed by common dual-tasking paradigms for ambulatory adults. This experiment leveraged participants' single-task cognitive function from the first experimental aim, determined participants' single-task motor function, and measured the simultaneous completion of motor and cognitive tasks along an unobstructed, 35-foot (10.67 m) pathway (**Figure 4.1**). We hypothesized that individuals who use manual wheelchairs would experience CMI due to prioritizing motor function (wheelchair propulsion), as indicated by a greater DTC to cognitive function.

The third experimental aim (see Chapter 4) sought to determine if increased environmental complexity impacts the CMI of wheelchair propulsion. This research leveraged participants' single-task cognitive function from the first experimental aim and the observed DTCs from the second experimental aim (used as a control condition). This experiment measured participants' single-task motor function and the simultaneous completion of motor and cognitive tasks along three 35-foot (10.67 m) obstacle courses varying in environmental complexity (**Figure 4.2**). We hypothesized that motor and cognitive DTCs would increase as the environmental complexity increased.

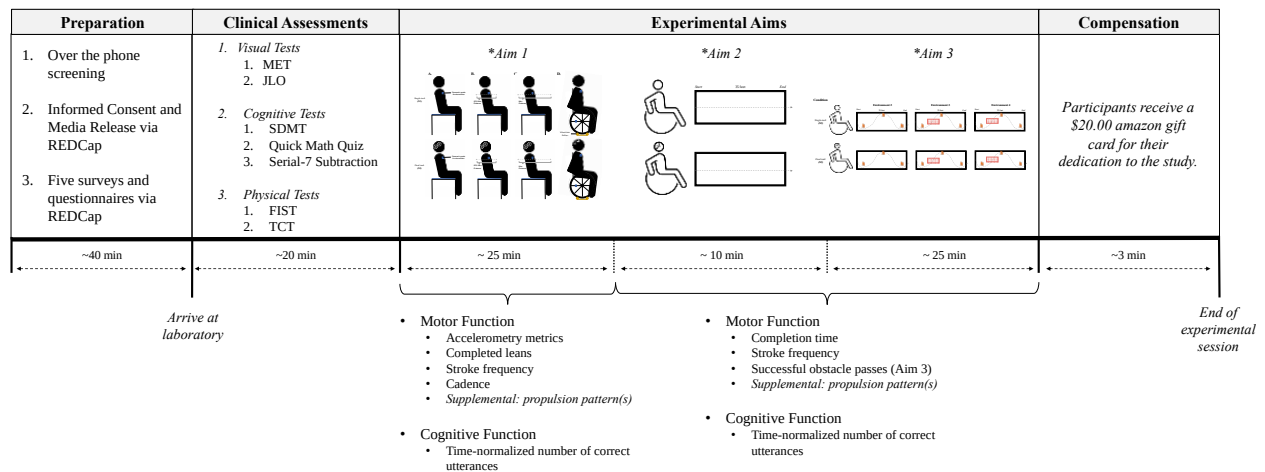


Figure 1.1. Schematic representation of the timeline, tests completed, and measurements obtained during the testing session. MET: Melbourne Edge Test, JLO: Judgment of Line Orientation, SDMT: (verbal) Symbol Digit Modalities Test, FIST: Function in Sitting Test, and TCT: Trunk Control Test. * Indicates that conditions are completed in a randomized order.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Overview

The planning, organization, and execution of human movement is a sophisticated process, whose success depends upon an individual's neurophysiological systems, which can be compromised by disease or injury. In a real-world setting, the difficulty of this process is further compounded by environmental complexity. Even the simplest of tasks, such as walking in a straight line to the kitchen could undergo interference from a family pet or eager child to start the day. In response, people are often required to dual-task or perform their primary motor task in coordination with a cognitive task during activities of daily living. As previously mentioned, cognitive-motor interaction (CMI) is when the performance of one or both tasks is altered in comparison to single-task performance², and operationalized as an individual's dual-task costs (DTCs)¹, measured by the percent change in motor and cognitive function when completed together ($[(\text{dual-task} - \text{single-task})/\text{single-task}] * 100$). Ambulatory clinical populations (e.g., older adults) have been seen to experience greater CMI than young adults²⁸, which has health implications such as heightened fall risk.^{3,13-15} The development of theoretical models^{10,29} has helped to explain the CMI observations in ambulatory adults but has never been extended to non-ambulatory adults. Determining if individuals who use manual wheelchairs experience CMI during attention-demanding wheelchair propulsion would expand the application and understanding of these pre-existing theoretical models and create an opportunity to develop CMI interventions for this population, which have shown promise in ambulatory individuals.^{6,9,16-18}

2.2 CMI Theoretical Models

Although the phenomenon of CMI has been well documented^{1-7,16}, the underlying mechanisms mediating these observations remain unknown. CMI is seen to occur when the supply of attentional resources cannot meet the attentional demand required to complete two simultaneous tasks. The allocation of attentional resources for the respective motor and cognitive tasks has been most explored using the following three theoretical models: The Attention Capacity Model¹⁰, Bottleneck Model³⁰, and Behavior Model²⁹.

2.2.1 *Attention Capacity Model*

The attention capacity model developed by Kahneman in 1973 proposes that all individuals have a pre-determined amount of attentional resources and the completion of any task that is not automatic will be deducted from the collective.¹⁰ Interestingly, even well-practiced motor tasks like locomotion²⁰, slow down when performed with a cognitive task, displaying the possibility of its own attentional demands.⁴ This example sheds light on one possible outcome when dual-tasking, which is that the tasks' attentional demands exceed the individual's attentional capacity, leading to compromised performance in one or both tasks. The other possibility is that the tasks' attentional demands do not exceed the individual's attentional capacity, allowing for the maintained performance of the simultaneously completed tasks. Within this model exist two primary variations: the flexible allocation model and the multiple resource model. The former includes the idea that individuals can select which task to prioritize when dual-tasking (similar to the behavior model), yet, no formal investigations have been conducted using this model to further understand CMI. The latter believes that individuals have a

pre-determined amount of attentional resources, but only tasks of the same “attentional resource subtype”, will compete with each other for resources (similar to the bottleneck model).

2.2.2 Bottleneck Model

The bottleneck model was developed by Pashler in 1994³⁰ and is similar to the attention capacity model in that it suggests individuals have limited executive processing resources but differs in the mechanism by which attentional resources (for the cognitive or motor task) are allocated. This model proposes that because of the limited ability for information processing, only one task can be completed at a time. This control, or bottleneck effect, of information, is what is believed to result in compromised dual-task performance. Considering the amount of stimuli an individual could be received at any given time, this model is most applicable for tasks that use the same neurological pathways or processing structures. One example of this is walking and standing balance, which are both spinally mediated tasks. Completing each requires the integration of sensory information that must be processed by high-order centers, running the risk of interfering with the simultaneous performed cognitive task. One way to think about this model is through the characteristics of a highway traffic jam. Often to avoid approaching roadwork, all lanes are forced to merge into one. While you will still get to your planned destination, the arrival time may be significantly delayed.

2.2.3 Behavior Model

The self-awareness prioritization (behavior) model developed by Yogev-Seligmann et al. in 2012 takes a behavioral-based approach to understand and describe dual-task outcomes.²⁹ This model proposes that an individual may select a different dual-tasking strategy (e.g., prioritization

of one task over the other) based on their hazard estimate and postural reserve. In this context, hazard estimate is comprised of an individual's self-efficacy/belief in their abilities and perception of the task's difficulty. Postural reserve represents an individual's objective physical abilities. When viewing dual-task performance from this perspective, it is reasonable to speculate that an individual with low self-efficacy in their walking might prioritize its performance over cognitive performance in a high-risk situation (e.g., walking on ice). This speaks to a general motor control principle that recognizes the influence of the individual, environment, and task on motor performance. Naturally, CMI finds itself situated at the crosshairs of these different factors.

2.2.4 Testing CMI Theoretical Models

Throughout the current investigation, the attention capacity model and behavior model are routinely discussed, and the bottleneck model is not. This is due to the lack of scientific examination between this model and observed CMI and the need for hi-tech brain imaging equipment to *directly* do so. Some examples of this necessary equipment include positron emission tomography, functional MRI, and near-infrared spectroscopy.^{31,32} Using this equipment allows researchers to detect changes in cortical metabolism and activation by measuring regional cerebral blood and blood oxygenation level from single- to dual-task conditions, respectively. In the event the current proposal used these methods, primary outcomes measures would be changes in cortical metabolism, followed by its relationship to task performance, making the explanation of these more neurophysiology focused.

Less direct methods of testing the bottleneck model can be completed through the use of overlapping task paradigms, which manipulate the psychological refractory period.^{33,34} Generally

speaking, this method is a way of understanding cognitive information processing by measuring the interference that one task creates for another. To perform these tests, two tasks (which are generally assumed to use similar neural structures) are performed separately and then simultaneously. During their simultaneous completion, the tasks are presented in close succession with varying levels of a time lag between the onsets of a first and second task stimulus. The key is that participants are given instructions to prioritize the completion of the first task. The assumption is that if these tasks share neural pathways/structures, the response time of the second task will be slowed (in comparison to its single-task performance) due to the nature of sequential processing. This decreased performance indicates the DTC in the context of the psychological refractory period. It should be explicitly noted that if using the bottleneck model was of primary interest, a similar research design would have been employed in the current investigation. In this case, the DTCs of various tasks would remain the primary outcome measure and infer that the two responses cannot be initiated simultaneously or in close succession. There are a few limitations to this approach, the first is that while delayed processing times can be observed, the direct evidence that this is due to shared neural structures is lacking. Changes in processing time could also be due to participants not following the instruction to focus on the first task, task preparation, sensory-perceptual processes, and overall focus/interest of the participant.

Throughout previous investigations, it is not often stated or determined if the two tasks share neurological pathways or processing structures, which could impact dual-task performance. As a result, researchers often employ the attentional capacity model when describing CMI due to its assumption that attention is a collective resource; perhaps making it the most referenced and discussed model of the three. Within this model, one seeks to understand the attentional demands

of a task. These demands are frequently quantified by an individual's ability to simultaneously perform a motor and cognitive task and operationalized as a participant's DTCs.¹ Observing a significant DTCs can imply decrements in performance and indicate that the individual's attentional capacity was exceeded while dual-tasking. If one task (motor or cognitive) yields a significant DTC and the other did not, the behavior model can help to provide insights as to if and why prioritization may have occurred.

The aims of the current investigation seek to understand the attentional demands of various elements within wheelchair propulsion (e.g., seated balance and arm action) and the influence of environmental complexity on the attentional demands of wheeled mobility. These questions are interested in the observed DTCs between tasks and environments. It is for this reason that using the attention capacity model and behavior model is both sufficient and appropriate.

2.3 The Environment

While completing activities of daily living, most individuals are required to navigate a variety of complex and attention-demanding environments. Despite this, traditional laboratory-controlled mobility measures tend to be performed in easy-to-navigate environments that lack ecological validity.⁴ One way in which researchers can reduce this limitation and develop a greater understanding of real-world trade-offs is by bringing environmental characteristics seen in the community into the lab setting. Recent evidence points to the notion that dual-task walking more closely resembles community ambulation than normal walking.³⁵ Although few in number, CMI investigations have sought to manipulate the environment through the use of virtual³⁶ and outdoor environments¹⁸, in the participant's home³⁷, experimental conditions that affect the

motor task^{17,38}, and lab-based obstacle crossing^{8,39}. A recent investigation by Wajda et al.⁸, had individuals with multiple sclerosis and age-matched controls complete single- and dual-task trials of four walking conditions: normal walk, obstacle walk, walk on a narrowed pathway, and walk on a narrowed pathway with obstacles. Results illustrated that as environmental complexity increased, both groups declined in cognitive function, and those with multiple sclerosis more so than the controls. This same phenomenon was also seen during virtual and lab-based obstacle-crossing in healthy older adults.^{36,39} This suggests that in the presence of environmental hazards participants prioritized their walking performance, supporting the previously described behavior model.²⁹ Regardless of the type of environmental manipulation, it appears that the environment plays an important role in determining what task will be prioritized and to what degree.

The presence of this trade-off in complex environments begins to dive into the clinic importance of this research area. Along with environmental complexity impacting dual-task performance, researchers interested in CMI, have demonstrated that the ability to dual-task affects daily active/community participation in ambulatory clinical populations¹² and is associated with fall risk in older adults.^{3,13–15} Although CMI during wheelchair propulsion and the influence of environmental complexity has not yet been investigated, there is reason to believe it too will have associations with health metrics such as fall risk. Take for instance the fact that falls often occur in complex environments when individuals who use manual wheelchairs are distracted (e.g., checking for cars while crossing a busy road) and do not perceive the environmental hazard.²⁶ Recently conducted interviews on the topic of assistive technology with wheeled device users exposed similar insights such as:

*“What is a problem for me sometimes is a rough or broken pavement when moving around outside. If I catch the front casters of my chair wrong on those, I’ll pitch forward and sometimes all the way out of the chair, and that’s obviously never good. Especially because it’s more likely to happen when I’m crossing the road because I’m trying to get across the crossing quickly. I’m having to pay more **attention** to how much time I have on the crosswalk, and where are cars, pedestrians, bicyclists, or whatever. Yeah, that’s definitely why it’s more likely to happen in a crosswalk because of the split **attention**. ”⁴⁰*

The most frequently reported environmental hazards are uneven surfaces and obstacles²⁶, which create enough danger for these individuals to be identified as a main fall risk factor within this population.⁴¹

The Americans with Disabilities Act of 1990 and efforts since²⁵ have improved the accessibility to buildings and facilities for individuals who use manual wheelchairs, but constraints remain. As a result, these individuals often face greater challenges than ambulatory adults in completing ordinary activities, such as pushing across grass or cobblestones, stepping over the lip of a doorway, or needing to consider if the door opens inwards or outwards. These are all minor examples of activities that require thought and planning for individuals who use manual wheelchairs and little to none for ambulatory adults. Without accounting for dual-tasking or the complexity of the environment (e.g., a busy restaurant), individuals who use manual wheelchairs face additional barriers to navigating most environments, which on its own could be attention-demanding. Determining the CMI during wheelchair propulsion and the influence of environmental complexity can help in the development of rehabilitative interventions and identify suitable candidates to reduce the impact of environmental hazards on their fall risk.

2.4 Diverse Populations

2.4.1 Ambulatory Adults

Physical and cognitive functions vary on an individual level and can influence CMI. However, numerous observations have been made comparing CMI across groups such as healthy and clinical populations. Walking is an involved motor skill and to achieve an efficient and reproducible walking pattern one must have a high degree of trunk and limb coordination and neural control. In healthy populations, that have not experienced an injury to or disease of the central nervous system, this process is rhythmic and almost entirely automatic.²⁰ With regard to walking, automaticity is “*the ability of the nervous system to successfully control typical steady-state walking with minimal use of attention-demanding executive control resources*”.¹⁹ This low attentional demand of walking allows for greater allocation of resources to simultaneous cognitive tasks (or those that require executive control), limiting observed dual-tasking costs. Executive control will be utilized in cases where an individual’s experience compromised automaticity of walking, limiting the available resources for the successful completion of a simultaneous task that also requires executive control.

