

The effect of dual-task difficulty on automatic and conscious postural control

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Abstract

Young healthy adult posture-cognition dual-task (DT) control relies on some degree of automatic mechanisms; however, the use of automatic control strategies while dual-tasking, in various contexts, has received little attention. This thesis aimed to examine how combined manipulations of postural and cognitive tasks influenced automatic and conscious postural control strategies. Chapter 2 focused on cognitive task difficulty (six levels) under two postural challenges. Findings showed automaticity to increase when distracted; this increase did not depend on the postural challenge and cognitive task difficulty. Chapter 3 considered combined postural (six levels) and cognitive (two levels) task challenges. Findings demonstrated that some automatic control remained despite stability challenges; however, relatively less automatic control may be used when the overall DT challenge increases. Together these findings suggest that young healthy adults continue to use some automatic mechanisms when distracted in various DT contexts.

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List of Abbreviations

ANOVA	Analysis of Variance
AP	Anterior-Posterior
BOS	Base of Support
CMP	Conscious Motor Processing
COM	Centre of Mass
COP	Centre of Pressure
DT	Dual-Task
DTC	Dual-Task Cost
EC	Eyes Closed
EO	Eyes Open
HMD	Head Mounted Display
ML	Medial-Lateral
MSRS	Movement Specific Reinvestment Scale
PSD	Power Spectral Density
RMS	Root Mean Square
SampEn	Sample Entropy
SD	Standard Deviation
ST	Single-Task

Study 1 Cognitive Conditions

m3	Subtraction by 3s or minus 3s
m3.3	Subtraction by 3.3s or minus 3.3s
m7	Subtraction by 7s or minus 7s
m7.7	Subtraction by 7.7s or minus 7.7s
p3	Addition by 3s or plus 3s
QS	Quiet Standing

Study 2 Stance Conditions

EOF	Eyes open, firm surface
ECF	Eyes closed, firm surface
SRF	Sway-referenced visual surround, firm surface
EOS	Eyes open, foam (soft) surface
ECS	Eyes closed, foam (soft) surface
SRS	Sway-referenced visual surround, foam (soft) surface

Chapter 1: Introduction

Multi-task interactions are common when completing activities of daily living (e.g., standing upright while washing dishes and talking on the phone). While completing various tasks at once, individuals are challenged to divide their attention amongst to be completed tasks. Even seemingly simple tasks, such as standing upright, requires some attentional involvement to remain stable (Woollacott & Shumway-Cook, 2002). Attention allocation requirements of the overall task can vary depending on the relative load or difficulty imposed by task components, which can pose challenges for individuals to appropriately divide their attention between tasks to remain upright. Simplifying multi-task interactions as dual-task (DT) interactions can assist in understanding the mechanisms behind multi-task interactions. Given that remaining upright is critical to individual safety and fall avoidance when completing activities of daily living, understanding mechanisms underlying DT interactions and postural control can help explain how individuals are able to do various tasks at once and can encourage informed strategies or advice to remain stable.

This thesis consists of four chapters. Chapter 1 includes a literature review outlining the concepts of upright stance, dual-tasking, DT difficulty, and automatic postural control. A conceptual model of the proposed thesis is presented along with the objectives of the studies completed. Two studies were completed to answer the research questions. Chapter 2 focuses on Study 1, and Chapter 3 focuses on Study 2. Chapter 4 presents a general discussion that brings findings from Study 1 and Study 2 together, reflects on the conceptual model, and includes the overall takeaway messages from this thesis.

1.1 Literature review

1.1.1 Postural control

Bipedal stance is a seemingly simple yet fragile stance position common in everyday life. It requires the integration of three main sensory modalities: visual, vestibular, and somatosensory (Peterka, 2002). Each of these modalities provides feedback on the body's orientation in the visual environment, relative to Earth's vertical, and relative to the support surface, respectively (Peterka, 2002). Mechanically, upright stance can be modelled as an inverted pendulum with the body representing a rigid portion pivoting at the ankles. Deviating from an upright position (e.g., leaning forwards) imposes a moment due to gravity that pulls the body away from the original upright stance position. Sensory modalities can provide sensory feedback signaling the deviation (Peterka, 2002). To bring the body back to the original upright position, a corrective torque may be applied to counter this deviation to maintain an upright body position (Peterka, 2002), or the body may react to bring the body back to the original position (Loram & Lakie, 2002).

Postural stability may be lost when upright stance is not preserved, which can be indicated when one's centre of mass (COM) falls outside their base of support (BOS). The COM is the origin of the downward vertical force vector acting on the body from gravity and can be conceptualized as the weighted average of each body segment's COM in space (Winter et al., 2009). One's BOS refers to a region surrounding an individual's feet (i.e., their base). Increases in postural sway can lead one to sway closer to the edges of their BOS. Postural sway can be measured through force platforms and associated centre of pressure (COP; i.e., the average value of all ground reaction forces under the feet) analyses (Winter et al., 2009).

1.1.2 Dual-task paradigms

DT paradigms can be used to further challenge the postural system. Dual-tasking is defined as concurrently performing two tasks with distinct goals that can be performed and measured independently (McIsaac et al., 2015). In static upright stance DT studies, the posture or stance task may be one task, and a cognitive task may be another. Dual-tasking can result in interactions between the two tasks, which can include decrements or improvements in one or both tasks (Bayot et al., 2018). No change in either task may reflect a non-observable or absent DT interaction.

While postural control has been thought to be a highly automatic task that requires minimal conscious effort to remain upright (Roerdink et al., 2011), there is some attentional involvement in postural control (Woollacott & Shumway-Cook, 2002). Attention, in this context, refers to an individual's information processing capacity; each task (i.e., posture and cognitive tasks) is proposed to require a portion of one's processing capacity (Woollacott & Shumway-Cook, 2002). Interference may become evident when the total required processing capacity needed to complete cognitive tasks is not readily available. Divided processing capacity or a delay in processing may lead to DT interactions. Evidence of posture-related DT interactions, and thus attentional involvement in postural control, is present when assessing differences between postural sway outcome measures (e.g., COP area) with and without a cognitive task; details regarding these differences are expanded upon further below. Posture DT interference has been explained by various models (Bayot et al., 2018; Rizzato et al., 2021; Wulf et al., 2001). Three common models—the Capacity Sharing model, the Bottleneck model, and the Constrained-Action hypothesis—of DT interactions are outlined next.

1.1.2.1 Dual-task models

The Capacity-Sharing model proposes that posture-cognition interference occurs because of a limited-capacity parallel processor in which cognitive resources are divided among tasks to be completed (Bayot et al., 2018). While dual-tasking, dividing a finite source of attentional resources is suggested to result in a relative reduction of the total attention allocated to each task and impaired performance in at least one task (Bayot et al., 2018). Further, the Bottleneck model supposes that DTs are serially processed (Bayot et al., 2018). It is proposed that one task is processed at a time and the delay in processing results in impaired performance in one or both tasks (Bayot et al., 2018). Within posture DT studies, these theories are used to explain increased sway amplitude outcomes (Lanzarin et al., 2015; Morelli et al., 2020) since an increase in sway (representing poorer control in this context) is assumed to be due to a reduction of attention directed to control body sway due to some attention allocated to the cognitive task.

Alternatively, the Constrained-Action hypothesis proposes that internally focusing attention on a task (e.g., focusing on standing still) interferes with the natural automatic processes that regulate the task, whereas externally directing attention away from a task (e.g., focusing on a target ahead of an individual to divert attention away from the body) allows for less constrained and more automatic (i.e., more unconscious) task organization (Wulf et al., 2001). Since an internal focus is understood as a type of conscious control that may interfere with a motor task and an external focus diverts conscious resources elsewhere, external focus conditions are suggested to allow for less constrained control processes to naturally regulate movement (e.g., postural sway) (Wulf et al., 2001). DTs can mimic such external foci by encouraging attention to be diverted away from a posture task (Donker et al., 2007; Nafati & Vuillerme, 2011). Some posture DT studies support this relationship since standing upright while

completing a cognitive DT has been shown to decrease sway amplitude (Polskaia & Lajoie, 2016; Potvin-Desrochers et al., 2017; Resch et al., 2011; Ross et al., 2011; St-Amant et al., 2020), which is suggested to reflect less constrained and reduced interference with automatic control processes to regulate postural sway.

1.1.2.2 Applying dual-task models

DT models can be used to predict posture DT study outcomes. The Capacity-Sharing and Bottleneck models are used to explain DT interference in study populations of healthy older adults (i.e., seniors) and older adults with a history of falls (Huxhold et al., 2006; Rizzato et al., 2021; Shumway-Cook et al., 1997). It has been suggested that this older population may receive less sensory information to assist in remaining upright (Woollacott, 2000), such as through a reduction in the ability to integrate, and weigh, sensory inputs (Horak, 1989). In turn, older adults may require more attentional resources to remain upright, compared to younger adults (Woollacott, 2000). Applying the Capacity-Sharing model, adding a cognitive task that uses similar attentional resources as stance would predict that there would be a reduction of attentional resources available to regulate sway (Ward et al., 2022); postural interference would be illustrated as an increase in COP behaviour measures implying less sway control. Further, following the Bottleneck model, a delay in available attentional resources would lead to an increase in sway due to a delay in attentional processing to control sway (Ward et al., 2022). Older adults show this outcome since, with the addition of a DT, their sway amplitude has been shown to increase (Bernard-Demanze et al., 2009; Rizzato et al., 2021; Shumway-Cook & Woollacott, 2000; Shumway-Cook et al., 1997), which can imply less sway control.

In contrast, the Constrained-Action hypothesis is used to justify posture DT outcomes in healthy and young populations (Nafati & Vuillerme, 2011; St-Amant et al., 2020). Compared to seniors, healthy young adults have effective sensory modalities and have demonstrated less attentional involvement in postural control compared to older adults since young adults have maintained control of their postural sway under conditions older adults have not (Bernard-Demanze et al., 2009; Potvin-Desrochers et al., 2017; Shumway-Cook & Woollacott, 2000). Young adult DT study outcomes have shown a decrease in COP amplitude measures under DT conditions compared to single-task (ST) conditions (Andersson et al., 2002; Bernard-Demanze et al., 2009; Dault et al., 2001; Polskaia & Lajoie, 2016; Potvin-Desrochers et al., 2017; Resch et al., 2011; Ross et al., 2011; St-Amant et al., 2020; Vuillerme & Vincent, 2006), which supports the notion of an external focus removing attention from stance allowing for greater automatic sway regulation.