The automaticity of walking is informed by the cerebellum and brainstem but can be largely attributed to the *central pattern generator* circuits of the spinal cord. These circuits can stimulate the gait pattern without input from the brain and are believed to be present from birth.⁴² One of the first and most renowned investigations on the topic was performed by Sherrington in 1910, where the walking pattern of a decerebrate cat was observed when the spinal cord was stimulated.⁴³ While spinal stimulation of most animals’ front and hind limbs can achieve a walking pattern, this circuitry in humans is unique to the lower limbs to support our upright stance. Evidence for this pattern can be seen when rhythmic, alternating stances and swing

phases of the lower limbs were observed when epidural electrical stimulation was applied to the lumbar spinal cord of individuals with a complete spinal cord injury.⁴⁴ Once up and walking, these spinally mediated tasks require the spinal reflex pathways in modulating outputs based on sensory information such as pain, proprioception (e.g., stretch and tension), and tactile somatosensation (e.g., vibration). Collectively, these findings suggest that standard walking patterns are largely produced and supported by the spinal cord, with little to no input from the brain.

The spinal circuitry is proficient at performing steady-state walking at various speeds but requires executive control from the prefrontal cortex when starting/stopping walking, performing walking that requires significant posture and limb control, dual-task walking, using an assistive device (e.g., cane), or when an individual is unable to rely on automaticity due to damage or disease of the central nervous system.¹⁹ For these clinical populations, walking has heightened attentional demands and is often prioritized over cognitive function⁸, resulting in CMI.¹¹ A large body of evidence conducted on older adults^{7,11,28,45,46}, stroke survivors², and those with Multiple Sclerosis^{1,8}, support this posture-first approach. Only those living with Parkinson's Disease appear to take a posture-second approach, in which cognitive function is prioritized over balance and gait.^{5,47} It is not clear what mechanisms may be causing this riskier approach, but researchers believe it may be due to reduced movement automaticity, dopamine-mediated dysfunction of the basal ganglia, or the presence of a nondopaminergic pathology.⁵ Fortunately, practicing these difficult single- and dual-tasks can reduce the role of the pre-frontal cortex, making the pattern more automatic.¹⁹ This helps to explain how dual-task rehabilitative interventions have shown to be effective at improving CMI in ambulatory clinical populations.^{6,9,16–18}

2.4.2 Non-ambulatory Adults

2.4.2.1 Seated Balance

According to the United States Census Bureau, ~3.6 million citizens require a wheelchair for mobility.⁴⁸ For these individuals, wheeled mobility also supports their independence and quality of life by providing greater access to community engagements, health care, employment, and educational opportunities.^{49,50} There are numerous reasons for the use of a wheelchair, including acute and chronic injuries (e.g., fractures, spinal cord injury, and amputation), diseases (e.g., post-polio syndrome, Multiple Sclerosis, and Parkinson's Disease), or congenital abnormalities (e.g., spina bifida). The reason for wheelchair use appears to be age striated with younger individuals most often utilizing a wheelchair due to Multiple Sclerosis or paralysis, while older adults tend to use one because of arthritis, stroke, or Multiple Sclerosis.⁵¹

Regardless of etiology, most individuals who use a wheelchair have experienced damage to their nervous system that often results in permanent changes to body functions, such as spasticity and dampened or loss of sensation and strength, distal to the damaged site.⁵² These alterations can negatively impact the complex interplay of sensory processing and motor outputs^{53,54} required to preserve seated balance⁵⁵, which is the ability to maintain one's center of mass within stability boundaries while in a seated position. Low to high tech options have been developed to measure seated balance ranging from clinical assessments, with the most common being the Function in Sitting Test^{56–58} and Trunk Control Test⁵⁹, to numerous research-grade technology including three-dimensional motion capture techniques^{60,61}, video-based measurements⁶², research-grade and smartphone accelerometry⁶³, and force plate measured seated posturography.^{55,61} For individuals who use manual wheelchairs, adequate seated balance is integral to safely performing activities of daily living (e.g., reaching, scooting, transfers, and

propulsion)⁴¹; making its improvement a common goal of rehabilitation interventions.⁶⁴

Fortunately, the ability to improve the seated balance has been shown to be feasible within a pilot fall prevention intervention.²⁷

2.4.2.2 Automaticity of Wheelchair Propulsion

To date, there is little evidence to suggest that equally robust neurological processes that support the automaticity of gait are present during wheelchair propulsion. It is thought that the primary neural circuitry supporting the passive elements of wheelchair propulsion is due to cutaneous reflexes. These reflexes help facilitate the contralateral coordination of the gait cycle and provide functional responses to disturbances while walking.⁶⁵ Most cutaneous reflexes act on the lower limbs, but the superficial branch of the radial nerve will also evoke a cutaneous reflex if stimulated (associated with local muscle activity). The location of this reflex in the upper limbs is thought to help synchronize the arm and leg movements when walking. Evolutionarily, to support the use of our hands during various activities (e.g., manipulating tools and carrying children), the strength of this contralateral connection is weaker between the arms than it is between the legs. However, having a reflex that encourages rhythmic movements in each arm, with a limited connection between the arms, may help support the *generally* symmetrical arm action of wheelchair propulsion.⁶⁶

An investigation on the topic compared the cutaneous reflex of individuals who use manual wheelchairs (2-28 years of experience) and a control group via random stimulation of the superficial radial nerve during manual wheelchair propulsion.²¹ Due to the reliance on the upper limbs, it was anticipated that this reflex would be heightened for individuals who use manual wheelchairs. This would not be unique as modulation of reflexive activity to favor performance

has been seen following lower limb cycling training.⁶⁷ However, results showed that there were no differences in amplitude modulation of the cutaneous reflexes between the two groups. Unfortunately, this finding suggests that experience with wheelchair propulsion does not enhance the circuitry that is most likely to support passive elements of the task. Findings such as these bring about many questions, including 1) what feature of the lower limbs makes it more susceptible to these adaptations, 2) to what degree does the cutaneous reflex contribute to the overall task performance, 3) what implications might these findings have on high-order processing and therefore the task's attentional demands, and 4) are there any additional strategies to make wheelchair propulsion more automatic? While the answers to most of these are not clear and information is limited, there is some evidence that points to the latter two questions.

In general, higher-order processing is needed when a task lacks automaticity.¹⁹ The first investigation conducted in 2020 on brain imaging during mock real-world environments demonstrated the dependence on higher-order processes for simple wheelchair propulsion.²² In this investigation, brain activity during the completion of a flat pathway free of obstacles was the same for individuals who are experienced in wheelchair propulsion and a control group.²² Findings from the study showed that individuals who use manual wheelchairs demonstrated less overall brain activity when compared to controls during the completion of a trial with four obstacles and had greater activation in brain areas associated with motor planning. These individuals were also significantly faster than the control group in both conditions. Such findings collectively suggest that the cutaneous reflex during wheelchair propulsion is not strong enough to support the automaticity of the movement but practicing the task can improve motor function and allocation of cognitive resources. It is reasonable to expect that dedicated practice to this

motor pattern will increase its automaticity¹⁹, but there appears to be an upper limit to what can be achieved.

2.4.2.3 Wheelchair Propulsion Patterns

To achieve mobility, individuals who use manual wheelchairs must consciously coordinate their seated balance and upper limbs to apply a force to the wheels' push rims (push phase). The recovery phase follows each stroke, where the hands release from the push rims and reset for the next stroke. The hand trajectories during this reset will influence the type of propulsion pattern utilized, of which there are four: arc propulsion, semicircular propulsion, single loop over propulsion, and double looping over propulsion (**Figure 2.1**). While no biomechanical differences have been seen between the arc, single loop, and double loop patterns⁶⁸, there is some evidence to suggest that the semicircular pattern increases efficiency, through increasing push angles, and lower stroke frequencies.^{69–71} In the long run, this greater efficiency may allow for less upper-extremity pain and injuries from overuse⁷², which are common in this population.⁷³ Other investigations have been limited in their ability to compare the semicircular pattern to the other patterns because no one in the study used it.⁶⁸ Likewise, some individuals who use manual wheelchairs employ the same pattern during all movement, while others use one pattern during start-up, and switch to another once up to speed.⁷⁴ Unlike the gait cycle, there is no innate or reflexive pattern to wheelchair propulsion, and these examples speak to the fact that variability in propulsion techniques may be in part due to individual differences in impairment and exposure to wheelchair skills training. While efforts should be made to improve one's propulsion technique to avoid upper-extremity decline, in a real-world setting, an individual is considered a 'functional

propeller' if they can meet the average velocity required to cross an intersection safely (1.06 m/s).⁷⁵ Generally speaking, it matters less about the pattern employed during this task and more about their ability to meet this threshold. Consequently, using these patterns as a metric for performance may be inappropriate but identifying if an individual's pattern changes in the presence of greater attentional demands may highlight underlying mechanisms that support consistent motor/cognitive function or task prioritization.

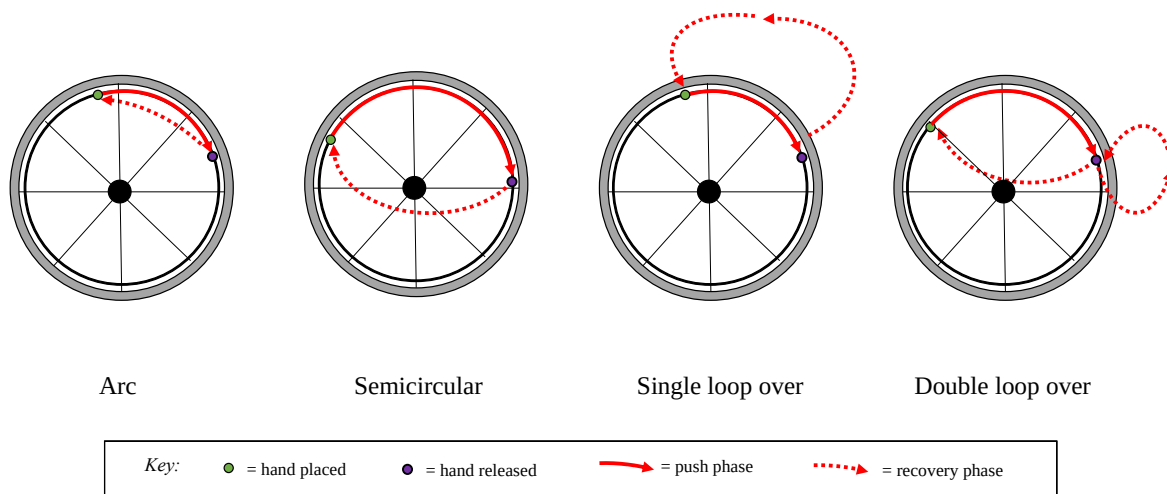


Figure 2.1. Illustrates the four main wheelchair propulsion patterns. Graphic inspired by drawing from Sisto et al. 2009.

There has been no scientific examination of the attentional demands of wheelchair propulsion. Yet, considering the evidence from other clinical populations, it is logical to speculate that individuals who use manual wheelchairs would also experience CMI. Firstly, it is possible that these individuals are a member of one of the aforementioned clinical populations and thus susceptible to various underlying disease characteristics (e.g., cognitive decline associated with multiple sclerosis).⁵¹ Secondly, attentional demands of a task increase as the stability requirements for the task increase^{23,24}; which is likely to further compromise those who

have significant difficulties with seated balance. Thirdly, wheelchair propulsion lacks the circuitry that would support automaticity, making executive function the primary contributor to motor output. Lastly, individuals who use manual wheelchairs experience additional barriers to accessibility when navigating diverse environments. The summation of these factors, however, weighted for an individual, will likely result in wheelchair propulsion having high attentional demands and individuals experiencing CMI when dual-tasking.

2.5 Conclusion

Simultaneously completing motor and cognitive tasks within various environments is common throughout daily activities. An individual's ability to safely and successfully do so is partly dependent on the health of their neurophysiological systems. Consequently, most clinical populations (with compromised motor and/or cognitive functions) experience significant CMI, or a decline in performance of one or both tasks when completed together. The ability to dual-task has been associated with numerous health metrics, such as fall risk and daily activity. It is for these reasons that developing successful CMI interventions to improve individuals' abilities to dual-task holds clinical promise. While there is no data on CMI during wheelchair propulsion, there are reasons to believe that it will be attention-demanding and characterized by CMI within stable and complex environments. These predictions stem from the evidence that many individuals who use manual wheelchairs have difficulties with seated balance, that wheeled propulsion is not an automatic motor pattern, and that there are more barriers to navigating various environments. Applying CMI theoretical models to better understand the attentional demands of wheelchair propulsion is a novel approach that will advance both theory and practice.

CHAPTER 3: THE ATTENTIONAL DEMANDS OF WHEELCHAIR PROPULSION

3.1 Introduction

Motor and cognitive functions have traditionally been investigated independently, but it is becoming increasingly common for researchers to determine the interaction between the two when simultaneously performed. Under this condition, a decrease in the performance of the motor, cognitive, or both tasks is indicative of cognitive-motor interaction (CMI).² This phenomenon is most routinely operationalized through dual-task costs (DTCs)¹, which is measured by the percent change in motor and cognitive performance from single- to dual-task trials. In practical terms, understanding when and why CMI occurs is important due to its association with health outcomes in ambulatory adults, such as decreased activity levels¹² and increased fall risk.^{3,13–15}

Although CMI has been well documented among healthy and clinical ambulatory populations^{1–7,16}, the mechanisms mediating these observations remain unknown. A common theoretical framework used to explain CMI is the attention capacity model.¹⁰ This model suggests that individuals are limited in their attentional capacity and the successful completion of motor and cognitive tasks requires a given amount of attentional resources. When tasks are completed together but do not exceed the individual's attentional capacity, the level of performance is maintained. This suggests that observing CMI becomes more likely as a task's attentional demands increase, which often derives from complexity/difficulty.

It is for this reason that ambulatory clinical populations, commonly experience significant decrements in the performance of one or both tasks when dual-tasking^{1–7}, and often prioritize motor performance over cognitive performance.⁸ In fact, a reduction in cognitive performance

has been observed when limiting an individual's base of support^{23,28} or performing dynamic balance tasks (leaning limits of stability)²⁴ and progressively declines from a seated position to standing and from standing to walking.^{23,28} Overall, this evidence suggests that as the stability requirements for the task increase, so do the attentional demands. Fortunately, interventions that are targeted to reduce the impact of CMI have demonstrated the ability to improve dynamic balance and gait variables across various ambulatory clinical populations.^{6,9,16–18}

There is reason to believe that individuals who use manual wheelchairs may be equally susceptible to CMI, and perhaps its negative health outcomes, but scientific evidence is lacking. Unlike the gait cycle, wheelchair propulsion lacks the neural circuitry to support automaticity.^{21,22} While dedicated practice to a motor pattern can increase its automaticity²², it will likely not reach the same degree as a reflexive movement.¹⁹ This pulls to question the attentional demands of arm action during wheeled mobility. While there is some evidence to suggest that the utilized propulsion pattern (i.e., arc, semicircular, single loop over, and double loop over) may impact efficiency^{69–71}, it is not clear if some patterns are more attentionally demanding than others. Observing changes from one pattern to another during dual-task trials could be a compensatory mechanism for lowering the task's attentional demands. Lastly, wheelchair propulsion also requires adequate seated balance, which many users have significant difficulty maintaining, but can improve with appropriate interventions.²⁷ Understanding which elements of wheelchair propulsion (i.e., arm action and static and dynamic seated balance) are most attentionally demanding would expand the application and understanding of the attention capacity model and create an opportunity to develop CMI interventions for individuals who use manual wheelchairs.