These relationships between cognitive tasks and postural sway may have some dependence on the attentional requirements of each task. Young adults have been shown to mimic behaviours observed in DT studies involving older adults by demonstrating increases in sway while completing a cognitive task under challenging stance conditions (e.g., varying the sensory modalities available) (Andersson et al., 2002; Lanzarin et al., 2015; Morelli et al., 2020). Teasdale et al. (1993) suggested that when standing upright under conditions of reduced sensory input, upright stance requires a greater attentional capacity. Given that individuals tend to prioritize stability at the extent of other tasks (Bloem et al., 2001) and despite the evidence for automatic control in young and healthy adult DT studies, the degree of automaticity elicited may be limited in instances when either the stance task or the cognitive task requires greater attention.

1.1.3 Dual-task difficulty

Throughout the literature, posture DT studies vary by the type of stance conditions and cognitive conditions used. DT interactions may depend on the relative difficulty of the posture and cognitive task (Bernard-Demanze et al., 2009; Donker et al., 2007); completed alone and concurrently. Studying DT interactions with various stance and cognitive conditions can help uncover and explain the mechanisms underlying DT postural control.

1.1.3.1 Upright stance difficulty

Bipedal stance difficulty can vary depending on the BOS size, sensory modalities available, or both. Variations in foot placement (e.g., shoulder width, feet together, heel-to-toe) manipulate the size of one's BOS. Standing with feet together compared to standing with feet apart can lead to increases in body sway (Albertsen et al., 2017; Rемаud et al., 2012). A smaller BOS reduces the area for the COM to move. When the COM falls outside the BOS the upright position may not be maintained, and stability can be challenged or lost.

A reduction of sensory feedback, such as removing or creating inaccurate sensory inputs, can challenge one's ability to remain stable and lead to increases in body sway (Riley & Clark, 2003; Shumway-Cook & Horak, 1986). Traditionally, the Sensory Organization Test, which consists of six stance conditions, has been used to manipulate upright stance sensory feedback (Shumway-Cook & Horak, 1986). The six conditions are composed of three visual manipulations including present and accurate, absent, as well as present and inaccurate visual input, and two surface manipulations including accurate and inaccurate somatosensory feedback (Shumway-Cook & Horak, 1986). Present and absent visual feedback is typically created by having an individual stand with their eyes open (EO) or eyes closed (EC). Inaccurate visual and

somatosensory input may be created by sway-referencing visual and ankle somatosensory modalities, respectively. Sway-referencing vision entails having participants view an environment that moves in proportion to their sway (Nashner, 1982). To sway-reference ankle somatosensory inputs, a tilting platform is commonly used to tilt in proportion to an individual's anterior-posterior (AP) sway, which results in nulled ankle sensory inputs (Bloem et al., 2003); alternatively, foam surfaces have been used with the intention to distort ankle somatosensory feedback (Shumway-Cook & Horak, 1986).

When maintaining upright stance with a combination of present, absent, and/or inaccurate sensory feedback, sensory reweighting is suggested to occur. Sensory reweighting proposes that the relative emphasis placed on each sensory modality adjusts to compensate for absent (Peterka, 2002) and inaccurate (Shumway-Cook & Horak, 1986) sensory inputs. The challenge of remaining upright with and without sensory modalities can be heightened when attempting to remain upright when reweighting demands are thought to be high (e.g., standing without vision and accurate somatosensory modalities). These sensory modality manipulations have been associated with postural sway increases (Riley & Clark, 2003; Shumway-Cook & Horak, 1986), which leads to the COM approaching the BOS boundaries and, in turn, challenging stability.

1.1.3.2 Cognitive task difficulty

Cognitive task difficulty varies within DT studies. Huxhold et al. (2006) proposed a U-shaped relationship to explain the influence of cognitive task difficulty on sway amplitude measures (e.g., sway area), in which sway amplitude was represented along the y-axis and study conditions were represented along the x-axis. Beginning with an ST condition (i.e., a study condition without explicit cognitive instructions), postural sway would be at a baseline level.

When taking part in a distracting cognitive task, sway amplitude decreases from the baseline level (i.e., the downward or left portion of the U-shaped trend). Then, relative to the bottom of the U-shape, engaging in cognitive tasks that are too challenging, which may require a large amount of attentional resources, may interfere with postural control resulting in sway increases (i.e., the upward or right portion of the U-shaped trend) (Huxhold et al., 2006). The initial sway decrease (i.e., the downward or left portion of the U-shaped trend) can be explained by a demanding cognitive task acting as a sufficient distractor to facilitate reductions in postural sway (Swan et al., 2007). These tasks would be required to continuously direct attention away from stance (Lajoie et al., 2016; Potvin-Desrochers et al., 2017). Considering the later sway increase (i.e., the upward or right portion of the U-shaped trend) tasks found to be too challenging may utilize a greater attentional capacity (Rizzato et al., 2021), and such tasks may not be able to maintain distraction due to the increase in attentional resources required to complete the cognitive task alongside the stance task. Huxhold et al. (2006) showed that the U-shaped relationship was more obvious in an older adult compared to a younger adult population; they suggested that engaging in a cognitive task, without any stance manipulations, was not enough to tax a young adult postural control system.

The relative load of a cognitive task can influence the significance allocated to the cognitive task. This can relate to dividing or allocating attentional resources between DT components (Bayot et al., 2018). Studies have assessed how working memory cognitive tasks influence postural sway (Dault et al., 2001; Riley et al., 2003; Swan et al., 2004; VanderVelde et al., 2005). Working memory refers to the process of holding information (Harvey, 2019) and can be manipulated to vary cognitive task load. Baddeley (1983) discussed a model for working memory that includes a central executive allocating to be stored information in a phonological

loop (i.e., storing auditory information) or a visual-spatial scratch-pad (i.e., storing images of physical aspects of an item). Studies have proposed numeric tasks to utilize working memory resources (Bristow et al., 2016; Raghubar et al., 2010) and the visual-spatial scratch-pad (Chong et al., 2010). Specific to numeric tasks, working memory demands are manipulated by varying the number of digits to recall (e.g., recalling digit strings) (Bustillo-Casero et al., 2017; Nafati & Vuillerme, 2011; Riley et al., 2003; Ueta et al., 2015) and varying the requirements of the task (e.g., recall n values back) (Woollacott & VanderVelde, 2008). Such working memory tasks can act as a continuous distractor while manipulating cognitive task difficulty.

1.1.4 Automatic postural control

Overall DT difficulty depends on the combination of the stance and the cognitive conditions selected. While being tasked with dividing and prioritizing attention, under DT paradigms, individuals may control posture more automatically or consciously. The relative contributions of automatic and conscious postural control strategies have been modelled on a continuum; the relative contribution of each strategy varies depending on various contexts (Roerdink et al., 2011). For instance, Roerdink et al. (2011) hypothesized that automatic contributions increase when attention is directed away from a postural task and throughout recovery from disease or injury (e.g., a stroke). Contexts that include remaining upright with an increased perceived threat (e.g., at a height) and/or reducing sensory information, are thought to shift postural control strategies away from relatively more automatic and toward relatively more conscious control (Roerdink et al., 2011).

As mentioned previously, relatively more automatic postural control can be elicited by a cognitive task mimicking an external focus drawing attention away from stance (Wulf et al.,

2001). Voluntarily minimizing sway (i.e., standing as still as possible) can lead to increases in conscious control, which can increase sway by imposing an internal focus and interfering with automatic control processes (Nafati & Vuillerme, 2011). Throughout the literature, automatic postural control is thought to be evidenced by analyzing a COP signal and obtaining the following outcomes: an increase in a non-linear metric, sample entropy (SampEn; Roerdink et al., 2011), a decrease in total power (Ueta et al., 2015), and a decrease in COP amplitude measures. Since more automatic postural control is evident in young adult DT studies, assessing the nature of young adult postural control under conditions of various cognitive and stance tasks as well as considering overall task difficulty (i.e., the combined influence of the stance and cognitive tasks) can expand knowledge related postural control strategies and underlying control mechanisms.

1.1.4.1 Sample entropy

SampEn is proposed to be a marker of attentional involvement in postural control that indicates more or less automatic postural control (Roerdink et al., 2006; Roerdink et al., 2011). It is a non-linear metric that provides insight into sway dynamics and the underlying control mechanisms (Ladislaos & Fioretti, 2007). SampEn has been presented as a gradient from total conscious to total automatic control (Roerdink et al., 2011). SampEn assesses the self-similarity within a time-series signal (Richman & Moorman, 2000). The outcomes are understood as a more regular (i.e., more self-similarity) or a less regular (i.e., less self-similarity) pattern; these outcomes are illustrated by relatively lower and higher SampEn values, respectively (Richman & Moorman, 2000). A more regular pattern (i.e., decreased SampEn value) may represent relatively more conscious control and a less regular pattern (i.e., increased SampEn value) may represent

relatively more automatic control (Roerdink et al., 2011). In DT studies, SampEn and automaticity relationships tend to be discussed relative to other test conditions.

SampEn quantifies the self-similarity within a time-series signal primarily based on two parameters: m and r . m represents the vector length or group of data points compared and r represents the tolerance window or numeric range to define a match (Yentes, 2016). m and r parameter selection vary throughout the literature. When selecting m and r parameters, research has focused on determining which parameter combination results in consistent outcome relationships. SampEn has shown relative consistency (Richman & Moorman, 2000), meaning that the relative relationship between SampEn outcomes (i.e., relatively higher or lower) tends to remain despite the parameters selected. Posture-related studies have commonly used m equal to 2 or 3 and r between 0.1–0.25 multiplied by the standard deviation (SD) of the data as parameters (Yentes, 2016) and continue to be able to quantify the self-similarity within a time-series. Measuring the self-similarity of a COP time-series signal can infer statistically significant non-linear outcomes in the absence of changes in sway amplitude measures (Cavanaugh et al., 2005).

DT studies that use SampEn to study automatic postural control have shown an increase in SampEn outcomes and a decrease in COP amplitude outcomes with a DT compared to ST conditions. This is thought to indicate relatively more automatic sway control while taking part in a cognitive task. This outcome may be from less attention focused on sway permitting less constrained movement (Stins et al., 2009), which allows for natural variations in human movement (e.g., postural sway) to occur (Stergiou & Decker, 2011) to control sway around a central position. A less constrained system can be seen as more flexible, adaptable, and healthy than a more constrained system, which can be seen as the opposite (Stergiou & Decker, 2011). Neither a fully constrained nor a fully unconstrained system is said to be desirable for human

movement; a balance between the two is suggested to be ideal (Stergiou & Decker, 2011). Clinical populations (e.g., stroke, concussion) have shown decreases in natural sway dynamics (Cavanaugh et al., 2005; Roerdink et al., 2006); post-injury, COP displacement SampEn outcomes initially decrease and then increase after rehabilitation interventions and throughout recovery (Roerdink et al., 2006).

1.2 Summary and rationale

Multi-tasks in everyday life include task components that can vary by the relative difficulty and cognitive load imposed. Concepts related to these interactions are presented in a conceptual model that presents the main ideas that were used to frame this thesis (Figure 1.1). As outlined at the top of the conceptual model in solid lines, posture-cognition DT studies are composed of a stance task and a cognitive task. A stance task can include a task where one is required to remain upright while standing on two feet with the goal to remain steady and stable. A cognitive task is a task that engages some attentional resources and can act as a distractor to reduce attention directed to other tasks. Completing a stance and cognitive task simultaneously creates a DT paradigm. In solid lines to the left of the conceptual model, the relative difficulty of a stance task can be varied by the BOS size (Albertsen et al., 2017; Remaud et al., 2012) and sensory modality manipulations, such as manipulating the availability and accuracy of sensory inputs (Lanzarin et al., 2015; Morelli et al., 2020). Cognitive conditions, in solid lines to the right of the conceptual model, can vary by the relative load or degree of distraction and, in turn, the difficulty of a cognitive task (Huxhold et al., 2006). The combined influence and difficulty of a stance task and a cognitive task manipulate the nature of a DT paradigm; this combined influence was operationalized as overall task difficulty.

It has been established that young and healthy adults increase automatic postural control while distracted; however, details regarding the nature of this automatic postural control, under various cognitive and stance conditions, have received less attention throughout the literature. These relationships are outlined as dashed lines in the middle of the conceptual model. Exploring the nature of automatic postural control can help explain the mechanisms behind dual-tasking while providing a refined explanation for how individuals can complete various tasks at once and remain stable in their daily life.

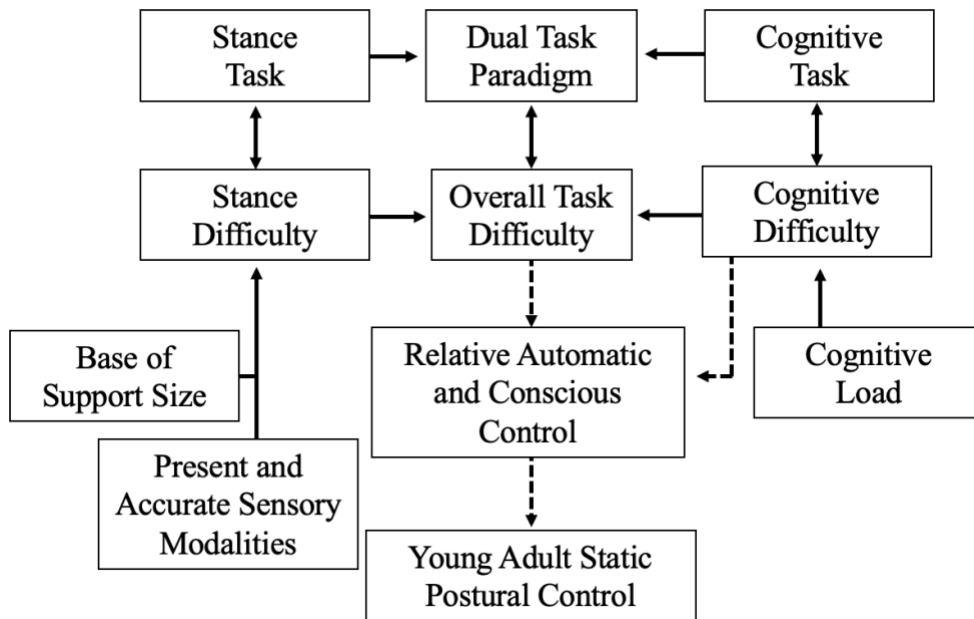


Figure 1.1 A conceptual model outlining the scope of this thesis. Solid lines represent relationships that helped establish the initial framework for the thesis. Dashed lines represent relationships that were probed throughout this thesis.

1.3 Objective and hypotheses

The overall objective of this thesis was to determine how manipulating overall static postural task difficulty by implementing various stance and cognitive challenges can influence

automatic and conscious static postural control in young healthy adults. This objective was achieved by conducting two studies.

1.3.1 Study 1: The influence of cognitive task difficulty on automatic postural control

The purpose of Study 1 (Chapter 2) was to explore how the differences in cognitive task difficulty, by varying relative cognitive loads, combined with a postural challenge may influence automatic and conscious postural control strategies and possible changes in postural sway amplitude. In addition, Study 1 was conducted to help inform the cognitive task chosen for Study

2. Specifically, the following research questions were considered:

1. Does cognitive task difficulty influence the degree of automatic postural control? Is this potential influence dependent on the stance challenge?
2. How do cognitive tasks of varying difficulty affect postural sway amplitude? Is this potential influence dependent on the stance challenge?

These questions were explored by assessing six cognitive tasks of varying loads under EO and EC stance conditions. The role of cognitive task difficulty and the degree of automatic postural control was assessed primarily through SampEn. It was hypothesized that cognitive tasks of greater load will draw more attention away from stance (i.e., increase SampEn) (Roerdink et al., 2011). It was also hypothesized that the degree of attention drawn away from stance will depend on the stance condition with relatively less attention available to draw on in the EC condition (Roerdink et al., 2011). Exploring the effect of cognitive task difficulty and postural sway amplitude was assessed through COP amplitude measurements. It was hypothesized that as cognitive task difficulty increases, COP area and root mean square (RMS) will decrease

(Huxhold et al., 2006). This decrease was expected to depend on the stance challenge with less sway amplitude decreases evident when standing under EC conditions.

1.3.2 Study 2: Automatic and conscious postural control in response to manipulations of overall task difficulty

The purpose of Study 2 (Chapter 3) was to explore how the influence of a cognitive task combined with variable stance conditions, to increase the overall task difficulty beyond that of Study 1, could elicit possible shifts between relatively more or less automatic postural control. Specifically, the following research questions were considered:

1. Do increases in overall task difficulty continue to elicit a shift from automatic to conscious postural control?
2. Is there a sway amplitude cost from potential changes in overall task difficulty, automatic, and conscious control?

The questions were explored by assessing six stance conditions, varied by sensory modalities available, with and without a cognitive task. The influence of overall task difficulty on automatic and conscious postural control was primarily assessed through SampEn dual-task cost (DTC) outcomes. It was hypothesized that the use of automatic control will not remain and a shift to relatively more conscious control will be evident in tasks of a greater overall difficulty (Roerdink et al., 2011). It was expected that negative SampEn DTC outcomes and reduced magnitudes of SampEn DTC outcomes would be evident under stance conditions with absent and/or inaccurate sensory modalities. COP RMS was used to assess sway amplitude. It was hypothesized that a sway amplitude decrease, due to more automatic control, will not remain and increases in sway amplitude will be evident in tasks of greater overall difficulty (Lanzarin et al., 2015; Morelli et

al., 2020). This was expected to be evident through the emergence of positive DTC outcomes and reduced magnitudes of RMS DTC outcomes under stance conditions with absent and/or inaccurate sensory modalities.

Chapter 2: The influence of cognitive task difficulty on automatic postural control

2.1 Abstract

Multi-tasking during activities of daily living is composed of various task components. Each task component requires some attentional involvement, which may depend on the relative difficulty of each component. Posture-cognition dual-task (DT) paradigms are used to manipulate the influence of a DT challenge on upright stance, which can be used to study mechanisms underlying dual- and multi-tasking in daily life. When engaging in a cognitive task, young adults have been shown to increase automatic postural control; however, the nature and usage of automatic postural control, under difficult DT conditions, have not been thoroughly explored. Thus, this study determined how cognitive task difficulty and a postural challenge influenced automatic postural control. Twenty-six participants completed twelve upright stance trials that varied by cognitive task difficulty (six levels of challenge) and stance task difficulty (two levels of challenge). Results showed that partaking in a cognitive task sometimes increased automatic postural control (i.e., increase sample entropy (SampEn)) and reduced postural sway amplitude (i.e., decrease sway area and variability). This outcome was not dependent on cognitive task difficulty and was not influenced by the stance challenge. Since the stance challenge may not have been challenging enough to influence DT interactions, exploring the overall difficulty of a DT, by further manipulating stance conditions, can help explain everyday life instances when automatic postural control may help one remain stable.

2.2 Introduction

Activities of daily living are commonly composed of various task components that require some degree of attentional involvement. Upright stance has been shown to use some

attentional resources (Woollacott & Shumway-Cook, 2002). Engaging in cognitive tasks can redirect attention away from a posture task and toward the cognitive task, which may increase the automatic control of sway (Donker et al., 2007; Nafati & Vuillerme, 2011). Despite less attention directed to stance, young healthy adults tend to remain stable. Given that remaining upright is important for fall avoidance and individual safety, studying young healthy adult postural control under a DT paradigm can uncover mechanisms underlying postural control and help inform strategies to assist others in remaining stable.

2.2.1 Automatic postural control

In young adult DT studies, a reduction in postural sway amplitude is observed when completing a cognitive task (Polskaia & Lajoie, 2016; Potvin-Desrochers et al., 2017; Resch et al., 2011; Ross et al., 2011; St-Amant et al., 2020). While engaging in a cognitive task, attention is diverted away from the stance task and toward the cognitive task, which is suggested to increase postural control automaticity (Donker et al., 2007; Nafati & Vuillerme, 2011). Under more automatic control, the postural control system can be seen as a less constrained system that permits natural sway adjustments to tightly regulate sway (Cavanaugh et al., 2007; Stergiou & Decker, 2011). Such a system is described as more flexible, adaptable, and healthy, compared to a more constrained system (Stergiou & Decker, 2011). In contrast to cognitive task conditions, internally focusing on sway can increase sway amplitude and reflect a more constrained system (Wulf et al., 2013).

SampEn has been proposed to be a marker of attentional involvement and automaticity in postural control (Roerdink et al., 2006; Roerdink et al., 2011). It provides an estimation of the randomness of the underlying control system by quantifying the degree of self-similarity or

regularity within a time-series signal. A more random and variable time-series signal is described as less regular or constrained, conversely, a less random and variable time-series signal is described as more regular or constrained (Richman & Moorman, 2000). Increases in SampEn are suggested to reflect more automatic postural control contributions and decreases in SampEn are thought to reflect less automatic postural control contributions (Roerdink et al., 2011). In addition, to sway amplitude decreases and SampEn increases, decreases in total power in the frequency spectrum of a centre of pressure (COP) signal are also suggested to reflect more automatic postural control (Ueta et al., 2015).