Consequently, the purpose of the current investigation was to determine the kinesthetic contributions mediating the attentional demands of wheelchair propulsion. It was hypothesized that arm action during stationary propulsion and seated balance will both be attentionally demanding and that the highest attentional demands will occur during the motor task with the greatest stability requirements.

3.2 Methods

3.2.1 Participants

3.2.1.1 Participant Inclusion and Exclusion Criteria

To be eligible for participation, individuals were required to be between 18 and 70 years old, utilize a manual wheelchair as their primary form of mobility (regardless of etiology), have ≥ 1 year(s) of experience with a manual wheelchair, be able to sit unsupported for ≥ 5 minutes, have normal or corrected to normal hearing and vision, and able to read and speak English. Potential participants were excluded from the investigation if they did not meet these criteria, had significant cognitive impairment as indicated by a score of < 20 on the Modified Telephone Interview for Cognitive Status⁷⁶, or were experiencing upper extremity pain/injury that impacts activities of daily living. Potential participants were screened over the phone and those who met the inclusion criteria were invited to participate in the investigation. Eligible participants received an informed consent document to review and sign via REDCap.⁷⁷ All procedures obtained approval from the University of Illinois at Urbana-Champaign (UIUC) Institutional Review Board (*see Appendix C for approval letter*) and all participants provided informed consent before engaging in research activities.

3.2.1.2 Participant Recruitment Efforts

Numerous recruitment avenues were perused during the current investigation, including participant subject pools from UIUC, posting of physical researcher flyers around the campus and community, online announcements (i.e., UIUC eWeeks and social media platforms), sharing the opportunity through individual groups/organizations (e.g., adaptive sports teams), and personal networks and word of mouth (*see Appendix A for full recruitment details*).

3.2.2 Study Protocol

3.2.2.1 Online Surveys and Questionnaires

After enrolling in the study, participants completed five online surveys/questionnaires, including a demographic and health history questionnaire (e.g., fall prevalence in the past 6-months), the Wheelchair Skills Test Questionnaire⁷⁸, the Spinal Cord Injury Fall Concerns Scale⁷⁹, the Community Participation Indications⁸⁰, and the World Health Organization Quality of Life Questionnaire (BREF version)⁸¹ (*see brief descriptions below*). Since this is the first investigation exploring the CMI during wheelchair propulsion, these surveys/questionnaires were used to thoroughly characterize the participant cohort.

- Participant Background/Demographics Survey: Used to collect general information about the participants such as age, marital status, fall history, occupation, etc.
- Wheelchair Skills Test Questionnaire (WST-Q)⁷⁸: The WST-Q allows for the subjective reporting of 32 manual wheelchair skills (e.g., turning in place and picking objects off the floor). Participants will indicate their ability, level of confidence, and frequency of the various skills. If applicable, reporting No Part = “The wheelchair does not have the parts to allow this skill” is also allowed.

- Spinal Cord Injury-Falls Concern Scale (SCI-FCS)⁷⁹: The SCI-FCS examines concerns about falling by asking participants to rate their level of concern for falling on a 4-point scale ranging from 1=not at all concerned to 4=very concerned when performing 16 common activities of daily living.
- World Health Organization Quality of Life Questionnaire (BREF version) (QHOQOLBREF)⁸¹: This assessment asks participants how they feel about their quality of life, health, and other areas of life within the past 2-weeks. Answers are provided on a 4-point scale ranging from 1=not at all to 4=completely.
- Community Participation Indications (CPI)⁸⁰: The CPI is composed of 48 items that are used to evaluate 2 domains of community participation: participation in activities that are deemed important to the individual (importance) and their control over their level of community participation (control).

3.2.2.2 In-Person Testing Session

Upon arrival at the laboratory, participants completed two baseline assessments of visual function (Melbourne Edge Test⁸² and Judgment of Line Orientation⁸³), three assessments of cognitive function (verbal Symbol Digit Modalities Test⁸⁴, a 5-minute (pre-professional) Math Quiz, and Serial-7 Subtraction⁸), and two assessments of seated balance/postural control (the Function in Sitting Test)^{56–58}, Trunk Control Test⁵⁹) (*see brief description below*). Except for Serial-7 Subtraction, these assessments were also used to characterize the participant cohort.

- Melbourne Edge Test (MET)⁸²: This test is used to determine an individual's edge contrast sensitivity. Participants will be provided a sheet containing 20 total circles with half of all circles shaded. The orientation of the shaded portion varies between vertical, horizontal, right-leaning, and left-leaning. Participants will be asked to verbally report the

orientation of the shaded section of each circle. The test will end if an incorrect answer is reported or when they finish all 20 circles.

- Judgment of Line Orientation (JLO)⁸³: JLO is a standardized test of visuospatial skills. This test will measure your ability to match the angle and orientation of lines in space.
- 5-minute Math Quiz: This 5-minute assessment is designed to assess the participant's baseline mathematical abilities. Before the task begins, participants will be provided paper, a pencil, and a calculator to assist them in the problem-solving of 12 basic (pre-professional) calculations. Questions can be skipped if needed.
- Symbol Digit Modalities Test (SDMT)⁸⁴: The SDMT is a 90-second substitution task that is commonly used to assess cognitive function and concentration in healthy and clinical populations. Performance on the SDMT is underpinned by attention, perceptual speed, motor speed, and visual scanning. The number of correct substitutions completed is the main outcome. Within this investigation, the research team will record participants' verbal substitutions.
- Serial-7 Subtraction⁸: This task assesses cognitive function and concentration and is usually completed for a short duration (e.g., 10 or 30 seconds). Participants will be given a three-digit number ranging from 150 to 199 and asked to count backward by sevens. All responses will be recorded.
- Function in sitting test (FIST)⁵⁶⁻⁵⁸: The FIST will be administered while participants sit on a mat table with their feet supported on the floor and 3/4 of their femurs supported by the mat table. Based on the guidelines (Gorman et al., 2010), each item is scored on a scale from 0 to 4, with 0 indicating that the individual is incapable of performing the sitting task and 4 indicating that the individual is fully capable of performing the sitting task. Individual item scores were summed, yielding a total score ranging from 0 to 56, where 0 equates to an inability to perform any of the sitting tasks and 56 equates to full ability to perform all tasks.

- The Trunk Control Test (TCT)⁵⁹: The TCT examines four aspects of trunk movement. To complete the test the participant will complete a variety of tasks that challenge trunk control (e.g., sit up from lying down, and sit in a balanced position on the edge of a matted table). Each one of these tasks will be scored, receiving a 0, 1, or 2 based on their ability to complete the task successfully and without the need for upper limb support. The total score of TCT is the sum of points from all tasks.

The cognitive assessment, Serial-7 Subtraction, was used throughout testing to determine changes in cognitive function from single- to dual-tasking conditions. Two trials, beginning from different numbers, were performed and the average time-normalized number of correct utterances was calculated. Scripted instructions were used to ensure the accuracy and consistency of the test (*see Appendix B for the recited instructional prompts*). This cognitive assessment was selected due to its use of mental tracking (i.e., an internal interfering factor). Such tasks have been shown to elicit greater DTCs than external interfering factors, such as reaction time.⁴ Presenting a cognitive task that is sufficiently challenging is needed to identify if CMI occurs within the current population.

The following four, 30-second motor tasks were used to determine changes in motor function from single- to dual-tasking conditions: Static Sitting, Short Leans, Maximal Leans, and Stationary Propulsion (on wheelchair rollers) (**Figure 3.1**). All tests with exception of Stationary Propulsion were completed on a mat table. These tests were chosen because of their ability to challenge the seated postural control of wheeled device users and are characteristic of the underlying motor pattern of wheelchair propulsion. The order of these tasks was randomized to control for potential practice or ordering effects. Once randomized, each task was completed twice for single- and dual-task conditions in alternating order. For safety, participants wore a gait

belt and were allowed to briefly practice the movements before the start of the trial. Spotters were present in the event an individual lost balance during testing.

During dual-tasking conditions, these four motor tasks were simultaneously completed with the cognitive task (Serial-7 Subtraction). Cognitive and motor outcome measures were consistent with that of the single-task assessment. Before testing, participants received instructions to ensure that there was an equivalent emphasis placed on the completion of cognitive or motor tasks (*see Appendix B for the recited instructional prompts*).

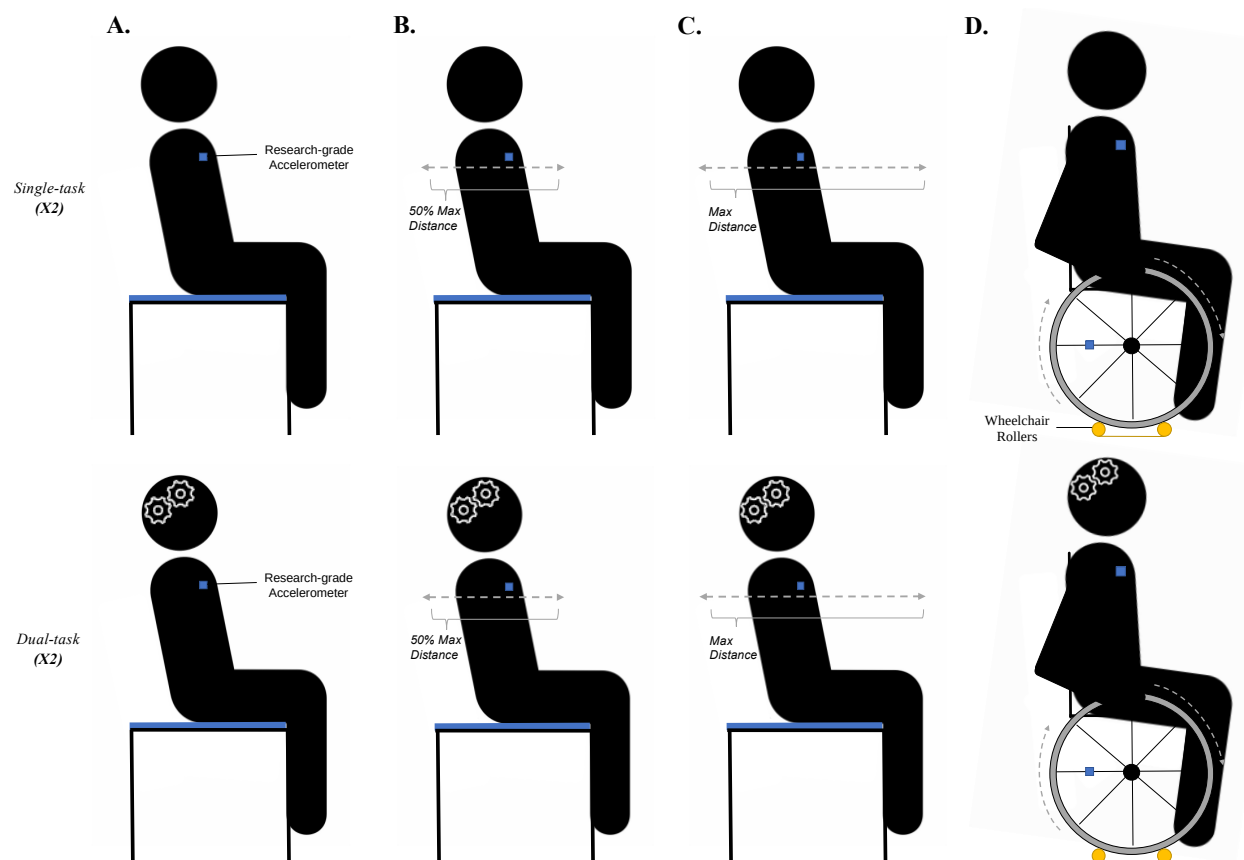


Figure 3.1. Provides a summary of the first experience's experimental conditions. Column A: Static Sitting; B: Short Leans; C: Maximal (Max) Leans; D: Stationary Propulsion. The order of motor tasks will be randomized, and all tasks were completed twice.

3.2.2.3 Motor Task Assessments

During the Static Sitting task (**Figure 3.1A**), participants sat still with their best posture and balance. To assign the necessary distances during the leaning trials, participants completed a maximal forward and backward lean. Measurements for the forward lean were taken from the sternum when in an upright seated position to the sternum's position when leaning as far forward as possible. Measurements for the backward lean were taken from the center of the scapula when in an upright seated position to the center of the scapula when leaning back as far as possible. Half of these distances were continuously performed during the Short Leans trial (**Figure 3.1B**), while the full distances were continuously performed during the Maximal Leans trial (**Figure 3.1C**). A string was horizontally placed in front and behind the participant to indicate the distance that was to be achieved. During the Short and Maximal leaning trials, a lean that went far enough to touch the string in front or behind the participant was considered a 'completed lean'. Only the number of completed leans was recorded and used to represent an individual's motor function. Participants completed the Stationary Propulsion trials (**Figure 3.1D**) in their personal manual wheelchair. Once positioned on the wheelchair rollers, participants were acclimated to the equipment and procedures by propelling their wheelchair at a self-selected, comfortable pace for 3 minutes, followed by a 2-minute rest period. During the testing trials, participants completed a self-selected pace that most closely resembled being late to class or work. An emphasis was made to ensure this pace could be maintained throughout the 30-second trial. Cadence (revolutions per minute [rpm]), stroke frequency (strokes/second [sec]), and utilized propulsion pattern(s) were determined throughout the Stationary Propulsion trials and used to represent an individual's motor function.

To determine cadence, one of the participant's wheelchair wheels was fitted with a research-grade accelerometer (The Opal, APDM Wearable Technologies, Portland, OR).²⁴ This allowed for easy identification of the number of completed revolutions following the testing session. Similarly, stroke frequency and utilized propulsion pattern(s) were identified following the session through video recordings of the trials. For stroke frequency, researchers counted the number of completed strokes during the 30-second trials. The methods for identifying utilized propulsion pattern(s) were informed by previous research.⁷⁴ Two raters familiar with the literature on propulsion patterns separately identify the propulsion pattern of each stroke of all trials from a recorded video (capturing the sagittal plane). Raters completed their assessments within uniform excel workbooks. Final assessments were compared, and raters came to a consensus where differences were seen by reviewing the stroke or trial together. If a consensus could not be reached, a third experienced reviewer reviewed the stroke or trial in question. The number of strokes used for each of the four possible propulsion patterns (i.e., arc, semicircular, single loop over, and double loop over) were summed for the single- and dual-task conditions and reported as a percentage of the total strokes **(Figure 3.2)**.