2.2.2 Posture and cognitive task components

Posture-cognition DT paradigms can be manipulated based on the posture and cognitive task used. Given that cognitive tasks can reduce the attentional involvement in postural control and that the attentional involvement in a cognitive task may depend on the relative difficulty of a cognitive task, manipulating cognitive task difficulty may help uncover the mechanisms underlying postural control. Huxhold et al. (2006) proposed a U-shaped relationship between cognitive task difficulty and postural sway amplitude; study conditions were represented along the x-axis and sway amplitude was represented along the y-axis. Huxhold et al. (2006) explained that relatively simpler and distracting cognitive tasks would decrease sway amplitude, from a no task (e.g., quiet stance or ST) baseline sway level (i.e., the downward portion of the U-shape trend), and cognitive tasks that are too challenging would increase sway amplitude, compared to the easier tasks at the bottom of the U-shape (i.e., the upward portion of the U-shape trend). A decrease in sway amplitude may be explained by a cognitive task acting as a sufficient distractor to elicit more automatic control (Donker et al., 2007; Nafati & Vuillerme, 2011), which can

tightly regulate sway (Cavanaugh et al., 2007; Stergiou & Decker, 2011). The increase in sway amplitude may be explained by a cognitive task overloading attentional resources and interfering with sway control (Rizzato et al., 2021), or by a cognitive task unable to act as a sufficient distractor providing opportunities to constrain or consciously control sway (Lajoie et al., 2016; Potvin-Desrochers et al., 2017). Cognitive tasks have further been described as discrete and continuous. Discrete tasks entail cognitive tasks that intermittently occupy one's attention and continuous tasks include cognitive tasks that sustain one's attention (Lajoie et al., 2016; Potvin-Desrochers et al., 2017). Lajoie et al. (2016) suggested that automaticity is better elicited when cognitive tasks continuously direct an individual's attention away from upright stance.

The influence of a cognitive task may also have some dependence on the postural task challenge. For instance, sway amplitude increases, while completing a cognitive task, have been observed in populations (e.g., older adults) with less effective sway control mechanisms (e.g., sensory integration) (Bernard-Demanze et al., 2009; Rizzato et al., 2021; Shumway-Cook & Woollacott, 2000; Shumway-Cook et al., 1997). Additionally, the cognitive task difficulty U-shaped relationship is more evident in an older compared to a younger adult population (Huxhold et al., 2006). Young adults have also been shown to increase sway amplitude while completing a cognitive task when standing under conditions with reduced sensory inputs (Lanzarin et al., 2015; Morelli et al., 2020). When not all visual, vestibular, and somatosensory sensory modalities are available, upright stance may require a greater attentional capacity (Teasdale et al., 1993) and reduce the amount of automaticity elicited by cognitive tasks of varying difficulty.

2.2.3 Objective and hypotheses

Exploring cognitive task difficulty alone and combined with a postural challenge can probe automatic postural control and further explain young adult postural control mechanisms while dual-tasking. For reference, the following research questions and associated hypotheses were considered:

1. Does cognitive task difficulty influence the degree of automatic postural control? Is this potential influence dependent on the stance challenge?

It was hypothesized that cognitive tasks of greater load will draw more attention away from stance (i.e., increase SampEn) and the dependence on the degree of attention drawn away from stance will be evident with relatively less attention available to draw on in the eyes closed (EC) condition (Roerdink et al., 2011).

2. How do cognitive tasks of varying difficulty affect postural sway amplitude? Is this potential influence dependent on the stance challenge?

It was hypothesized that as cognitive task difficulty increases, sway area and root mean square (RMS) will decrease (Huxhold et al., 2006) and this decrease will be less evident when standing under EC conditions.

2.3 Methods

2.3.1 Participants

A sample size estimate indicated that a minimum of 23 participants were required for this study. Using the G*Power 3 program (Faul et al., 2007) an Analysis of Variance (ANOVA) repeated measures within factor priori analysis was conducted using an alpha of 0.05, power of

0.80, one group, 12 measurements, and an estimated effect size of 0.89 (based on Cohen 1988). The estimated effect size was determined from previous literature that assessed healthy young adult postural control with and without engaging in cognitive tasks while standing upright with feet together (St-Amant et al., 2020). A main effect of cognitive condition in medial-lateral (ML) SampEn outcomes, with $\eta^2=0.440$ (i.e., an effect size of 0.89), was found (St-Amant et al., 2020).

Thirty-eight healthy young adults were recruited from York University and the surrounding community. Participants were required to be between the ages of 18–40 years old, have no self-reported history of a recent concussion, or neurologic injury, and no current muscle or skeletal foot or leg injury. If a past concussion or neurologic injury was reported, participation was permitted only if the prospective participant was symptom free for at least one year. Data from these participants ($n=5$) were closely assessed and removed from the analysis due to contributing to outliers in the data. Previous literature has reported instances of instability post-concussion (Guskiewicz et al., 2003), and not all sway measures have been shown to reflect recovery post-concussion (Sweeny et al., 2020). Additional participants were excluded due to equipment errors ($n=5$; faulty amplifier) and the inability to adhere to protocol instructions ($n=2$). Therefore, data from 26 healthy young adults were assessed; the descriptive characteristics of the analyzed sample are presented in Table 2.1. This research was approved by the York University Research Ethics Board (Certificate #: 2021-373).

Table 2.1 Study 1 analyzed sample ($n=26$) descriptive characteristics.

Characteristic	Sample Outcome
Age (years)	22.2 (2.2)
Height (m)	1.7 (0.1)
Weight (kg)	67.0 (12.9)
Years of Education (years)	16.8 (2.1)
Sex	20 female; 6 male

Numeric outcomes presented as mean (SD).

2.3.2 Experimental design

This study consisted of 12 trials that varied by stance condition and cognitive load. Each cognitive task was completed under each stance condition. Data was collected in the Sherman Health Science Research Centre at York University.

2.3.2.1 *Stance conditions*

Two stance conditions, eyes open (EO) and EC, were used to challenge the postural system. The EC stance condition was intended to pose a greater challenge compared to the EO condition due to the elimination of vision. Remaining upright without vision has resulted in an increase in sway compared to remaining upright with vision (Riley & Clark, 2003), which can be indicative of a stance challenge.

For each trial, participants stood on a force plate in socks. Foot position was standardized by having each participant align their feet with a taped upside down “T” (approximately 9.5cm from the posterior edge of the plate) on the force plate; heels were aligned with the horizontal portion of the “T” and feet were parallel surrounding the vertical portion of the “T” (approximately 25cm from the lateral edge of the plate). The feet were positioned close together, but not touching, to further challenge posture. Furthering the posture challenge is justified since healthy young adults have a healthy postural control system and may require a greater stance challenge to challenge stability. Positioning feet close together reduces one’s base of support (BOS) and challenges participants to keep their centre of mass (COM) within a smaller area. In addition to the foot position, participants stood with their hands by their sides and with their shoulders, neck, and head relaxed. The intention was for participants to stand in a comfortable and relaxed body position.

2.3.2.2 Cognitive conditions

Six cognitive conditions of varying load were used to impose cognitive challenges. The six conditions included an uncontrolled load condition and five arithmetic conditions. The quiet standing (QS) or uncontrolled load condition was a single-task (ST) trial without explicit cognitive instructions and acted as a baseline condition.

Arithmetic cognitive tasks utilize working memory (Bristow et al., 2016; Raghubar et al., 2010) and attention (Bristow et al., 2016) cognitive resources, which when occupied can act as distractors under DT conditions. With the intent to vary the cognitive load, the following arithmetic tasks starting at a 3-digit value were used: addition by 3s (p3), and subtraction by 3s, 7s, 3.3s, and 7.7s (m3, m7, m3.3, m7.7). Addition by 3s and serial 3s (i.e., minus 3s) were intended to be the simplest tasks because of the small operand and little carrying demand (Masson & Pesenti, 2014). Carrying occurs when values from the right columns are applied left. For example, when adding 16 and 7, the number '1' is carried from the ones column to the tens column since $6 + 7 = 13$. Serial 3s and serial 7s have previously been shown to measure continuous subtraction (Bristow et al., 2016). Bristow et al. (2016) suggested that serial 7s require a greater cognitive demand than serial 3s. Successful serial 7s performance places a greater dependence on carrying than serial 3s. Arithmetic problems frequently involving carrying tend to result in more errors and slower response times than arithmetic problems with a less carrying demand (Masson & Pesenti, 2014). Subtraction by 3.3s and 7.7s were intended to be of a greater load than serial 7s due to the novelty of the task and the greater working memory demand from the decimal place. It was intended for subtraction by 3.3s to be relatively simpler

than subtraction by 7.7s since larger operands increase calculation challenge (Masson & Pesenti, 2014).

2.3.3 Experimental procedure

Prior to participating in this study, participants reviewed and signed a consent form and completed a self-report demographic and medical history form; each form was approved by ethics. Data collection sessions consisted of a minimum of 12 80 second trials. The 12 trials were randomized and completed by each participant. An 80 second trial duration has been shown to be sufficient to provide stable and reliable COP summary measures (Carpenter et al., 2001).

Optional self-selected breaks were permitted between trials.

The 12 trials included two ST conditions: EO and EO, and ten DT conditions: EO and EC adding by threes and EO and EC subtracting by 3s, 7s, 3.3s, and 7.7s. Participants were instructed to look straight ahead at a black drop sheet with a fixation point (a white 'X') placed approximately 1.5m in front of participants when completing EO trials. For the EC trials, participants were asked to keep their eyes closed. The experimenter confirmed eyes were appropriately open or closed after each trial. Each DT condition consisted of the experimenter providing the participant with a start value. Addition trials had a start value between 100–200 and subtraction trials had a start value between 600–700. Decimal subtraction start values were four digits long (e.g., 659.6) and the rest of the start values were three digits long (e.g., 128, 667).

Each trial began with the experimenter instructing the participant of the trial condition (e.g., “standing with your eyes closed subtract by 7s starting at 612”). The participant then stepped onto a force plate, with an elevated surface that matched the height of the force plate,

and settled into the stance position for 10 seconds. This 10 second phase was not recorded. At five seconds of settling in, participants were reminded of the trial condition and the DT start value (if applicable). For ST conditions, participants were instructed the trial began and for DT conditions, participants were instructed to begin counting; the 80 second trial then began. During the collection, the experimenter recorded cognitive task performance on a collection sheet. After 80 seconds, the experimenter instructed the participant to stop counting, step off the force plate, and confirmed with the participant whether their eyes were open or closed during the trial. Trials were repeated if a participant failed to open or close their eyes. Other incomplete or abnormal trials (e.g., collection interruption, participant aborted a trial, etc.) were also repeated. Repeated trials were completed with a new start value (if applicable) at the end of the initial trial sequence.

2.3.4 Data collection and processing

Using the AMTI force plate (OR6-7-1000-3985) and a National Instruments analog-to-digital converter (USB-6218), raw COP data were collected using a custom LabVIEW (National Instruments, USA) code. Data was collected at 1024Hz. Raw force and moment data—along the x, y, and z axes—were converted to N/Nm units using a custom LabVIEW calibration code. A second-order low-pass Butterworth filter, with a cut-off frequency of 10Hz, was applied to the ML and anterior-posterior (AP) COP time-series. The first and last 10 seconds of each trial were discarded before analysis.

COP data points for the ML and AP directions were calculated using the following equations:

$$COP_y = \frac{M_x + F_y * Z_0}{F_z}$$

$$COP_x = \frac{-(M_y + F_x * Z_0)}{F_z}$$

Since Z_0 , an offset value, is effectively 0, each equation was simplified to the following:

$$COP_y = \frac{M_x}{F_z}$$

$$COP_x = \frac{-M_y}{F_z}$$

F and M represent force and moment outputs, respectively, along the x, y, and z axes.

Cognitive performance was recorded by the experimenter using custom data collection sheets. The experimenter recorded the responses within the first 60 seconds of each trial for analysis.

2.3.5 Data analysis

Input data was expressed as mean-removed, directional COP data points along the ML and AP time-series and used to calculate SampEn, 95% confidence ellipse area, RMS, and total power. SampEn was primarily used to assess automatic postural control. The 95% ellipse area and RMS primarily assessed postural sway amplitude. Total power was a secondary measure that supplemented each outcome. Variable explanations and calculation procedures are outlined below.

2.3.5.1 Sample entropy

SampEn is a non-linear metric that is a regularity statistic to assess the self-similarity within a time-series (Richman & Moorman, 2000). Lower SampEn values indicate more regularity and more self-similarity of a time-series (Richman & Moorman, 2000). More specifically, SampEn (m, r, N) is the negative natural logarithm of the conditional probability that

two sequences of values that are similar for m points (i.e., a certain number of data values) will remain similar at the next point, with the exclusion of self-matches (Richman & Moorman, 2000). SampEn ranges from values of approximately zero indicating an almost perfectly repeating pattern to values approaching infinity indicating an almost perfectly random pattern (Yentes, 2016). SampEn parameters include m , r , and N . m defines the length of vectors compared, r is the tolerance window to define a match, and N represents the length of the time-series (Yentes, 2016).

To calculate the SampEn of a time-series, the series is divided into vector lengths defined by m and $m+1$. Each vector is compared with the rest, except itself. If a vector is similar (i.e., all values compared are within $\pm r$) then the vector is a match (Yentes, 2016). The total number of matches (i.e., similar vectors) is divided by the number of comparisons, which results in conditional probabilities—expressed as C_i^m and C_i^{m+1} for m and $m+1$, respectively (Yentes, 2016). The following calculation procedure, which is similarly defined for the ML direction, was used (Yentes, 2016):

$$SampEn_{Ap} = -\ln\left(\frac{A}{B}\right)$$

where,

$$B = \frac{(N - m - 1)(N - 1)}{2} B_i$$

$$A = \frac{(N - m - 1)(N - 1)}{2} A_i$$

and,

$$B_i = \frac{\sum C_i^m}{N - m}$$

$$A_i = \frac{\sum C_i^{m+1}}{N - m}$$

SampEn parameters chosen included $m=2$, $r=0.2*SD$, and $N=7680$. The combination of $m=2$ and $r=0.2*SD$ was used to align with previous COP-displacement SampEn assessments that have successfully differentiated posture-related study conditions (Borg & Laxåback, 2010; Potvin-Desrochers et al., 2017; St-Amant et al., 2020). SampEn is independent of N (Yentes, 2016); however, $N=7680$ was chosen to reduce the computation burden in LabVIEW. This was achieved by downsampling the data to 128Hz.

SampEn is thought to be positively correlated with the amount of attentional involvement and, thus, automaticity in postural control (Roerdink et al., 2006; Roerdink et al., 2011). It provides an estimation of the randomness of the underlying control system and has been said to be indicative of a flexible, adaptable, healthy, and less constrained biological system (Stergiou & Decker, 2011). More automatic postural control can be indicated by an increase in SampEn (i.e., a less regular time-series), whereas less automatic postural control can be evidenced by a decrease in SampEn (i.e., a more regular time-series) (Roerdink et al., 2011).

2.3.5.2 95% confidence ellipse area

The 95% confidence ellipse area quantifies the size of a stabilogram to provide an overall measure of postural steadiness (Prieto et al., 1996). Specifically, it estimates the area of an ellipse that is expected to contain 95% of the points along the COP path. The following equation from Prieto et al. (1996) was used:

$$95\% CE = 2\pi F_{0.05[2,n-2]}(S^2_{AP}S^2_{ML} - S^2_{APML})^{1/2}$$

S^2_{AP} and S^2_{ML} are the variances of the mean-removed COP time-series in the respective AP and ML directions (Prieto et al., 1996). S^2_{APML} is the co-variance of the sample. Since the number of

data points assessed was large, $F_{0.05[2,n-2]} = F_{0.05[2,\infty]} = 3$ to ensure a 95% confidence level. An increase in the 95% ellipse area indicated a greater sway amplitude.

2.3.5.3 Root mean square

RMS represents the variability of the COP tracing (Palmieri et al., 2002) and provides a measure of postural sway amplitude (Zaback et al., 2019). Specifically, it quantifies the position variation of the COP around an average COP point. The following equation from Prieto et al. (1996), which is similarly defined for the ML direction, was used:

$$RMS_{AP} = \left(\frac{1}{N} \sum AP[n]^2 \right)^{1/2}$$

$AP[n]$ is the mean-removed COP_{AP} data point and N is the total number of data points (Prieto et al., 1996). A greater RMS value indicated less of an ability to control upright stance around an average position (Palmieri et al., 2002).

2.3.5.4 Total power

The total power of a COP signal quantifies the amount of power over an entire frequency range of interest. This is obtained by integrating the area under the power spectrum (Prieto et al., 1996). COP time-series' in the ML and AP directions were represented in the frequency domain using the TSA Welch VI in LabVIEW. The TSA Welch VI computes the one-sided power spectral density (PSD) using the Welch method (National Instruments, 2022). The Welch method implements a sliding window, of a predefined length, that performs a Fourier transform within each window and averages each transform to result in a smooth PSD (Welch, 1967). The COP signal was assessed according to Lin et al. (2019); the total power represented the energy within 0–6.25Hz of the signal. The trapezoidal integration method was used for numeric integration;

outcomes were presented as absolute values. A decrease or increase in total power has been associated with greater or less automatic postural control, respectively (Bernard-Demanze et al., 2009; Ueta et al., 2015).

2.3.5.5 Cognitive task performance

Cognitive task performance was assessed by comparing the number of correct responses and the rate of attempted responses (i.e., the total number of responses per second). Quantifying the number of correct responses allowed for the assessment of the successful completion of the tasks. Further, the response rate is associated with arithmetic difficulty (Masson & Pesenti, 2014). Problems including carrying, larger operands, and subtraction rather than addition show an increase in response times (Masson & Pesenti, 2014). Relatively difficult cognitive tasks were indicated by fewer correct responses and a slower response rate.

2.3.6 Statistical analysis

Separate 2 (vision) x 6 (cognitive load) repeated measures ANOVAs were conducted in SPSS (IBM, USA) for each calculated measure (i.e., SampEn, area, RMS, total power). The within-subject variables included vision at two levels (i.e., EO, EC) and cognitive load at six levels (i.e., QS, p3, m3, m7, m33, m77). The main effect of cognitive load was used to test the hypothesis that difficult cognitive tasks will draw more attention away from stance (i.e., increase SampEn) and that as cognitive load increased, sway area and RMS decreased. The hypothesis that these relationships depended on the stance condition challenge was assessed through the vision*cognitive load interaction. Each variable was assessed for normality using the Shapiro-Wilks test for normality. The majority of tests, for each condition, were significant, thus all non-

normal outcome measures were log-transformed. Not all log-transformed data became normally distributed. These deviations were determined to be from outliers. Outliers were determined by assessing z-scores that were greater than two SDs from the mean. However, since ANOVAs are robust against deviations from normality (Blanca et al., 2017; Blanca et al., 2023), the planned repeated measures ANOVAs were conducted. The Greenhouse-Geisser correction was used to report P-values if Mauchly's test of sphericity was significant. Significant main effects were explored through post-hoc pairwise comparisons with a Bonferroni correction. All interactions were not significant.

To confirm the intended difficulty of cognitive tasks (i.e., p3, m3, m7, m33, m77 listed from least to most intended difficulty), the number of correct responses and the total response rate were assessed through separate EO and EC non-parametric Friedman Tests since the data were non-normal and remained non-normal after transformations were applied. Wilcoxon signed-rank tests, assessed with a Bonferroni correction, were used for post-hoc analyses. The following post-hoc comparisons were made: p3m3, p3m7, p3m33, p3m77, m3m7, m3m33, m3m77, m7m33, m7m77, and m33m77. Statistical significance was set at $p < 0.05$.

2.4 Results

2.4.1 Cognitive task difficulty and automatic postural control

2.4.1.1 Sample entropy

The analysis of SampEn in the ML and AP directions generally showed that while completing a cognitive task, SampEn tended to increase, and EC SampEn tended to be greater

than EO SampEn. The dependence of the cognitive and stance variables did not seem to be evident.

Specific to the ML direction, ML SampEn showed a statistically significant main effect of vision ($F(1,25)=13.136$, $p=0.001$, $\eta^2=0.344$). Post-hoc tests confirmed a significant difference between EO and EC ML SampEn ($p=0.001$) with greater EC than EO ML SampEn. ML SampEn also showed a statistically significant main effect of cognitive load ($F(5,125)=26.357$, $p<0.001$, $\eta^2=0.513$; Figure 2.1). Post-hoc tests identified significant differences between QS and p3, m3, m7, m33, m77 ($p<0.001$ each); QS was less than all other conditions. A statistically significant difference between m3 and m77 ($p<0.001$) was also identified with m3 greater than m77. No other cognitive load statistical significance was present. A statistically significant interaction was not detected ($F(5,125)=0.302$, $p=0.911$, $\eta^2=0.012$).

In the AP direction, AP SampEn showed a statistically significant main effect of vision ($F(1,25)=34.898$, $p<0.001$, $\eta^2=0.583$). Post-hoc tests confirmed EC AP SampEn to be greater than EO ($p<0.001$). AP SampEn showed a statistically significant main effect of cognitive load ($F(3.271,81.763)=6.606$, $p<0.001$, $\eta^2=0.209$; Figure 2.1). Post-hoc tests found a statistically significant difference between QS and p3 ($p=0.001$) and m3 ($p=0.025$) with QS less than each. No other cognitive load statistical significance was present. A statistically significant interaction was not detected ($F(5,125)=0.533$, $p=0.751$, $\eta^2=0.021$).