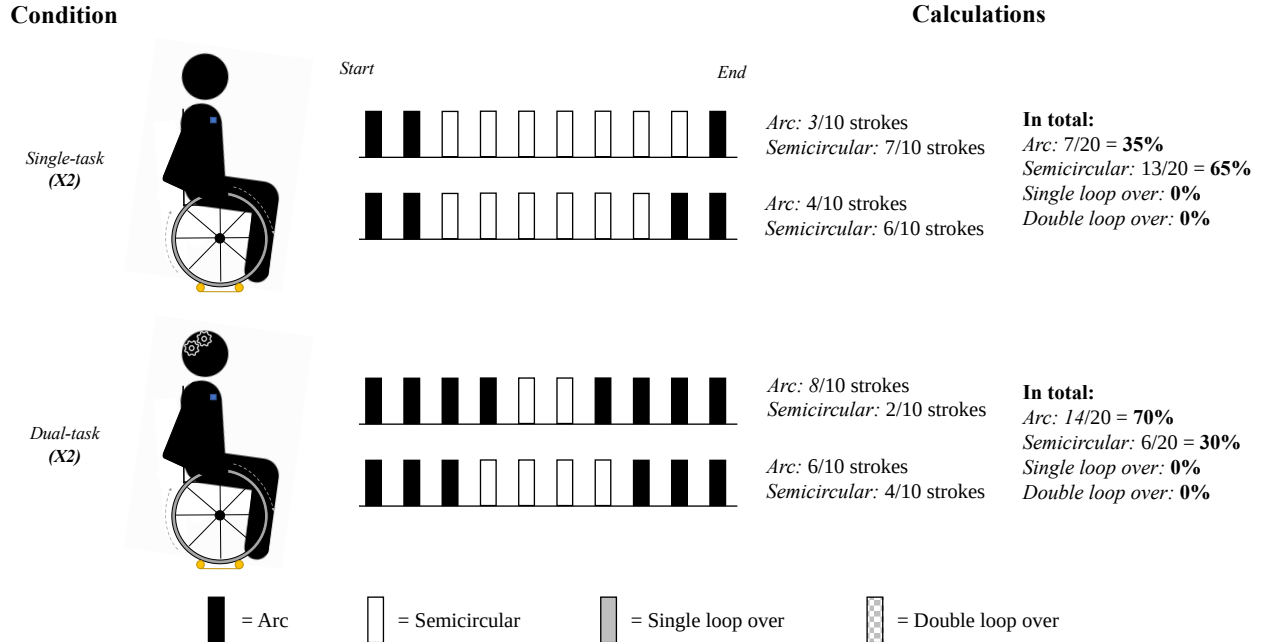


Figure 3.2. Depicts an example of how the percentage of each propulsion pattern will be determined during single- and dual-task conditions for all participants.

Participants seated balance was recorded through all trials and used to represent motor function. To do so, a research-grade accelerometer (The Opal, APDM Wearable Technologies, Portland, OR) was affixed to participants' sternums in a standardized orientation using a strap similar to a heart rate monitor.

3.2.2.4 Data Analyses

A custom MATLAB script (MathWorks Inc., Natick, MA) was used to downsample all seated balance accelerometry data to 100 Hz and filtered using a 4th-order lowpass Butterworth filter set to 5 Hz.⁵⁵ The time series used for analysis was 30 seconds. Maximum (MAX) and root mean squared (RMS) acceleration time-series from each device along the anterior-posterior (AP) and medial-lateral (ML) axes, as well as the calculation for 95% confidence ellipse area (CEA). These measures are seen to be a valid assessment of postural stability⁸⁵ and sensitive enough to identify impairment in ambulatory⁸⁵⁻⁸⁷ and non-ambulatory⁶³ populations.

3.2.2.5 Outcome Measures

The primary outcome measures for the study are the DTCs of motor and cognitive function during cognitively demanding motor tasks. DTCs of motor function were determined by the percentage change in the accelerometry measures, the number of completed leans (during the leaning tasks), and the stroke frequency and cadence (during Stationary Propulsion) from the single- (i.e., motor tasks only) to dual-task condition (i.e., motor tasks and Serial-7 Subtraction together). DTCs of cognitive function were determined by the percentage change in the average time-normalized number of correct utterances verbalized from the single- (i.e., Serial-7 Subtraction only) to dual-task condition (i.e., motor tasks and Serial-7 Subtraction together).⁸ Supplementary analyses were conducted to identify differences in propulsion pattern percentages from the single- to dual-task conditions.

3.2.3 Statistical Analyses

IBM Statistical Package for the Social Sciences (SPSS) for Windows, version 28 (IBM Inc., Chicago IL) was used to perform all statistical analyses on recorded data with statistical significance set at $\alpha=0.05$. Descriptive statistics were calculated (mean $\pm$ standard deviation) for all survey/questionnaires and the Melbourne Edge Test, Judgment of Line Orientation, verbal Symbol Digit Modalities Test, Math Quiz, Function in Sitting Test, and the Trunk Control Test.

To determine the significant differences between average single- and dual-task outcome measures (i.e., accelerometry parameters, completed leans, cadence, stroke frequency, and time-normalized number of correct utterances), a two-tailed paired samples *t*-test was performed on each variable. To further understand these differences, effect sizes (Cohen's *d*) were calculated,

and classified as small ($d=0.20$), medium ($d=0.50$), and large ($d=0.80$).⁸⁸ The percentage change of these variables from the single- to dual-task condition was calculated and represents the DTCs of motor and cognitive function ($[(\text{dual-task} - \text{single-task})/\text{single-task} * 100]$).

To determine if motor tasks differ in attentional demands, within-subjects, repeated-measures analysis of variance (ANOVA) were performed to determine significant differences in the DTC of each average measurement (i.e., accelerometry parameters, and the time-normalized number of correct utterances) across the four motor tasks. Bonferroni post hoc analyses were completed with corrections for familywise error rate and eta-squared (η_p^2) was calculated to better understand the magnitude of differences within the completed ANOVAs. Normality and sphericity were determined through the Shapiro-Wilks and Mauchly's tests, respectively. If assumptions of sphericity were violated, Huynh-Feldt or Greenhouse-Geisser corrections were applied.⁸⁹ Common recommendations⁹⁰ suggest utilizing a Huynh-Feldt correction when epsilon is >0.75 , and a Greenhouse-Geisser correction when epsilon is <0.75 .

Interrater reliability for each stroke of the entire data set was determined by calculating the Fleiss' kappa (κ) statistic. Kappa values were classified as none (0–0.20), minimal (0.21–0.39), weak (0.40–0.59), moderate (0.60–0.79), strong (0.80–0.90), and almost perfect (≥ 0.91) interrater reliability.⁹¹ As a rule, kappa values at or above 0.60 indicate adequate agreement among the raters and provides confidence in the study results.⁹¹ Two-tailed paired samples t -tests were performed to determine the difference between average single- and dual-task propulsion pattern percentages.

3.3 Results

3.3.1 *Participant Demographics*

Fourteen individuals who use a manual wheelchair as their main form of mobility (age: 37.8 ± 16.3 ; sex: 8 males, 6 females) participated in the current study. Given the greater attentional demands associated with locomotion and maintaining postural stability in older adults^{11,28,45,46}, data acquired from individuals >65 years old (n=1) needed to be within normal range of the remaining group (i.e. not an outlier) before being included in the data set. Participant demographic information is provided in **Table 3.1**. **Table 3.2** presents participant clinical assessment outcomes.

Table 3.1. Participant demographic information. Values are reported as mean $\pm$ standard deviation (SD). STEM: Science, Technology, Engineering, and Mathematics; n: sample size.

Demographic	Mean	SD
Age (years)	37.8	16.3
Body Mass Index	25.1	8.6
Sex, n (%)		
<i>Males</i>	8 (57)	
<i>Females</i>	6 (43)	
Years Using Mobility Device	21.4	14.2
Reason for Wheeled Mobility, n (%)		
<i>Sacral Agenesis</i>	1 (7)	
<i>Stroke</i>	1 (7)	
<i>Multiple Sclerosis</i>	2 (14)	
<i>Cerebral Palsy</i>	3 (21)	
<i>Spinal Cord Injury</i>	7 (50)	
History of Falls (≥ 1 falls/year), n (%)	11 (79)	
Needs Assistance Rising From a Falling, n (%)		
<i>Yes</i>	4 (29)	
<i>No</i>	7 (50)	
<i>Sometimes</i>	3 (21)	
Formal Education in STEM, n (%)		
<i>Yes</i>	5 (36)	
<i>No</i>	8 (57)	
<i>I don't know</i>	1 (7)	
Level of Education, n (%)		
<i>High school graduate/GED</i>	1 (7)	
<i>Some or in-progress college/Associate degree</i>	4 (29)	
<i>Bachelor's degree</i>	2 (14)	
<i>Master's degree</i>	5 (36)	
<i>Doctoral degree</i>	2 (14)	
Wheelchair Skills Test Questionnaire		
<i>Performance Score</i>	47.4	11.3
<i>Confidence Score</i>	50.2	15.6
<i>Frequency Score</i>	44.6	16.3
Spinal Cord Injury Fall Concerns Scale	25.1	5.4
Community Participation Indications		
<i>Importance</i>	50.9	10.5
<i>Control</i>	56.0	7.1
World Health Organization Quality of Life Questionnaire		
<i>Total</i>	59.4	7.0
<i>Physical Health</i>	15.0	2.5
<i>Psychological Health</i>	14.1	1.7
<i>Social Relationships</i>	13.7	3.3
<i>Environment</i>	16.6	2.2

Table 3.2. Participant clinical assessment outcomes. SD: standard deviation; TICS-M: Modified Telephone Interview for Cognitive Status; MET: Melbourne Edge Test and Judgment of Line Orientation; SDMT: verbal Symbol Digit Modalities Test; FIST: Function in Sitting Test; TCT: Trunk Control Test.

Clinical Assessment	Range	Median	Mean	SD
TICS-M	21.0, 31.0	27.0	26.8	2.8
MET	19.0, 24.0	21.0	21.1	1.7
JLO	5.0, 20.0	17.5	16.6	4.9
SDMT	19.0, 62.0	48.5	47.1	12.2
FIST	10.0, 56.0	49.0	44.6	14.2
TCT	13.0, 24.0	19.5	18.6	4.0
Math Quiz (%)	16.7, 83.3	58.3	51.2	19.8

3.3.2 Dual-task Costs

Findings from the paired samples *t*-tests suggest that participants' cognitive function, as indicated by their time-normalized number of correct utterances during Serial-7 Subtraction, was maintained from the single- to dual-task conditions across the four motor tasks ($p=0.12-0.74$; $d=0.09-0.44$) (**Table 3.3**). Differences in cognitive DTCs between motor tasks were observed within the ANOVA model ($p<0.001$; $\eta_p^2=0.44$; observed power=1.00). Post-hoc analyses indicate that this difference originated from participants experiencing significantly greater deficits to cognitive function during the Maximal Leans task (DTC =~22%) than in the Static Sitting (DTC=~5%; $p<0.01$; $d=1.30$), Short Leans (DTC=-1%; $p=0.02$; $d=0.70$), and Stationary Propulsion (DTC=13%; $p<0.01$; $d=1.16$) tasks (**Figure 3.3**).

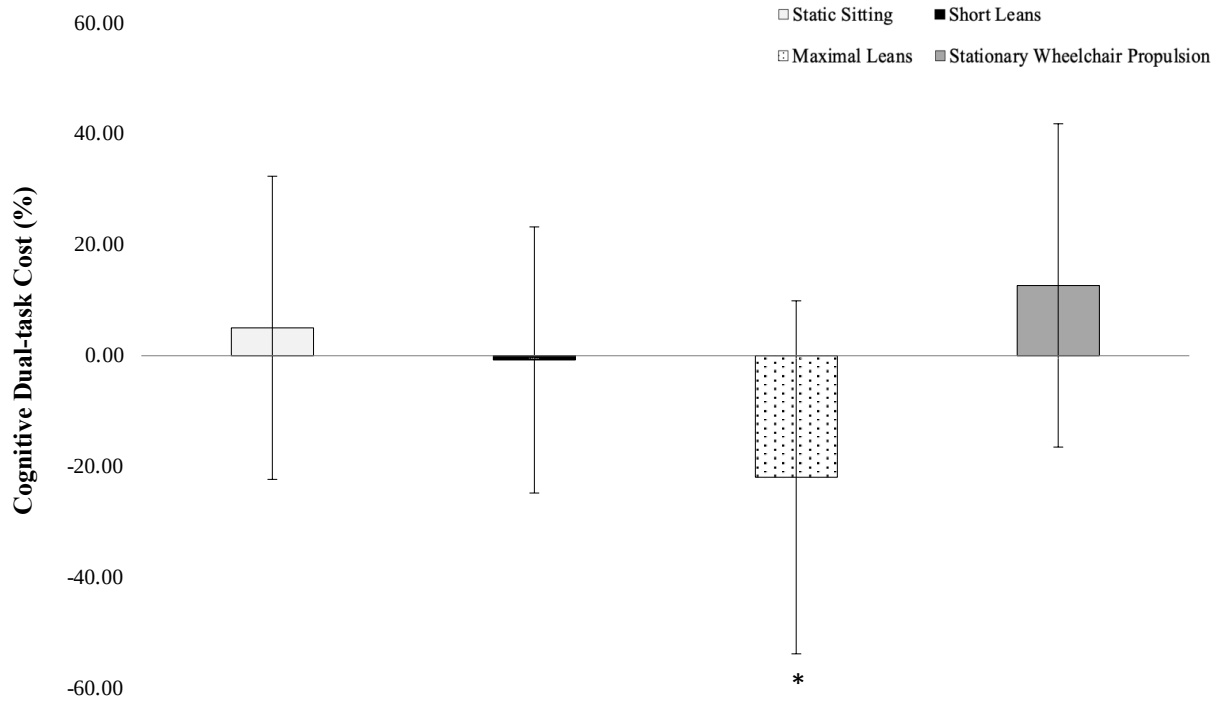


Figure 3.3. Illustrates the dual-task costs of participants' time-normalized number of correct utterances across four motor tasks: Static Sitting, Short Leans, Maximal Leans, and Stationary Propulsion. Values are reported as mean $\pm$ standard deviation. * Indicates a significant difference ($p < 0.05$) from all other tasks.

In terms of participants' motor function, results from the paired samples t -tests illustrate that only the number of completed leans ($p < 0.01$; $d = 1.10$) during the Short Leans and stroke frequency ($p < 0.01$; $d = 1.21$) during Stationary Propulsion yielded significant deficits, $\sim 15\%$, and 11% , respectively, from the single- to dual-task condition (**Table 3.3**).

Table 3.3. Differences from single- to dual-task performance in time-normalized number of correct utterances, number of completed leans, stroke frequency, and cadence across four motor tasks. * Denotes a comparison between single- and dual-task performance. ** Indicates significant differences where $p \leq 0.01$ and * represents $p < 0.05$. •• Indicates a large effect size.

Dependent Variable	Motor Task	Single-task		Dual-task		Dual-task Costs (% Change)		t	p-value*	Cohen's d*
		Mean	SD	Mean	SD	Mean	SD			
Time-normalized Number of Correct Utterances	Static Sitting			0.31	0.22	5.04	27.3	-1.03	0.32	0.27
	Short Leans			0.28	0.17	-0.76	24.0	0.33	0.74	0.09
	Maximal Leans	0.29	0.16	0.25	0.22	-21.9	31.8	1.19	0.26	0.32
	Stationary Propulsion			0.32	0.20	12.7	29.2	-1.66	0.12	0.44
Number of Completed Leans	Short Leans	16.5	6.00	14.3	5.98	-14.9	14.0	4.10	<0.01**	1.10••
	Maximal Leans	11.5	4.63	10.8	5.45	-9.57	17.6	1.64	0.13	0.44
Stroke Frequency (strokes/sec)	Stationary Propulsion	1.24	0.30	1.11	0.27	-10.6	7.42	4.54	<0.01**	1.21••
Cadence (rpm)	Stationary Propulsion	11.0	4.43	10.5	4.77	-4.23	12.5	1.39	0.19	0.37

Paired samples *t*-tests yielded significant changes in all accelerometry variables during Static Sitting ($p<0.01$ - 0.03 ; $d=0.67$ - 1.17), with exception of RMS AP ($p=0.14$; $d=0.42$), and Stationary Propulsion ($p<0.01$; $d=0.77$ - 1.17) (Table 3.4). For Static Sitting, these changes were due to a ~43% to 122% increase in acceleration from the single- to dual-task condition. Conversely, the changes observed during Stationary Propulsion were due to a ~-7% to -23% decrease in acceleration from the single- to dual-task condition. No changes to accelerometry variables were observed during the Short ($p=0.32$ - 0.88 ; $d=0.04$ - 0.27) and Maximal Leans ($p=0.12$ - 0.93 ; $d=0.02$ - 0.45) motor tasks.

Table 3.4. Differences from single- to dual-task performance in maximum (MAX) acceleration, root mean squared (RMS) acceleration, and 95% confidence ellipse area (CEA) along anterior-posterior (AP) and medial-lateral (ML) axes across four motor tasks. * Denotes a comparison between single-and dual-task performance. ** Indicates a significant difference where $p\leq 0.01$ and * represents $p<0.05$. • Indicates a medium effect size and •• indicates a large effect size.

Motor Tasks	Accelerometry Variable	Single-task		Dual-task		Dual-task Costs (% Change)		t	p-value*	Cohen's <i>d</i> *
		Mean	SD	Mean	SD	Mean	SD			
Static Sitting	MAX ML	0.28	0.13	0.42	0.23	56.3	57.3	-3.27	<0.01**	0.87••
	MAX AP	0.41	0.24	0.58	0.27	53.3	45.4	-4.38	<0.01**	1.17••
	RMS ML	0.08	0.04	0.11	0.06	43.3	56.3	-2.76	0.02*	0.74•
	RMS AP	0.14	0.08	0.18	0.12	32.0	60.2	-1.56	0.14	0.42
	CEA	0.16	0.17	0.30	0.27	121.7	165.9	-2.49	0.03*	0.67•
Short Leans	MAX ML	2.10	1.27	2.07	1.23	4.54	26.7	0.21	0.83	0.06
	MAX AP	3.01	1.72	2.99	1.50	3.85	13.8	0.16	0.88	0.04
	RMS ML	1.03	0.64	1.05	0.79	0.35	25.0	-0.22	0.83	0.06
	RMS AP	1.87	1.22	1.81	1.11	-0.06	10.9	1.02	0.32	0.27
	CEA	15.7	21.6	13.6	15.7	0.28	32.4	0.96	0.36	0.26
Maximal Leans	MAX ML	2.41	1.41	2.27	1.37	-2.52	19.4	1.19	0.25	0.32
	MAX AP	3.78	1.63	3.77	1.58	0.50	14.0	0.09	0.93	0.02
	RMS ML	1.33	1.01	1.27	0.96	-3.60	14.0	1.66	0.12	0.44
	RMS AP	2.44	1.40	2.34	1.27	-2.20	8.00	1.44	0.17	0.39
	CEA	26.8	24.6	24.1	20.5	-4.81	19.4	1.69	0.12	0.45
Stationary Propulsion	MAX ML	10.0	3.83	8.06	2.80	-15.0	18.3	3.29	<0.01**	0.88••
	MAX AP	6.29	1.91	5.69	1.69	-7.48	15.0	2.89	<0.01**	0.77•
	RMS ML	2.81	1.26	2.24	0.98	-17.9	12.2	4.38	<0.01**	1.17••
	RMS AP	1.89	0.70	1.69	0.70	-9.29	14.7	2.88	<0.01**	0.77•
	CEA	99.7	62.2	70.1	43.6	-23.4	21.6	4.06	<0.01**	1.09••

ANOVA results indicate significant main effects of task on the DTCs of all accelerometry variables: MAX ML, MAX AP, RMS ML, RMS, and CEA ($p \leq 0.04$; $\eta_p^2 = 0.27-0.56$; observed power = 0.57-1.00). Post-hoc analyses showed that Static Sitting yielded significantly greater DTCs to MAX ML, MAX AP, RMS ML, acceleration than all other tasks ($p < 0.01-0.03$; $d = 0.63-1.22$), and significantly greater DTCs to RMS AP acceleration than Maximal Leans ($p = 0.05$; $d = 0.56$) and Stationary Propulsion ($p = 0.02$; $d = 0.71$). Additionally, Short Leans illustrated a greater DTC to MAX AP than Stationary Propulsion ($p = 0.04$; $d = 0.60$), Maximal Leans had great DTC to CEA than Stationary Propulsion ($p = 0.04$; $d = 0.61$), and Short and Maximal Leans had greater DTCs to RMS ML than Stationary Propulsion ($p = 0.26$ and 0.01 ; $d = 0.67$ and 0.79 , respectively) (**Figure 3.4**).

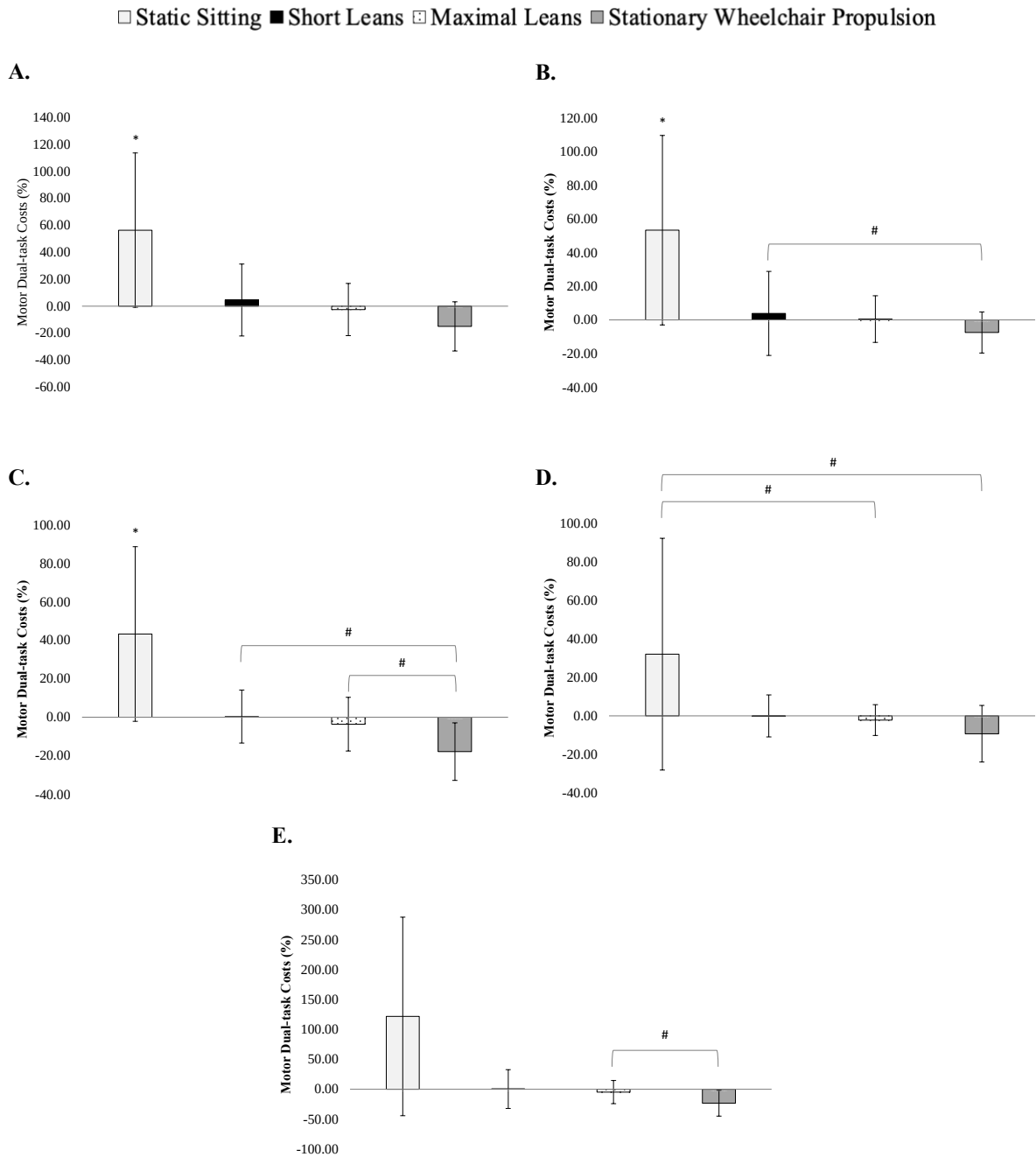


Figure 3.4. The dual-task costs of acceleration across four motor tasks: Static Sitting, Short Leans, Maximal Leans, and Stationary Propulsion. Values are reported as mean $\pm$ standard deviation. A: Maximum medial-lateral acceleration; B: Maximum anterior-posterior acceleration; C: Root mean squared medial-lateral acceleration; D: Root mean squared anterior-posterior acceleration; E: 95% confidence ellipse area. * Indicates a significant difference ($p < 0.05$) from all other tasks, and # indicates a significant difference ($p < 0.05$) between two tasks.

3.3.3 Propulsion Patterns

Moderate interrater reliability was achieved when identifying the propulsion pattern used during each stroke of the entire data ($\kappa=0.69$; $p<0.01$). No participants were seen to employ the single loop over or double loop over stroke patterns throughout single- or dual-tasking Stationary Propulsion. During the single-task trials $88\pm30\%$ and $12\pm30\%$ of all strokes utilized arc and semicircular stroke patterns, respectively. During dual-tasking, $79\pm41\%$ of strokes utilized the arc pattern, and $21\pm41\%$ utilized the semicircular pattern. These changes in average propulsion percentages did not yield significant differences between single- and dual-task trials ($p=0.24$; $d=0.34$, both). Overall, twelve participants exclusively used the arc pattern, one exclusively used the semicircular pattern, and one utilized both the arc and semicircular patterns. The participant that used both patterns began all trials with between two to nine strokes of the arc pattern before switching to the semicircular pattern.

3.4 Discussion

The current investigation sought to understand the kinesthetic contributions mediating the attentional demands of wheelchair propulsion. Findings from the study demonstrate that healthy individuals who use manual wheelchairs were able to maintain their cognitive function from single- to dual-task trials during the four motor tasks. Conversely, significant deficits to motor function were observed during three motor tasks, specifically impaired balance during Static Sitting (i.e., greater trunk accelerations), less completed leans during Short Leans, and a more conservative approach to Stationary Propulsion, as indicated by lower stroke frequency and trunk accelerations. The only motor task to not yield deficits in motor function was Maximal Leans, which posed the greatest challenge to participants' seated balance. Successfully and safely

completing Maximal Leans appears to have required more cognitive resources than the other tasks, as indicated by significantly lower cognitive DTC. Since the largest DTC occurred during the easiest motor task, Static Sitting, there is reason to believe that seated balance has high attentional demands for individuals who use manual wheelchairs. The next largest DTC occurred during Stationary Propulsion, indicating that the rhythmic arm action also contributes to the attentional demands of wheelchair propulsion. Lastly, findings reveal that individuals who use manual wheelchairs may prioritize cognitive function during motor tasks that are perceived to have low postural requirements or risk.

Seated balance, which is the ability to maintain one's center of mass within stability boundaries while in a seated position, is fundamental for individuals who use manual wheelchairs to safely perform activities of daily living (e.g., reaching, transfers, and propulsion).⁴¹ Maintaining balance requires a complex interplay of sensory processing and motor outputs to detect and correct for changes in posture.^{53,54} The loss of balance suggests a failure within these processes. One potential reason for this could be the inability of higher-order processing centers to provide the necessary attentional resources to support balance. In alignment with the attention capacity model, there is potential for this to occur when dual-tasking^{45,46} and it becomes increasingly likely as the stability requirements for the motor task, and thereby attentional demands, increase.^{23,24}

It is therefore interesting that significant deficits to seated balance were observed during the easiest motor task, Static Sitting. This finding is demonstrative of the high attentional demands to maintaining balance for participants and supports our first hypothesis. Participants continued to experience compromised motor function as they engaged with a form of dynamic balance during Short Leans. Given that the successful completion of Short Leans required a

specific motor pattern with fewer degrees of freedom than Static Sitting⁹², it is unsurprising that participants completed fewer leans instead of altering their trunk accelerations. Stationary Propulsion also yielded significant DTCs to motor function, yet no changes were seen in the use of propulsion patterns from the single- to dual-task trials. This may suggest that the attentional demands associated with arm action can be more attributed to the lack of neural circuitry to support reflexive movement and less so on the individual patterns utilized. However, similar to the difficulties in other investigations⁶⁸, we were limited in our ability to compare the performance of the single and double loop over patterns to the other patterns because they were not observed during the study.

So far, these findings suggest that individuals who use manual wheelchairs prioritize cognitive function over motor function when dual-tasking. However, this insight becomes more nuanced when motor function was maintained during Maximal Leans. It appears as though this was achieved through the relocation of attentional resources from the cognitive task to the motor task. These results are supportive of our second hypothesis and suggests the use of a posture-first approach to dual-tasking. In this context, an individual may select a different dual-tasking strategy (e.g., prioritization of one task over the other) based on their self-efficacy, perception of the task/environment, and objective personal abilities.²⁹ In general, motor function is prioritized at the expense of cognitive function, typically to reduce risk and ensure safety.⁸ This logic appears to be consistent with the current findings, given that a shift in prioritization occurred during the most challenging seated balance task.

What should stand out as a bit concerning, is that maximal physical effort was required to encourage participants to shift their approach to dual-tasking; even though detriments to motor function were present throughout easier tasks. Given that most activities

of daily living are of low intensity, yet require adequate seated balance⁴¹, consistent prioritization of cognitive function may be a contributing factor to negative health outcomes, such as falls.^{41,93–95}

Limitations of the current study include a limited sample size, albeit with a diverse range of physical (e.g., seated postural control) and cognitive abilities. Future research should incorporate a larger sample to further investigate the attentional demanding elements of wheelchair propulsion and determine the correlates of the DTCs of wheelchair propulsion. This information would likely further inform population-specific health outcomes, help the development of CMI interventions for individuals who use manual wheelchairs, and more easily identify those who are appropriate candidates for participation. Preliminary results indicate that interventions should capitalize on physical rehabilitation to improve seated balance and subsequently, positively impact an individual's ability to dual-task.

3.5 Conclusion

Findings suggest that seated balance is likely the primary contributor to the attentional demands of wheelchair propulsion followed by rhythmic arm action. Overall, changes in motor and cognitive function indicate that individuals who use manual wheelchairs may only consider taking a posture-first approach to dual-tasking when the motor task nears maximal effort. The concern with this is that individuals may be more apt to compromise motor function and put themselves at risk (e.g., experience a fall) when in difficult and complex situations.

CHAPTER 4: WHEELCHAIR PROPULSION IN STABLE AND COMPLEX ENVIRONMENTS

4.1 Introduction

Roughly 3.6 million Americans aged 15 years and older use a manual wheelchair.⁴⁸ Although individuals experience benefits from wheeled mobility, such as increased independence and quality of life⁵⁰, they also face unique risks, including environmental hazards/barriers and accidents (e.g., falls).^{50,94} In fact, environmental hazards create enough danger for individuals who use manual wheelchairs that it has been identified as a main fall risk factor within this population.⁴¹ Most falls that occur in complex environments happen when individuals are distracted or multi-tasking and do not ‘perceive’ the environmental hazard, which is most commonly uneven surfaces and obstacles.²⁶

This decline in motor (e.g., wheelchair propulsion) and/or cognitive (e.g., surveying the environment) function when simultaneously performed is emblematic of cognitive-motor interaction (CMI). Simply put, CMI occurs when the performance of one or both dual-tasks is altered in comparison to single-task performance.² This phenomenon is operationalized as an individual’s dual-task costs (DTCs)¹, or the percent change in motor and cognitive performance from single- to dual-task trials.