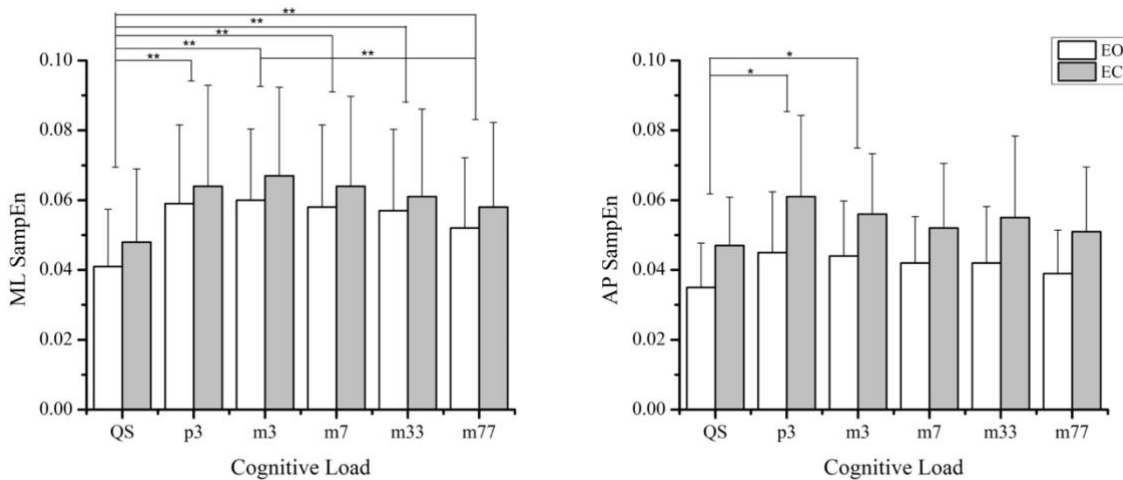


Figure 2.1 Mean and SD of ML SampEn and AP SampEn for EO (white) and EC (grey) conditions. Significance is indicated for statistically significant differences between cognitive load conditions (* $p < 0.05$, ** $p < 0.001$).

2.4.2 Cognitive task difficulty and postural sway amplitude

2.4.2.1 95% confidence ellipse area

Overall, the analysis of the 95% ellipse area tended to demonstrate a decrease in area while completing a cognitive task. EO and EC area outcomes did not seem to differ. The dependence of the cognitive and stance variables was not evident.

The main effect of vision was not statistically significant ($F(1,25)=1.404$, $p=0.247$, $\eta^2=0.053$). Area showed a statistically significant main effect of cognitive load ($F(5,125)=10.399$, $p < 0.001$, $\eta^2=0.294$; Figure 2.2). Post-hoc tests identified statistically significant differences between QS and p3, m3, m7, and m33 ($p < 0.001$ each) as well as a difference between QS and m77 ($p=0.003$); QS was greater than all other conditions listed. No other cognitive load statistical significance was detected. The interaction was not statistically significant ($F(5,150)=2.265$, $p=0.052$, $\eta^2=0.083$).

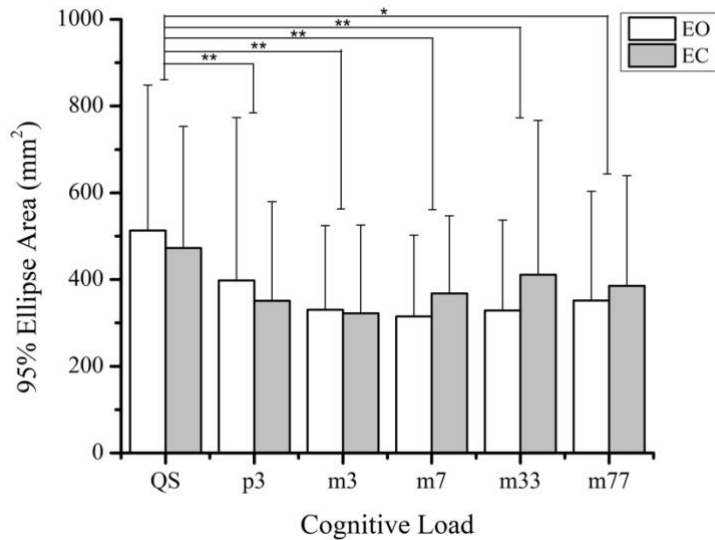


Figure 2.2 Mean and SD of sway area (mm^2) for EO (white) and EC (grey) conditions. Statistical significance is only indicated for the main effect of cognitive load (* $p < 0.05$, ** $p < 0.001$).

2.4.2.2 Root mean square

In general, the analysis of the RMS, in the ML and AP directions, tended to show a decrease with the addition of a cognitive task; however, this decrease did not seem to be consistent in the AP direction. EC RMS showed to be greater than EO in the ML direction only. The dependence of the cognitive and stance variables did not seem to be evident.

ML RMS showed a statistically significant main effect of vision ($F(1,25)=12.921$, $p=0.001$, $\eta^2=0.341$). Post-hoc tests confirmed EO and EC ML RMS to significantly differ ($p=0.001$) with a greater EC than EO ML RMS. A statistically significant main effect of cognitive load was also detected ($F(3,185,79.624)=15.311$, $p < 0.001$, $\eta^2=0.380$; Figure 2.3). Post-hoc tests identified statistically significant differences between QS and p3, m3, m7, m77 ($p < 0.001$ each) as well as QS and m33 ($p=0.002$) with QS ML RMS greater than each condition. No other cognitive load statistically significant differences were

identified. No statistically significant interaction was detected

($F(3,268,81.687)=0.854, p=0.476, \eta^2=0.033$).

AP RMS did not show a statistically significant main effect of vision

($F(1,25)=0.910, p=0.349, \eta^2=0.035$; Figure 2.3). A statistically significant main effect of

cognitive load was identified ($F(5,125)=3.794, p=0.003, \eta^2=0.132$). Post-hoc tests identified a

statistically significant difference between QS and m3 ($p=0.010$) and m33 ($p=0.047$) with AP

RMS QS greater than m3 and m33. No other cognitive load statistically significant differences

were identified. An interaction of statistical significance was not detected

($F(5,125)=1.882, p=0.120, \eta^2=0.070$).

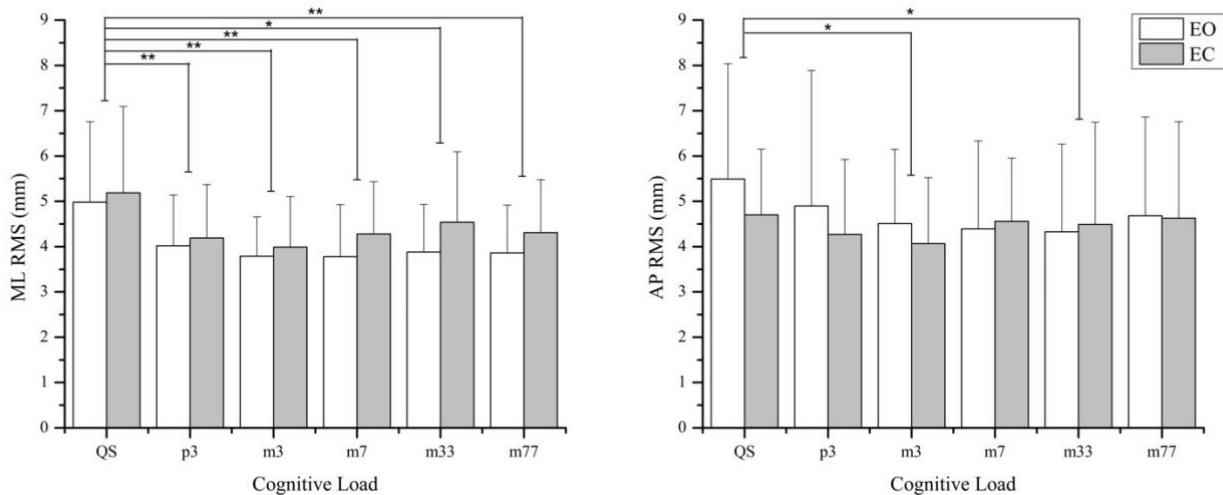


Figure 2.3 Mean and SD of ML RMS (mm) and AP RMS (mm) for EO (white) and EC (grey) conditions. Statistical significance is only indicated for the main effect of cognitive load (* $p<0.05$, ** $p<0.001$).

2.4.3 Supplementary measure

2.4.3.1 Total power

The analysis of total power in the ML and AP directions generally revealed a decrease in total power with the addition of a cognitive task; however, this decrease did not seem to remain

in the AP direction while completing tasks of greater load. EC total power appeared to be higher than EO total power in the ML direction, yet this did not seem to remain in the AP direction. The dependence of the cognitive and stance variables was not evident.

The total power in the ML direction showed a statistically significant main effect of vision ($F(1,25)=6.271$, $p=0.019$, $\eta^2=0.201$). Post-hoc tests showed EC total power to be greater than EO ($p=0.019$). A main effect of cognitive load was evident ($F(5,125)=8.185$, $p<0.001$, $\eta^2=0.247$; Figure 2.4). Post-hoc tests revealed QS ML total power was greater than p3 ($p=0.005$), m3 ($p<0.001$), m7 ($p<0.001$), m33 ($p=0.017$), and m77 ($p=0.005$). No other cognitive load statistically significant differences were identified. The interaction was not statistically significant ($F(5,125)=1.207$, $p=0.310$, $\eta^2=0.046$).

Total power in the AP direction did not show a statistically significant main effect of vision ($F(1,25)=0.005$, $p=0.945$, $\eta^2=0.000$). A statistically significant main effect of cognitive load was identified ($F(3.276, 81.892)=4.471$, $p=0.005$, $\eta^2=0.152$; Figure 2.4). Post-hoc tests showed QS to be greater than p3 ($p=0.016$), m3 ($p=0.029$), and m7 ($p=0.014$). No additional statistically significant cognitive load differences were found. No statistically significant interaction was identified ($F(5,125)=1.422$, $p=0.221$, $\eta^2=0.054$).