The allocation of attentional resources has been most commonly explored using two theoretical models, the attention capacity model¹⁰ and the self-awareness prioritization model²⁹. The former believes that individuals have a set amount of attentional resources and the completion of any nonautomatic task will be deducted from the collective pool. Under this model, dual-tasking paradigms, and specifically, DTCs, are a way to gain insight into the

attentional demands of various motor and cognitive tasks. For instance, the additional sensory processing involved with surveying a complex environment for potential hazards may result in greater DTCs to the performance of one or both tasks when walking and talking in a complex environment over a stable environment. This differs from the latter model, which believes that individuals may select a dual-tasking strategy (e.g., prioritization of one task over the other) based on their self-efficacy, perception of the task/environment, and objective physical abilities. Previous research suggests³⁸ that when confronted with increasing environmental complexity, ambulatory healthy and clinical populations exhibited the self-awareness prioritization model, and compromised cognitive function over motor function (i.e., posture first approach). There is reason to believe that individuals who use manual wheelchairs may have heightened attentional demands for mobility, perhaps making them more susceptible to greater deficits in performance.

Unlike the gait cycle, there is little evidence to suggest that equally robust neurological processes support the automaticity of wheelchair propulsion. It also appears that the cutaneous reflex⁶⁶, which is believed to be the primary contributor to the passive elements of wheelchair propulsion, is unable to be modulated by experience to favor performance²¹; as seen in some lower limb reflexes.⁶⁷ This lack of automaticity will inevitably result in the dependence on higher-order processing.¹⁹ A recent study investigated this dependence via wireless functional near-infrared spectroscopy in novices and experienced individuals to wheeled mobility across simple (flat and free of obstacles) and complex (four total obstacles [rough terrain, side slopes, incline ramp, and weaving]) environments.²² Overall, findings illustrated the need for higher-order processes during the simple environment and observed similar brain activity between the groups. Individuals who are experienced in wheeled mobility demonstrated less overall brain activity when compared to novices during the complex environment and had greater activation in

brain areas associated with motor planning. These individuals were also significantly faster than the control group in both conditions. These findings confirm the lack of automaticity in wheelchair propulsion but indicate that dedicated practice of the task can improve motor function and the allocation of cognitive resources.

Determining the CMI during wheelchair propulsion and the influence of environmental complexity can help in the development of rehabilitative interventions and identify suitable candidates to reduce the impact of environmental hazards on their fall risk. Consequently, the purpose of this investigation is two-fold: 1) determine if individuals who use manual wheelchairs experience CMI during wheelchair propulsion in a stable environment and 2) determine if increased environmental complexity impacts the CMI of wheelchair propulsion. For the first purpose, we hypothesize that individuals who use manual wheelchairs will experience CMI due to prioritizing motor function (wheelchair propulsion), as indicated by a greater DTC to cognitive function. For the second purpose, we hypothesized that motor and cognitive DTCs will increase as the environmental complexity increases.

4.2 Methods

4.2.1 Participants

Individuals who participated in the first experimental aim (*Chapter 3*) continued into the second and third experimental aims. The text below offers an overview of participant details. Please refer to Chapter 3 for more information.

Fourteen individuals who use manual wheelchairs (age: 37.8 ± 16.3 ; sex: 8 males, 6 females) participated in the current investigation. The study's inclusion criteria required individuals to, i) be between 18 and 70 years old, ii) utilize a manual wheelchair as their primary

form of mobility, iii) have ≥ 1 year(s) of experience with a manual wheelchair, iv) be able to sit unsupported for ≥ 5 minutes, v) have normal or corrected to normal hearing and vision, and vi) be able to read and speak English. Potential participants were excluded from the investigation if they did not meet these criteria, had significant cognitive impairment as indicated by a score of < 20 on the Modified Telephone Interview for Cognitive Status⁷⁶, or reported to be experiencing upper extremity pain/injury that impacts activities of daily living. Screening for the study occurred over the phone and those who met the inclusion criteria were invited to participate in the investigation. If the individual expressed interest in participating, an informed consent document was shared with them to review and sign via REDCap.⁷⁷ After providing written consent, participants completed five online surveys/questionnaires via REDCap.

All procedures obtained approval from the University of Illinois at Urbana-Champaign (UIUC) Institutional Review Board, and all participants provided informed consent before engaging in research activities.

4.2.2 Study Protocol

Participants began the testing session by completing two baseline assessments of visual function, two assessments of seated balance/postural control, and three assessments of cognitive function. The cognitive assessment, Serial-7 Subtraction⁸, was used throughout testing to determine changes in cognitive function from the single- (i.e., Serial-7 Subtraction only) to dual-task (i.e., wheelchair propulsion and Serial-7 Subtraction) trials. To determine single-task performance, participants verbally received a three-digit number ranging from 150 to 199 and were asked to count backward by sevens for 30 seconds.⁸ Two trials, beginning from different numbers, were completed and the average time-normalized number of correct utterances was

calculated. To ensure accurate completion of the test, researchers read scripted instructions outlining what the test measures and how it is to be performed (*see Appendix B for the recited instructional prompts*). This assessment requires mental tracking (i.e., an internal interfering factor), which often results in greater DTCs than external interfering factors, such as reaction time.⁴ Presenting a cognitive task that is sufficiently challenging is needed to identify if CMI occurs within the current population. To allow for comparisons across experimental aims, the current investigation leveraged participants' single-task cognitive performance from the first experimental aim (*Chapter 3*).

To determine if individuals who use manual wheelchairs experience CMI while navigating a stable environment, participants completed a straight, unobstructed, 35-foot (10.67 m) pathway (Environment 1; **Figure 4.1**). To ensure that pathway lengths were consistent across testing conditions, this distance was set by the measured curvilinear pathway used during subsequent environments. Motor function during Environment 1 was indexed by the average trial completion time (seconds [sec]) and stroke frequency (strokes/sec) over two alternating single- (i.e., wheelchair propulsion only) and dual-task (i.e., wheelchair propulsion and Serial-7 Subtraction) trials.

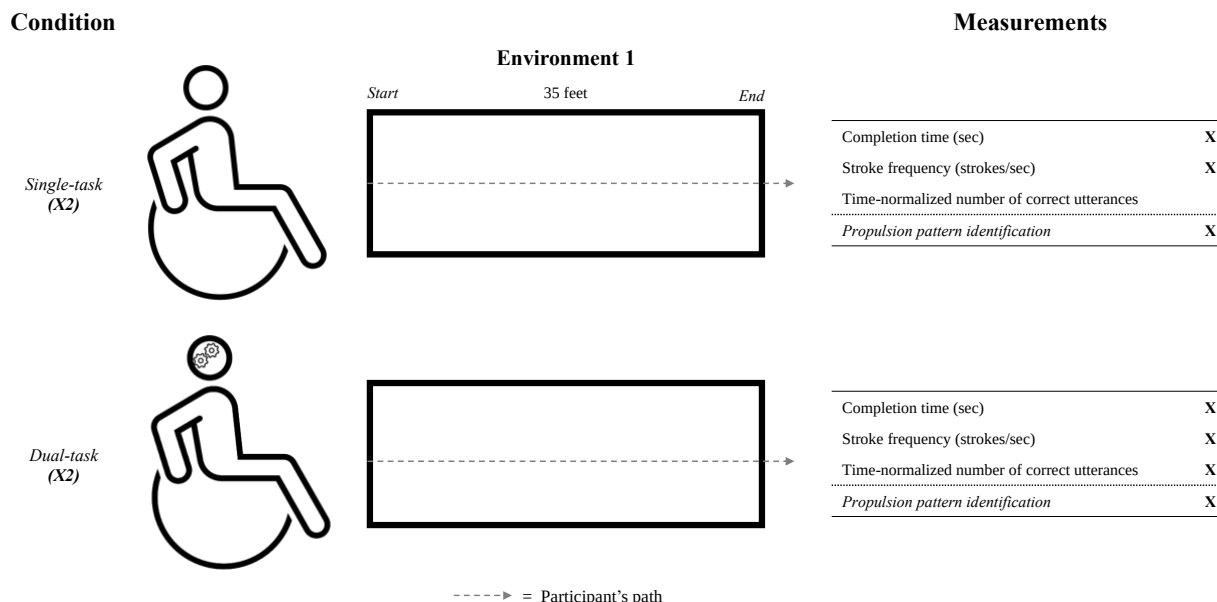


Figure 4.1. Depicts the stable environment testing condition (i.e., Environment 1) and its outcomes measures.

To determine if increased environmental complexity impacts the CMI of wheelchair propulsion, participants completed three distinct curvilinear, obstructed, 35-foot (10.67 m) pathways (Environment 2-4; **Figure 4.2**). Environment 2 required navigation around three traffic cones, Environment 3 required navigation around three traffic cones and over a rumble strip, and Environment 4 required navigation around three traffic cones and over a rumble strip and an elevated surface. Motor function during these conditions was indexed by the average trial completion time (sec), stroke frequency (strokes/sec), and the number of successful obstacles passed (%) during two alternating two single- and dual-task trials.

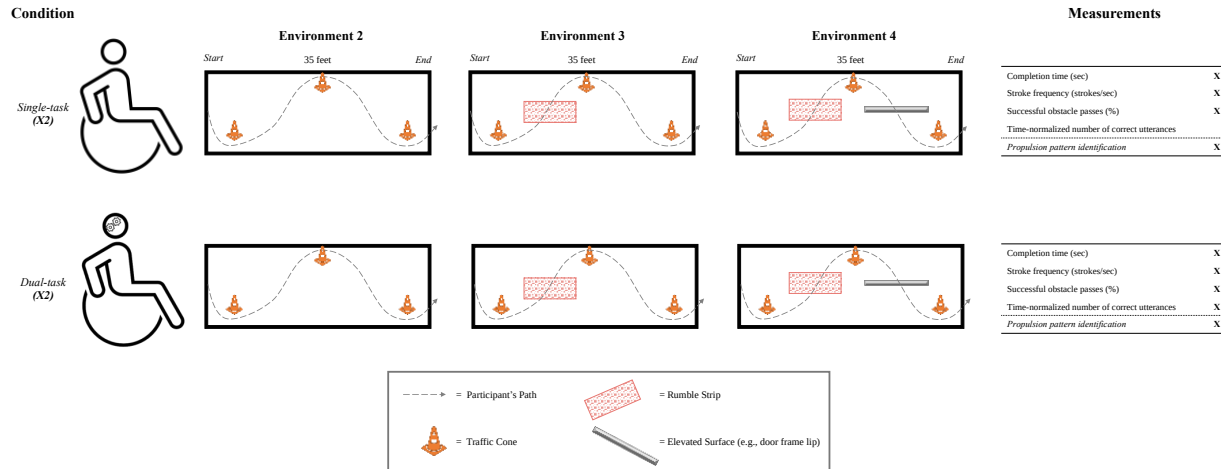


Figure 4.2. Depicts the complex environment testing conditions (i.e., Environments 2-4) and their outcomes measures.

The order of completion for these four Environments was randomized to control for potential practice or ordering effects. Participants were encouraged to perform the single- and dual-task trials “*as quickly and safely as possible*” and were reminded before all dual-task trials to perform their best at both the motor and cognitive tasks (see Appendix B for the recited instructional prompts). Before completing the first assigned environmental condition, the testing site’s floor type (i.e., finished wood or vinyl), brightness, and background noise were recorded via smartphone applications (Light Meter and Decibel X) to account for additional environmental factors that may influence an individual’s performance.

The propulsion pattern(s) utilized during each stroke of the four experimental conditions was also identified. Similar to previous research methods⁷⁴, two experienced raters (using uniform excel workbooks) independently reviewed videos that captured the participant’s sagittal plane while completing the Environments to identify the propulsion pattern of each stroke. The two assessments were compared, and differences were addressed by raters reviewing the stroke or trial together. If a consensus could not be reached, a third experienced rater would review the stroke or trial. The number of strokes used for each of the four possible propulsion patterns (i.e.,

arc, semicircular, single loop over, and double loop over) were summed for the single- and dual-task conditions and reported as a percentage of the total strokes. The differences in propulsion pattern percentages from the single- to the dual-task trials were examined.

4.2.2.1 Outcome Measures

The primary outcome measures for the study are the DTCs of motor and cognitive function during four distinct experimental conditions characterized by increasing environmental complexity. Supplementary analyses were conducted to identify the propulsion pattern(s) used during each stroke of the four experimental conditions.

4.2.3 Statistical Analyses

IBM Statistical Package for the Social Sciences (SPSS) for Windows, version 28 (IBM Inc., Chicago IL) was used to perform all statistical analyses on recorded data with statistical significance set *a priori* at $\alpha=0.05$. The testing site's floor type (i.e., finished wood or vinyl) was documented, and Independent samples *t*-tests were conducted to determine if the motor and cognitive DTCs during the four Environments differed between floor types. Descriptive statistics were calculated (mean $\pm$ standard deviation) for the site's brightness (Lux) and background noise (dB), and Spearman rank-order correlations were performed to determine the association between these factors and motor and cognitive DTCs during the four Environments. Correlation coefficients were considered small ($\rho=0.1$), moderate ($\rho=0.3$), and large ($\rho=0.5$).⁹⁶ If significant differences or associations were observed, the factor in question would be included in the DTC analysis of variance (ANOVA) model as a fixed covariate.

To determine the significant differences between average single- and dual-task trial outcome measures (i.e., completion time, stroke frequency, obstacle passes, and the average time-normalized number of correct utterances) for each experimental condition, a two-tailed paired samples *t*-test was performed on each variable. To further understand these differences, effect sizes (Cohen's *d*) were calculated, and classified as small ($d=0.20$), medium ($d=0.50$), and large ($d=0.80$).⁸⁸ DTCs of motor function were determined by the percentage change in average completion time, stroke frequency, and successful obstacle passes (Environments 2-4) from the single- to dual-task trials ($[(\text{dual-task} - \text{single-task}) / \text{single-task} * 100]$). DTCs of cognitive function were determined by the percentage change in the average time-normalized number of correct utterances verbalized from the single-task to dual-task trials.⁸

Separate within-subjects, repeated-measures ANOVAs were performed to determine significant differences in the DTCs of each measurement (i.e., completion time, stroke frequency, and the time-normalized number of correct utterances) across the four experimental conditions. The same approach was taken to determine significant differences in the DTC of successful obstacle passes, across the three conditions containing obstacles, Environments 2-4. Normality and sphericity were determined through the Shapiro-Wilks and Mauchly's tests, respectively. If violations of sphericity were evident, Huynd-Feldt or Greenhouse-Geisser correction would be applied.⁸⁹ Common recommendations⁹⁰ suggest utilizing a Huynd-Feldt correction when epsilon is >0.75 , and a Greenhouse-Geisser correction when epsilon is <0.75 . Bonferroni post hoc analyses were completed with corrections for familywise error rate and eta-squared (η_p^2) was calculated to better understand the magnitude of differences within the completed ANOVAs.