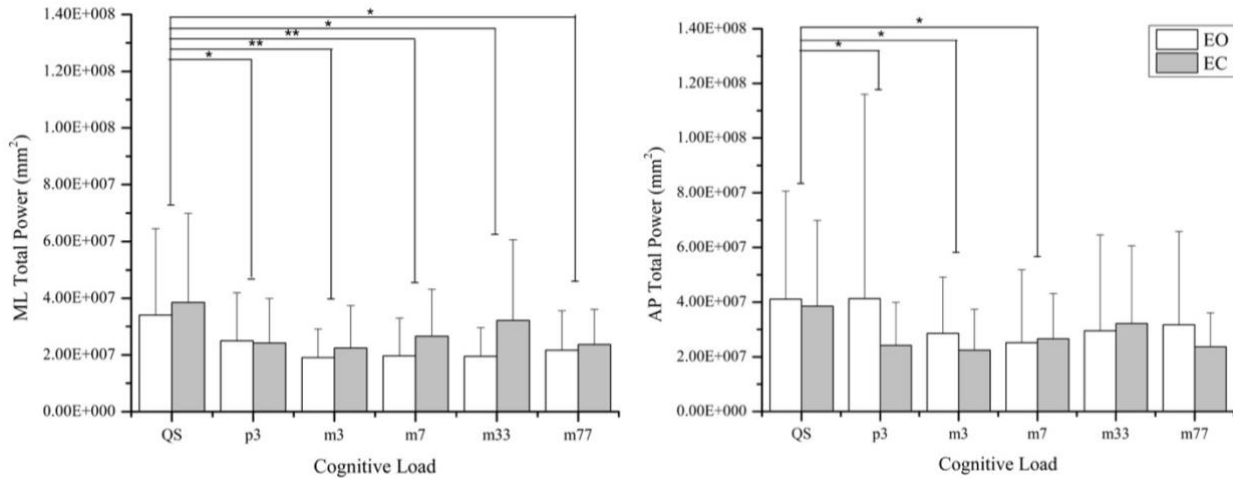


Figure 2.4 Mean and SD of ML Total Power (mm²) and AP Total Power (mm²) for EO (white) and EC (grey) conditions. Statistical significance is only indicated for the main effect of cognitive load (* $p < 0.05$, ** $p < 0.001$).

2.4.4 Cognitive performance

Overall, cognitive performance outcomes (Table 2.2) tended to decrease when the intended arithmetic difficulty increased. The intended order of difficulty, listed from least to most difficult, was p3, m3, m7, m33, and m77.

2.4.4.1 Correct responses

For EO, a statistically significant difference between the number of correct responses was identified ($\chi^2(4) = 101.452$, $p < 0.001$). Post-hoc analyses indicated that each cognitive task differed with the following outcomes: p3m3 ($Z = -4.376$; $p < 0.001$), p3m7 ($Z = -4.461$; $p < 0.001$), p3m33 ($Z = -4.461$; $p < 0.001$), p3m77 ($Z = -4.461$; $p < 0.001$), m3m7 ($Z = -4.378$; $p < 0.001$), m3m33 ($Z = -4.459$; $p < 0.001$), m3m77 ($Z = -4.461$; $p < 0.001$), m7m33 ($Z = -4.360$; $p < 0.001$), m7m77 ($Z = -4.461$; $p < 0.001$), and m33m77 ($Z = -4.223$; $p < 0.001$). These differences showed

the following relationship between tasks listed from the most to least correct responses: p3, m3, m7, m33, and m77.

EC also showed a statistically significant difference in correct responses ($\chi^2(4) = 99.518, p < 0.001$). Like EO, post-hoc analyses showed that each cognitive task differed. The following outcomes were found: p3m3 ($Z = -3.366; p < 0.001$), p3m7 ($Z = -4.461; p < 0.001$), p3m33 ($Z = -4.461; p < 0.001$), p3m77 ($Z = -4.459; p < 0.001$), m3m7 ($Z = -4.382; p = 0.001$), m3m33 ($Z = -4.463; p < 0.001$), m3m77 ($Z = -4.460; p < 0.001$), m7m33 ($Z = -4.385; p < 0.001$), m7m77 ($Z = -4.461; p < 0.001$), and m33m77 ($Z = -3.957; p < 0.001$). Similar to EO, the following relationship between tasks, from most to least correct, was identified: p3, m3, m7, m33, and m77.

2.4.4.2 Response rate

Response rate outcomes (Table 2.2) tended to decrease when the intended arithmetic difficulty increased. The intended order of difficulty, listed from least to most difficult, was p3, m3, m7, m33, and m77.

A statistically significant difference in response rate for EO was evident ($\chi^2(4) = 100.894, p < 0.001$). Post-hoc analyses showed each rate to differ with the following outcomes: p3m3 ($Z = -4.223; p < 0.001$), p3m7 ($Z = -4.462; p < 0.001$), p3m33 ($Z = -4.465; p < 0.001$), p3m77 ($Z = -4.460; p < 0.001$), m3m7 ($Z = -4.462; p < 0.001$), m3m33 ($Z = -4.460; p < 0.001$), m3m77 ($Z = -4.461; p < 0.001$), m7m33 ($Z = -4.354; p < 0.001$), m7m77 ($Z = -4.465; p < 0.001$), and m33m77 ($Z = -4.401; p < 0.001$). These differences showed the following relationship for EO response rate (listed from quickest to slowest): p3, m3, m7, m33, and m77.

Additionally, EC showed a statistically significant difference in response rate ($\chi^2(4) = 101.207, p < 0.001$). Post-hoc analyses identified that each task differed with the following outcomes: p3m3 ($Z = -3.793; p < 0.001$), p3m7 ($Z = -4.459; p < 0.001$), p3m33 ($Z = -4.461; p < 0.001$), p3m77 ($Z = -4.459; p < 0.001$), m3m7 ($Z = -4.376; p < 0.001$), m3m33 ($Z = -4.459; p < 0.001$), m3m77 ($Z = -4.460; p < 0.001$), m7m33 ($Z = -4.463; p < 0.001$), m7m77 ($Z = -4.462; p < 0.001$), and m33m77 ($Z = -4.209; p < 0.001$). Like EO, the following relationship of response rate (listed from quickest to slowest) was identified: p3, m3, m7, m33, and m77.

Table 2.2 Summary of the cognitive performance outcomes for the number of correct responses (within 60 seconds) and the response rate (response per second) for each cognitive condition with and without vision.

Vision		Cognitive Load				
		p3	m3	m7	m33	m77
Correct Responses	EO	25.8 (8.9)	18.8 (7.6)	11.5 (7.0)	4.7 (2.6)	1.7 (2.2)
	EC	25.4 (10.6)	21.7 (9.3)	12.0 (7.2)	4.6 (3.3)	1.9 (1.9)
Response Rate	EO	0.43 (0.15)	0.34 (0.15)	0.20 (0.11)	0.11 (0.05)	0.05 (0.04)
	EC	0.43 (0.17)	0.37 (0.15)	0.22 (0.11)	0.10 (0.05)	0.05 (0.03)

Numeric outcomes presented as mean (SD).

2.5 Discussion

Cognitive task difficulty and possible interactions with a postural challenge were explored through a DT paradigm that included two stance conditions and six levels of cognitive load. The preliminary findings of the analysis were that cognitive task difficulty did not consistently influence automatic postural control and sway amplitude despite evidence supporting the intended difficulty of arithmetic tasks (i.e., p3, m3, m7, m33, m77 from least to most challenging). The lowest levels of cognitive task difficulty were sufficient to alter automatic control, but this effect did not increase with more difficult cognitive tasks. The effect of cognitive task difficulty did not seem to depend on the stance challenge.

2.5.2 Cognitive task difficulty did not influence automatic postural control

SampEn was primarily used to assess the relationship between cognitive task difficulty and automatic postural control. The hypothesis regarding cognitive task difficulty and an increase in SampEn was partially supported since the addition of a cognitive task showed a relative increase in automaticity compared to QS (except for AP m7, m33, and m77). However, this increase in automaticity did not occur when assessing comparisons beyond QS (i.e., between cognitive tasks), other than m3 ML SampEn being greater than m77. The SampEn findings were mostly substantiated by total power outcomes. In general, it was demonstrated that automaticity sometimes increased with the addition of a cognitive task and that this increase in automaticity did not always differ between cognitive task conditions.

2.5.2.1 Cognitive load and automatic postural control

2.5.2.1.1 Cognitive tasks can elicit automaticity

Cognitive task difficulty and automaticity were primarily assessed through SampEn. Automaticity, in the context of static postural control, can be seen as an upright stance position that requires few attentional resources to remain stable. A more automatic control system state can be interpreted as one of relatively low constraint (Cavanaugh et al., 2007). A less constrained control system can permit frequent and random adjustments (e.g., sway adjustments) to tightly regulate the respected system (e.g., postural system) (Cavanaugh et al., 2007; Stergiou & Decker, 2011).

Each SampEn directional measure showed more regularity (i.e., less automaticity) in QS versus p3 and m3. This provides evidence for these cognitive tasks acting as sufficient distractors to facilitate automaticity and continuously hold attention away from stance. A continuous distraction would consistently occupy one's attention and reduce the opportunity for attention to be directed toward upright stance. Despite SampEn p3 and m3 being less regular than QS, only in the ML direction were m7, m33, and m77 less regular than QS. The interpretation of these findings is discussed further below.

In comparison to ML SampEn outcomes, AP SampEn findings provide only some support for automaticity while engaging in a cognitive task. A lack of evidence for automaticity, in the AP direction, while completing the m7, m33, and m77 cognitive tasks, may be due to the tasks being relatively more novel and challenging cognitive tasks. These tasks may have been too difficult for individuals to remain engaged, meaning that participants may have intermittently attended to cognitive tasks of greater difficulty. Discrete tasks (i.e., a task that does not sustain attention) have been shown not to induce automaticity as effectively as continuous tasks (i.e., tasks that sustain attention) (Lajoie et al., 2016; Potvin-Desrochers et al., 2017). Like discrete tasks, a task where engagement cannot be maintained provides opportunities for conscious control thus decreasing SampEn closer to a baseline (i.e., QS) level.

The lack of consistent findings between the ML and AP directions creates a challenge when interpreting postural control study outcomes. Previous literature suggested that changes in the regularity of a signal are likely to occur in the directions of greater sway as determined by comparing foot placements (i.e., bipedal vs. unipedal stance) (Lara et al., 2022). Lara et al. (2022) found statistically significant SampEn differences in the ML direction for unipedal stance and in the AP direction for bipedal stance when comparing different test conditions. In side-by-

side bipedal stance, AP sway has been shown to dominate (Winter et al., 1996), which helps justify interpreting study outcomes based on AP sway. The potential for conscious control in more discrete cognitive tasks, as mentioned above, may be directed in the AP direction to control sway. This can explain why AP SampEn outcomes for m7, m33, and m77 failed to show statistical significance compared to a baseline level.

Further, the foot position used in Study 1 required participants to stand with feet positioned close together. This foot position narrows one's BOS compared to a shoulder-width side-by-side stance. Narrowing the BOS, such as by standing with feet together, tends to increase ML sway compared to standing with feet to the side and apart (Kirby et al., 1987); the potential increase in ML sway can parallel that of unipedal stance in Lara et al. (2022). Thus, when interpreting automaticity, the ML outcomes have some relevance, in addition to AP outcomes. Overall, SampEn outcomes when comparing QS and cognitive task conditions, lend support to each cognitive task eliciting some degree of automatic postural control. This conclusion is corroborated by area outcomes, an outcome measure that considers both ML and AP sway, since area decreased with the addition of each cognitive task indicating a less constrained and tighter regulation of postural control.