Interrater reliability for each stroke of the entire data set was determined by calculating the Fleiss' kappa (κ) statistic. Kappa values were classified as none (0–0.20), minimal (0.21–0.39), weak (0.40–0.59), moderate (0.60–0.79), strong (0.80–0.90), and almost perfect (≥ 0.91) interrater reliability.⁹¹ As a rule, kappa values at or above 0.60 indicate adequate agreement among the raters and provides confidence in the study results.⁹¹ Two-tailed paired samples *t*-tests were performed to determine the difference between average single- and dual-task propulsion pattern percentages.

4.3 Results

4.3.1 Participant Demographics

Fourteen individuals who use a manual wheelchair as their main form of mobility (age: 37.8 $\pm$ 16.3; sex: 8 males, 6 females) participated in the current study. Participant demographic information and clinical assessment outcomes can be viewed in tables **Table 3.1** and **Table 3.2**; located in Chapter 3.

4.3.2 Additional Environmental Factors

Two participants completed testing on finished wood floors (e.g., basketball court) while the remaining participants tested on vinyl floors (e.g., dance studio). No differences in cognitive or motor DTCs were observed between floor type ($p=0.15$ - 0.96 ; $d=0.04$ - 1.20). The amount of light illuminating the testing area was 304.1 $\pm$ 23.4 Lux (range: 261.0 – 328.0 Lux) and the amount of background noise was 39.3 $\pm$ 4.7 dB (range: 34.8 – 49.8 dB). While there were no associations between background noise and motor and cognitive DTCs ($p\geq 0.15$; $\rho = -0.41$ - 0.24), Lux displayed large, positive correlations with cognitive DTC observed during Environments 2

($p < 0.01$; $\rho = 0.72$), 3 ($p = 0.04$; $\rho = 0.55$), and 4 ($p < 0.01$; $\rho = 0.70$) (**Figure 4.3**). Cognitive DTC from Environment 1 yielded an insignificant relationship with Lux ($p = 0.10$; $\rho = 0.46$).

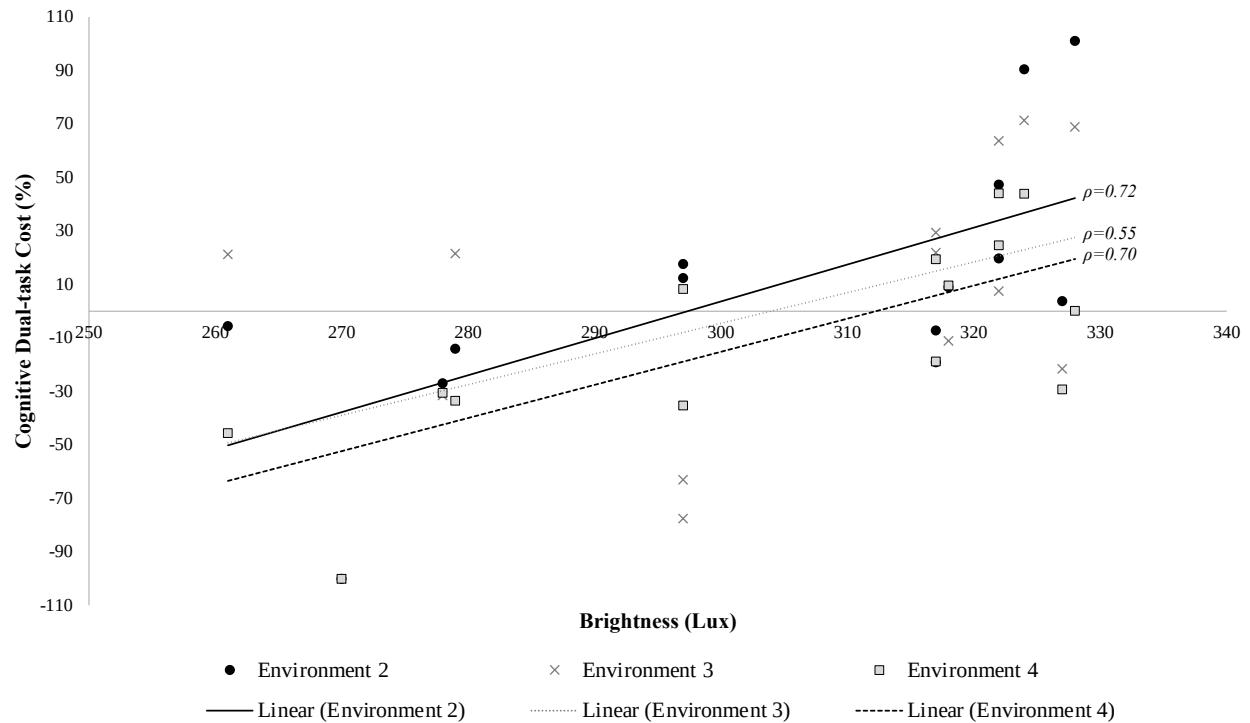


Figure 4.3. Illustrates spearman rank-order correlations (ρ) between the testing site's brightness (Lux) and dual-task costs to cognitive function during Environments 2, 3, and 4. Individual symbols represent participants' cognitive dual-task costs during the three presented environments.

4.3.3 Dual-task Costs

Findings from the paired samples t -tests suggest that participants' cognitive function, as indicated by their time-normalized number of correct utterances during Serial-7 Subtraction, was maintained from the single- to dual-task conditions during all four Environments ($p \geq 0.16$; $d \leq 0.40$) (**Table 4.1**). Environments 1 (DTC: 8.68%) and 2 (DTC: 9.27%) demonstrated a positive percent change, Environment 3 nearly split even (DTC: 0.13%), and the most complex condition, Environment 4, yielded a negative change (DTC: -10.15%). Although this begins to illustrate a trend that cognitive function declines as environmental complexity increases,

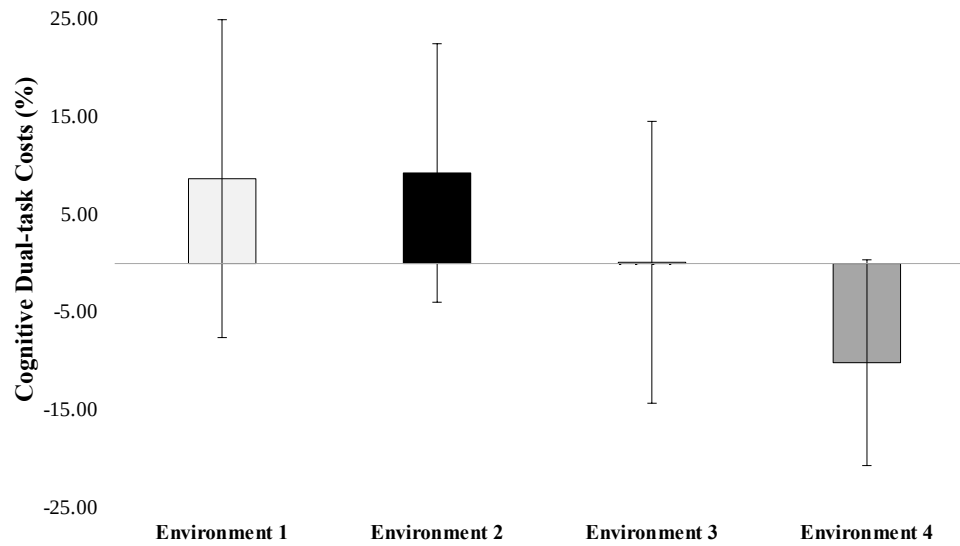
ANOVA results indicate that no significant main effect of condition was observed for participants' cognitive DTC ($p=0.80$; $\eta_p^2=0.03$; observed power=0.11) (**Figure 4.4**).

Table 4.1. Differences from single- to dual-task performance in time-normalized number of correct utterances, completion time, stroke frequency, and successful obstacle passes across four environments. ★ Denotes comparisons between single-and dual-task performance. ** indicates a significant difference where $p \leq 0.01$ and * represents $p < 0.05$. • Indicates a medium effect size and •• indicates a large effect size.

Environment	Dependent Variable	Single-task		Dual-task		Dual-task Costs (% change)		t	p-value★	Cohen's d★
		Mean	SD	Mean	SD	Mean	SD			
1	Time-Normalized Number of Correct Utterances	0.29	0.16	0.35	0.28	8.68	60.8	-1.50	0.16	0.40
	Completion Time (sec)	7.91	5.28	9.29	5.43	20.5	24.3	-2.52	0.03*	0.67•
	Stroke Frequency (strokes/sec)	1.29	0.31	1.14	0.22	-8.92	16.7	2.06	0.06	0.55•
2	Time-Normalized Number of Correct Utterances	0.29	0.16	0.33	0.25	9.27	49.5	-1.05	0.31	0.28
	Completion Time (sec)	11.5	7.89	12.8	8.31	12.5	13.9	-2.83	<0.01**	0.76•
	Stroke Frequency (strokes/sec)	1.34	0.30	1.21	0.20	-8.65	8.75	3.34	<0.01**	0.89••
	Successful Obstacle Passes (%)	95.2	12.1	96.4	9.65	3.57	21.9	-0.27	0.79	0.07
3	Time-Normalized Number of Correct Utterances	0.29	0.16	0.31	0.25	0.13	53.9	-0.43	0.68	0.11
	Completion Time (sec)	12.0	8.22	13.9	10.0	14.6	10.6	-3.44	<0.01**	0.92••
	Stroke Frequency (strokes/sec)	1.36	0.27	1.21	0.27	-10.9	7.37	4.93	<0.01**	1.32••
	Successful Obstacle Passes (%)	96.4	13.4	98.2	6.68	3.57	13.4	-1.00	0.34	0.27
4	Time-Normalized Number of Correct Utterances	0.29	0.16	0.27	0.18	-10.2	39.4	0.74	0.47	0.20
	Completion Time (sec)	13.8	9.15	15.8	11.3	13.1	13.7	-2.70	0.02*	0.72•
	Stroke Frequency (strokes/sec)	1.30	0.21	1.21	0.21	-6.50	7.94	3.09	<0.01**	0.83••
	Successful Obstacle Passes (%)	97.1	7.26	95.7	8.52	-1.43	5.35	1.00	0.34	0.27

For participants' motor function (i.e., completion time, stroke frequency, and successful obstacle passes), paired samples *t*-tests illustrated significant increases ($p \leq 0.03$; $d \geq 0.67$, DTC: ~13 to 20%) in completion time from the single- to dual-task trials during all four Environments (**Table 4.1**). Significant decreases (DTC: ~-7 to -11%) to stroke frequency were also observed during Environments 2-4 ($p \leq 0.01$; $d \geq 0.83$) and neared significance in Environment 1 ($p=0.06$; $d=0.55$) (**Table 4.1**). Participants' ability to successfully navigate obstacles was maintained (DTC: ~-1 to 4%) from the single- to dual-task trials during all four Environments ($p \geq 0.34$; $d \leq 0.27$) (**Table 4.1**). Results from the ANOVA models indicate that no significant main effects of condition were observed for participants' motor DTCs; completion time ($p=0.37$, $\eta_p^2=0.08$; observed power=0.27), stroke frequency ($p=0.62$; $\eta_p^2=0.04$; observed power=0.16), and successful obstacle passes ($p=0.66$; $\eta_p^2=0.03$; observed power=0.11) (**Figure 4.4**).

A.



B.

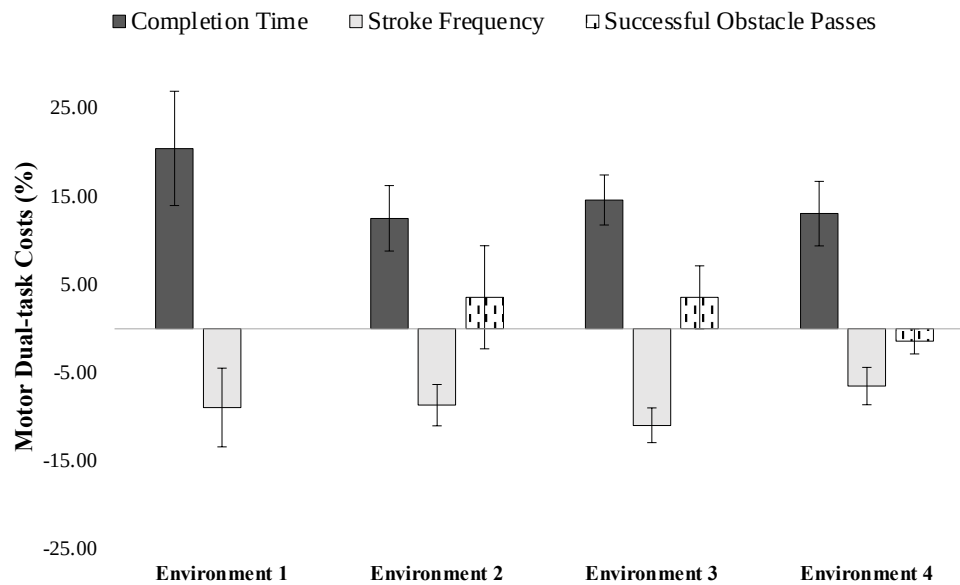


Figure 4.4. Panel A illustrates the cognitive dual-task costs across the four Environments. Panel B illustrates the motor dual-task costs of the four Environments. Values are reported as mean $\pm$ standard error. Note: with exception of completion time, positive dual-task costs are indicative of improved performance.

4.3.4 *Propulsion Patterns*

Strong to almost perfect ($\kappa=0.90-0.94$) interrater reliability was achieved when identifying the propulsion pattern used during each stroke of the four Environments ($p<0.01$). No participants were seen to employ the single loop over or double loop over stroke patterns throughout all four Environments. Participants exclusively utilized the arc propulsion pattern during the single and dual-task trials of Environments 2 and 3.

During the single-task trials of Environment 1, $69\pm39\%$ and $26\pm38\%$ of all strokes utilized arc and semicircular stroke patterns, respectively. During dual-task trials of Environment 1, $69\pm42\%$ of strokes utilized the arc pattern, and $37\pm46\%$ utilized the semicircular pattern. These changes in average propulsion percentages of arc ($p=0.99$; $d<0.01$) and semicircular ($p=0.18$; $d=0.38$) did not yield significant differences between single and dual-task trials. During Environment 1, eight participants exclusively used the arc pattern, one exclusively used the semicircular pattern, and five utilized both the arc and semicircular patterns. All five began the trials with the arc pattern and switched to the semicircular pattern after one to three strokes. Only one individual reverted to using the arc propulsion pattern at the end of their trials.

During the single-task trials of Environment 4, $68\pm7\%$ and $2\pm7\%$ of all strokes utilized arc and semicircular stroke patterns, respectively. During dual-task trials of Environment 4, $95\pm17\%$ of strokes utilized the arc pattern, and $5\pm17\%$ utilized the semicircular pattern. These changes in average propulsion percentages did not yield significant differences between single and dual-task trials ($p=0.34$; $d=0.27$, both). Overall, only one individual utilized the arc and semicircular patterns during Environment 4, and a clear pattern of use (e.g., begins with arc and switches to semicircular) was not present.

4.4 Discussion

The purpose of the current investigation was to determine if individuals who use manual wheelchairs experience CMI during wheelchair propulsion in a stable environment and if increased environmental complexity impacts the CMI of wheelchair propulsion. To achieve these objectives, participants completed single- and dual-task trials of four unique Environments varying in complexity. The research team's first hypothesis was that individuals who use manual wheelchairs would experience CMI within a stable environment due to prioritization of motor function, as indicated by a greater deficit (DTCs) to cognitive function. Results from the study do not support this hypothesis. The CMI observed during the stable environment was due to the prioritization of cognitive function, as indicated by significant deficits in motor function. Our second hypothesis stated that greater motor and cognitive DTCs would be observed as environmental complexity increased. Due to similarities in motor and cognitive DTCs across the environmental conditions, this hypothesis was also not supported.

In a stable environment, deficits in wheelchair propulsion may be synonymous with observed deficits in gait variables (e.g., speed, step-width, and step-length) when ambulatory adults engage in a dual-tasking activity.^{8,13,14} However, the approach to dual-tasking between many ambulatory populations and individuals who use manual wheelchairs appears to be different. Opting to compromise wheelchair propulsion over cognitive function as complexity increases may indicate a posture second approach to dual-tasking⁴⁷, which is less common and riskier than a posture first approach. Prior research investigating the impact of environmental complexity on CMI demonstrated that older adults⁹, those with multiple sclerosis⁸, and healthy controls⁸ preserved motor function as complexity increased at the expense of cognitive function. The prioritization of motor function suggests that attentional resources may be flexible and able

to be directed in a manner that best serves the individual. This concept was proposed in the self-awareness prioritization (behavior) model²⁹, which takes a more behavioral-based approach to describe dual-task outcomes than other theoretical models (e.g., attention capacity¹⁰ and bottleneck³⁰ models). This model focuses on hazard estimates, generated by an individual's task-specific self-efficacy and postural reserve (objective physical abilities). Given the mobility challenges that often accompany aging and multiple sclerosis, it is understandable that an individual might prioritize walking over cognitive performance in a high-risk situation.

In the current investigation, cognitive DTCs were statistically similar across the four Environments. However, an emerging trend illustrates a decline in cognitive function with the increase in environmental complexity. Although speculative, this too may indicate the reallocation of attentional resources from the cognitive task to the motor task. Over time, if this trend does not strengthen, it begs the question, why might individuals who use manual wheelchairs rely on a posture-second approach for dual-tasking? Based on the self-awareness prioritization model, it could be two likely possibilities; this population has exceptionally high self-efficacy or postural reserve. Apart from Maximal Leans, significant DTCs were recorded throughout all motor tasks of this experiment (*Chapters 3 & 4*), with the largest DTC occurring during the easiest motor task, Static Sitting. If participants had exceptionally high postural reserve these findings might be less likely, indicating that perhaps participants are exhibiting high self-efficacy. The concern with this approach is that individuals may be more likely to experience negative outcomes (e.g., falls) due to regularly compromised motor function or overconfidence in one's abilities. Potential evidence for this can be seen in a recent investigation that suggests individuals with a low concern for falling were more likely to experience multiple

falls, than their higher concerned counterparts.⁹⁷ Unfortunately, these events may be downstream from poor hazard estimates and self-awareness of physical limitations.

Working to align an individual's perceived and objective abilities appears to be an important factor to include in personalized CMI interventions, but additional evidence is warranted. Future research should seek to understand the relationship between personality/risk-taking behavior⁹⁸ and inherent dual-tasking approaches. In the meantime, immediate actions can be taken to support an individual's dual-tasking abilities, such as encouraging adequate lighting in a home or work environment. Results from the current study illustrate strong positive relationships between the brightness of complex environments and cognitive function. Being able to easily identify obstacles may reduce sensory processing and allow for more resources to be allocated to the task at hand.

Limitations of the current study include a relatively small sample size and compromised ecological validity. While the current sample size (n=14) may be limited, it consists of a diverse pool of participants ranging in factors such as the reason for and duration of wheeled mobility and physical and cognitive abilities. This variation makes significant findings with medium to large effect sizes arranged in a consistent pattern across experimental conditions compelling. As for ecological validity, it can be disputed that Serial-7 Subtraction is not representative of a typical, community-based dual-tasking activity. However, this test allowed for the control of cognitive task difficulty within and between numerous experimental conditions. This feature was necessary for the current investigation to identify changes to the attentional demands of newly presented obstacles. Increasing environmental complexity across experimental conditions required the addition of new obstacles. While some obstacles were taken directly from a community setting (e.g., rumble strip), testing was still performed in a controlled laboratory.

Lastly, it is possible that the Environments weren't challenging enough to result in increased attentional demands.

4.5 Conclusion

The current study is the first to investigate the presence of CMI in individuals who use manual wheelchairs while navigating stable and complex environments. Overall, significant deficits in motor function were seen in all Environments while cognitive function was maintained. Furthermore, the observed motor and cognitive DTCs were similar between Environments. These findings collectively suggest that wheelchair propulsion in a stable environment is attentionally demanding, individuals who use manual wheelchairs may prioritize cognitive function over motor function despite the surrounding complexity, and that laboratory-based environmental complexity does not pose significantly greater attentional demands to individuals who use manual wheelchairs. There is, however, some evidence to believe that other environmental factors, such as the testing site's brightness, could influence cognitive dual-task performance.

CHAPTER 5: CONCLUSION & FUTURE DIRECTIONS

5.1 Overview

Numerous investigations have sought to understand the attentional demands of balance and mobility in ambulatory populations, yet no literature on the topic has existed for individuals who use manual wheelchairs. Understanding the impact of the kinesthetic contributions (seated balance and arm action during stationary propulsion) and environmental complexity on the attentional demands of wheelchair propulsion can expand the application of cognitive-motor interaction (CMI) theoretical models and interventions and provide initial evidence for a potential new population-specific fall risk factor.

Overall, results from the current investigation indicate that: 1) of the four motor tasks, Static Sitting yielded the greatest dual-task costs (DTCs), suggesting that seated balance may be the primary contributor to the attentional demands of wheelchair propulsion, 2) wheelchair propulsion in a stable environment is attentionally demanding and yields CMI, and 3) environmental complexity may not pose additional attentional demands to individuals who use manual wheelchairs. Apart from Maximal Leans, significant deficits in motor performance were seen across all motor tasks and Environments while cognitive performance was maintained. Such findings have positive and negative implications. The ability to shift to a posture-first approach during a challenging seated balance task demonstrates cognitive flexibility and the opportunity for targeted interventions. However, the consistent use of a posture-second approach (during sub-maximal activities) raises concern that individuals who use manual wheelchairs may frequently put themselves at risk by comprising their motor function. These insights provide evidence that

the attention capacity model may not comprehensively describe the observed changes during dual-task performance, and that the behavior model is also needed.

5.2 Future Research

5.2.1 Immediate Next Steps

The cognitive and motor tasks utilized in the current proposal to understand the DTCs of wheelchair propulsion were Serial-7 Subtraction, four motor tasks, and four 35-foot pathways, varying in stability requirements and environmental complexity, respectively. Along with replicating the methodology of the current investigation, a deeper understanding of motor and cognitive DTCs in individuals who use manual wheelchairs might be achieved by exploring various dual-task combinations that range in difficulty, such as the performance of Serial Subtraction in ones⁹⁹ and threes¹⁴, verbal fluency¹⁰⁰, and the Symbol Digit Modality Task⁸⁴ in conjunction with wheelchair propulsion at various inclines/declines, in the presence of different obstacles, within virtual reality, and in outdoor environments. The methods of virtual reality may be uniquely suited to investigate the influence of motion information (e.g., optic flow and environmental distractions) and directional decision-making on the CMI during wheelchair propulsion. Future researchers could also leverage technology, such as functional near-infrared spectroscopy, to monitor the use of executive control resources within the prefrontal cortex during single and dual-task activities.¹⁹

Another promising avenue would be to collect a large enough sample size to determine the correlates of the DTCs of wheelchair propulsion. This information will likely further inform population-specific health outcomes (e.g., fall risk), help develop CMI interventions for individuals who use manual wheelchairs, and more easily identify appropriate candidates for

intervention participation. While numerous associations with demographic and clinical measures could be investigated, primary efforts should focus on perceived abilities, risk-taking behaviors, and fall-risk factors. Understanding the contribution of one's perceived abilities²⁹ and risk-taking behaviors⁹⁸ could provide insight into the use of a posture second approach to dual-tasking. Although speculative, this riskier approach to dual-tasking might contribute to the high frequency of falls in this population. Consequently, determining the associations between the following potential fall-risk factors might be appropriate: fall prevalence in the past 6 months, the Spinal Cord Injury Fall Concerns Scale⁷⁹, the World Health Organization Quality of Life Questionnaire⁸¹, and the Community Participation Indications⁸⁰, the Function in Sitting Test^{56–58}, the Trunk Control Test⁵⁹, the Wheelchair Skills Test⁷⁸, the Transfer Assessment Instrument¹⁰¹, American Spinal Injury Association Impairment Scale¹⁰², The Wheelchair User's Shoulder Pain Index¹⁰³, the Alcohol Use Disorders Identification Test¹⁰⁴, and cognitive assessments (e.g., the Symbol Digit Modality Task⁸⁴, Serial Subtraction⁸, Stroop Test¹⁰⁵, etc.).

5.2.2 CMI Interventions

Findings from Aim 1 (*Chapter 3*) helped identify the degree to which seated balance contributes to the attentional demands of wheelchair propulsion. Given the evidence to suggest that attentional demands of a task may increase as the stability requirements of the tasks increase^{23,28}, then improving an individual's seated balance should, in theory, lower the overall attentional demands of wheelchair propulsion. Fortunately, improvements to seated balance were achieved in a pilot fall prevention intervention for individuals who use wheeled devices.²⁷ Building off these efforts may be a feasible starting place for CMI interventions.

5.2.3 Assistive Technology

While environmental hazards have been recognized as a main fall risk factor for individuals who use manual wheelchairs⁴¹, there are no formal means of attenuating this dilemma on an individual basis. Technological developments may be uniquely suited to help alleviate the attentional demands of identifying potential hazards in a real-world setting (e.g., splits in the sidewalk/road, rumble strips, etc.). Initial end-user insights further support this notion by reporting a willingness to adopt discrete assistive technology that supports their independence and safety, particularly concerning falls and their environment.⁴⁰ Reactive hazard detection and avoidance technology might be one possible solution to consider, albeit much more research and consideration are warranted.

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APPENDIX A: PARTICIPANT RECRUITMENT EFFORTS

Numerous recruitment avenues were perused during the current investigation. To begin, individuals from the Disability Participation and Quality of Life subject pool, known contacts, and Disability Resources & Educational Services (DRES) Research Registry received a study description and research flyer via email (n=183). Individuals within these databases have participated in prior research and provided an interest in being contacted again for future studies.

To engage with a broader audience, physical researcher flyers were posted around the University of Illinois at Urbana Champaign and University of Kansas Medical Center's campuses and communities, online announcements were made through eWeeks (weekly) and social media platforms (e.g., Facebook), and individual groups/organizations were contacted to provide study details to be shared with their patrons. The following is a categorical list of these groups/organizations and the number of individual establishments that were contacted: academic advisors (n=9), assisted living communities (n=11), places of worship (n=10), adaptive sports coaches/teams (n=20), rehabilitation support groups/centers (n=33). Lastly, those that did participate in the study were encouraged to share the opportunity through personal networks and word of mouth.

APPENDIX B: INSTRUCTIONAL PROMPTS

Serial-7 Subtraction: “This next test will measure an aspect of cognitive function. I will provide you with a random three-digit number. When the test begins, I would like you to count backward out loud from this number by sevens. For example, if I gave you the number 100, you would say out loud ‘93, 86, 79, 72, 65...’ and so on until time is up. During the test, please be sure to clearly vocalize your responses. Do you have any questions?”

Experimental Aim 1 Testing

Single-task: “We will now complete a series of four, 30-second motor tasks, including static sitting, leaning forward and backward to 50% of your maximal lean distances, leaning forward and backward to your maximal leaning distances, and stationary propulsion. While these tasks will be described in this order, they will be completed in a randomized order during testing. All tasks except for stationary propulsion will be completed on a matted table. Stationary propulsion will be completed in your wheeled device. For static sitting, please sit still with your best posture and balance. Based on your performance during maximal forward and backward leans, we will set up a string in front and behind you to indicate how far would like you to lean during the two leaning tasks. Please make an effort to touch these strings with your chest and back during testing. Before the stationary propulsion trials, we will complete a 3-minute warm-up on the rollers at a self-selected comfortable pace. A 2-minute rest period will follow. For the stationary propulsion trials, I will ask you to select and maintain a pace that most closely resembles being late to class or work. Please be sure that this pace is sustainable for four. 30-second trials. I would prefer if you could perform the tests without using your hands for balance, but if you need

to use your hands, to steady or re-center yourself, you can [show example]. I will be right here next to you to make sure you are safe if you lose your balance. Do you have any questions?”

Dual-task: “I will now be asking you to complete these motor tasks while counting backward by sevens from an assigned three-digit number. We will complete two trials of each task, and for each trial, you will be given a new number to start from. During the testing, be sure to clearly vocalize your responses to the cognitive assessment and avoid using your hands for balance if possible. Please try your best at both tasks. I will be right beside you during the trials in the event you lose your balance. Do you have any questions?”

Experimental Aim 2 Testing

Dual-task: “I will now be asking you to complete this 35-foot course while counting backward by sevens from an assigned three-digit number. We will complete two trials, and for each trial, you will be given a new number to start from. As previously mentioned, please try to complete the trial as quickly and safely as possible and be sure to clearly vocalize your responses to the cognitive assessment. During the testing, please try your best at both tasks. I will be walking right beside you during the trials in the event you lose your balance. Do you have any questions?”

Experimental Aim 3 Testing

Dual-task: “I will now be asking you to complete a 35-foot obstacle course while counting backward by sevens from an assigned three-digit number. For each trial, you will be given a new number to start from. As previously mentioned, please try to complete the trial as quickly and

safely as possible and be sure to clearly vocalize your responses to the cognitive assessment. During the testing, please try your best at both tasks. In total, we will complete two trials of each of the six experimental conditions. Please let me know if you would like to take a break or get water at any point during the testing. I will be walking right beside you during the trials in the event you lose your balance. Do you have any questions?”

APPENDIX C: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER



Office of the Vice Chancellor for Research & Innovation

Office for the Protection of Research Subjects
805 W. Pennsylvania Ave., MC-095
Urbana, IL 61801-4822

Notice of Approval: New Submission

November 17, 2021

Principal Investigator	Laura Rice
CC	Mikaela Frechette
Protocol Title	<i>Cognitive-motor interaction during wheelchair propulsion</i>
Protocol Number	22273
Funding Source	Unfunded
Review Type	Expedited 4, 6, 7
Status	Active
Risk Determination	No more than minimal risk
Approval Date	November 17, 2021
Closure Date	November 16, 2026

This letter authorizes the use of human subjects in the above protocol. The University of Illinois at Urbana-Champaign Institutional Review Board (IRB) has reviewed and approved the research study as described.

The Principal Investigator of this study is responsible for:

- Conducting research in a manner consistent with the requirements of the University and federal regulations found at 45 CFR 46.
- Using the approved consent documents, with the footer, from this approved package.
- Requesting approval from the IRB prior to implementing modifications.
- Notifying OPRS of any problems involving human subjects, including unanticipated events, participant complaints, or protocol deviations.
- Notifying OPRS of the completion of the study.

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