2.5.2.1.2 Automaticity does not vary between cognitive tasks

The majority of the SampEn comparisons between arithmetic cognitive tasks (i.e., between p3, m3, m7, m33, and m77) failed to reveal statistically significant differences between relatively easier cognitive tasks and relatively more challenging cognitive tasks. The only statistically significant difference was found with ML SampEn in which m3 was greater than m77. This outcome can be explained by m77 possibly being more discrete than m3. Regarding

the other cognitive condition relationships, it is possible that the level of distraction a cognitive task elicited was held constant by participants compensating their response rate to maintain a comfortable level of distraction. Decreases in response rates during arithmetic problem-solving tend to occur when performing calculations involving carrying and larger operands (Masson & Pesenti, 2014). The evident slower response rate with an increased calculation challenge (i.e., p3, m3, m7, m33, and m77 listed from most to least challenging) may have been a way for participants to compensate for the increased calculation difficulty. Alternatively, a potential ceiling effect of maximal cognitive resource usage could have been met meaning that engaging in the cognitive tasks occupied the maximal amount of attentional resources that could be redirected away from upright stance. This has been previously suggested by Polskaia & Lajoie (2016), where a lack of statistically significant postural sway measurement differences between cognitive tasks of varying difficulty was found.

2.5.2.2 Visual effect on automaticity

Standing without visual input reduces a source of sensory information, which can challenge stability. Roerdink et al. (2011) suggested this to contribute to lower SampEn by increasing conscious postural control. Under challenging stance task conditions, individuals tend to prioritize their posture and safety (Bolem et al., 2001). This can be done by increasing one's postural sway awareness and conscious postural control, which could decrease SampEn (Roerdink et al., 2011). However, EC SampEn was greater than EO in both the ML and AP directions.

When standing with less present and/or accurate sensory modalities, the reduction of sensory input may be compensated for by sensory reweighting (Peterka, 2018); however,

postural control can remain challenged when varying sensory modalities available despite a proposed increased reliance placed on present and accurate sensory modalities (Riley & Clark, 2003; Shumway-Cook & Horak, 1986). When standing under conditions without some sensory modalities, individuals may be unable to exert what has been termed as effective postural control (i.e., control sway around a central position) to regulate the postural system due to fewer senses available to assist (Borg & Laxåback, 2010). Sensory information, mainly from the visual, vestibular, and ankle somatosensory systems, is important for the central nervous system to obtain an estimate of the body's orientation in space (Horak, 2006). With less available and accurate sensory inputs, the postural system is suggested to become too variable, noisy, or unconstrained, which is not desirable for human movement; a balance between a fully constrained and fully unconstrained system is thought to be ideal (Stergiou & Decker, 2011). Therefore, the increase in EC SampEn can be interpreted to demonstrate a less organized or too variable postural control system state.

2.5.3 Cognitive task difficulty did not influence postural sway amplitude

RMS and sway area assessed the effect of cognitive task difficulty on sway amplitude. The hypothesis that the magnitude of these metrics would decrease with DTs of varying loads was partially supported. An initial decrease from QS with a DT was found for area, ML RMS, and occasionally for AP RMS. No statistically significant differences between the other conditions were identified. In general, it was demonstrated that sway amplitude sometimes decreased with the addition of a cognitive task and this decrease did not show to differ between cognitive tasks of varying difficulty.

2.5.3.1 Cognitive load and postural sway amplitude

Automaticity, facilitated by a cognitive distraction, is commonly reflected as a decrease in postural sway amplitude (Potvin-Desrochers et al., 2017; St-Amant et al., 2020). Decreases in sway amplitude and automaticity have also been associated with decreases in total power (Bernard-Demanze et al., 2009; Ueta et al., 2015). Under automatic control, one's sway is less constrained and allowed to naturally self-organize (Wulf et al., 2001). Internally focusing attention can constrain and interfere with automatic control, reducing the tight regulation of postural sway, which is thought to result in increases in sway (Wulf et al., 2001).

2.5.3.1.1 Sway amplitude shows some evidence for automaticity

All cognitive conditions appeared to facilitate automaticity in COP 95% confidence ellipse area and ML RMS. These findings are corroborated by ML total power since less power, which has been associated with less sway (Bernard-Demanze et al., 2009), was found in all tasks compared to QS. However, a similar reduction in sway variability and total power was not evident in the AP direction. Since the experimental foot position required feet to be positioned close together, the narrowed BOS could have contributed to an increased need to control ML sway (Kirby et al., 1987). This may have led to the tighter regulation of postural control, and sway amplitude decreases, in the ML direction. Additionally, to remain stable, it has been suggested that some sway is required to explore the environment to obtain relevant sensory information (Carpenter et al., 2010) and information regarding stability limits (Riley et al., 1997). Given that automatic postural control has been shown to reduce sway amplitude and the study outcomes provided evidence for decreased ML sway, AP sway may have remained relatively closer to QS, indicated by a lack of statistically significant differences, to permit some

sway to help maintain stability. This sway would assist present sensory modalities to obtain information about the body's orientation in space. While ML and AP sway has been described to operate independently (Winter et al., 1996), some studies have reported that ML and AP control mechanisms may not be fully independent (Balasubramaniam et al., 2000; Nejc et al., 2010). Directional sway amplitude outcomes have shown to trade-off, where purposeful reductions of sway in one direction can lead to relatively greater sway in the other direction (Balasubramaniam et al., 2000).

2.5.3.1.2 Sway amplitude does not vary cognitive tasks

While it was expected that the intended cognitive task challenge would progressively suppress sway amplitude, this was not evident. Given that the protocol varied cognitive tasks within arithmetic tasks, participants could have maintained a comfortable or maximal level of distraction. Sway outcome differences identified between cognitive tasks have previously been elicited by varying task types (Huxhold et al., 2006). Varying task type allows for differing baseline challenges that cannot be compensated for. Moreover, despite ML SampEn showing m_3 to elicit more automaticity than m_{77} , the expected accompanying sway amplitude decrease, for m_3 compared to m_{77} , did not occur. This may reflect the increased differentiating sensitivity observed when comparing entropy-related sway and sway amplitude outcomes (Cavanaugh et al., 2005).

2.5.3.2 Visual effect on sway amplitude

EO and EC outcomes were not consistent across metrics. ML RMS EC conditions were greater than EO, which can be justified by a lack of vision. Standing with EC reduces a sensory

modality providing the central nervous system with information about upright stance orientation, which may contribute to increases in sway amplitude (Riley & Clark, 2003). However, AP RMS and area showed no effect of vision. In the absence of sensory modalities, available sensory signals are thought to reweigh to compensate for inaccurate or absent sensory cues (Peterka, 2002). When standing with EC, sensory reweighting would be hypothesized to be directed to vestibular and ankle somatosensory modalities (Peterka, 2018). AP sway control is concentrated at the ankle dorsi and plantar flexors (Winter et al., 1996). Theoretically increasing the weight on somatosensory signals may have allowed an individual to restrict AP sway and to permit ML sway to change according to the stance challenge. The lack of sway increase in the AP direction may have been enough to influence one's overall sway area.

2.5.4 Cognitive task difficulty was not influenced by a stance challenge

Cognitive task difficulty did not show to depend on the stance challenge in any metric as shown by statistically insignificant interaction effects. While it was expected that the degree of attention drawn away from stance, in the EC conditions, would have been less, and that sway amplitude trends would have decreased less under the EC conditions than the EO conditions, it is possible that the EO/EC challenge was not enough to differentiate the outcomes. Healthy young adults are confident and stable individuals. Despite the EC stance eliciting a possible lack of effective postural control (Borg & Laxåback, 2010), the relative effect on young healthy adults may have not been enough to interact with a DT. Studies that have identified differences in postural sway with and without a DT have found differences when sensory reweighting demands are thought to be high (Lanzarin et al., 2015; Morelli et al., 2020). Further exploring the

interaction of various stance conditions, that manipulate sensory modalities available to challenge postural control, with a DT, is warranted.

2.5.5 Limitations and future research

Inferences about automatic and conscious postural control did not consider subjective recounts of attention allocation. Both automatic and conscious control has the potential to decrease sway amplitude (Ueta et al., 2015). While the contribution of automatic control can be substantiated by SampEn, incorporating subjective accounts of attention allocation can assist with COP outcome interpretations and help form conclusions regarding postural control strategies used. Additionally, despite a clear indication of varying levels of difficulty between the arithmetic cognitive tasks, the effect of cognitive task difficulty on postural control may not have been apparent due to compensating (e.g., reducing response rate) for the task challenge. Further exploring DT difficulty, in ways that cannot be compensated for, can provide clarity regarding automaticity and task challenge.

2.6 Conclusion

Cognitive task difficulty does not influence the degree of automatic postural control. While adding a cognitive task increased automaticity, automaticity did not depend on the task load and overall task difficulty. Cognitive tasks of varying difficulty also showed to reduce postural sway, which aligns with automaticity predictions; however, sway changes did not depend on the interaction of the stance and cognitive task components. Generally, while dual- or multi-tasking in daily life, young and healthy individuals utilize some automatic and unconscious mechanisms to help remain stable and the usage of automatic mechanisms may not depend on

the degree of cognitive distraction. Further exploring overall task difficulty with task components that cannot be neglected or compensated for (e.g., varying the stance challenge) can assess the effectiveness and usage of automatic postural control that can help explain instances when automatic postural control mechanisms may be used in everyday life.

Chapter 3: Automatic and conscious postural control in response to manipulations of overall task difficulty

3.1 Abstract

Activities of daily living are comprised of various task components and occur in different environments. While each task component may use some attentional resources, the degree of attention allocated to each component can depend on the environmental context. Posture-cognition dual-task (DT) paradigms are used to study multi-task interactions and can be used to study the underlying mechanisms related to how individuals can attend to various tasks at once. Young healthy adults have been shown to use less conscious and more automatic postural control when engaging in a cognitive task regardless of the difficulty of the cognitive task; however, the continued use of automatic postural control mechanisms in different environmental contexts has not been thoroughly explored. This knowledge can increase the understanding of instances when automatic mechanisms underlie DT and, possibly, multi-task interactions in various environments. This study explored how the combined influence of a stance and cognitive challenge (i.e., overall task difficulty in the context of this thesis) influenced the use of automatic postural control. Thirty-one participants completed twelve upright stance trials that consisted of six stance challenges and two levels of cognitive load. Engaging in a cognitive task generally showed to reduce perceived conscious postural control and increased automaticity. Overall task difficulty did not entirely influence the degree of automatic postural control. Only standing on a foam surface without vision resulted in relatively less automatic control. Since automatic control tends to remain intact when one's stability is challenged, exploring the use of automaticity in additional contexts and with various outcome measurements can refine the characterization of automaticity, in multi-task contexts, and its applicability to everyday life.

3.2 Introduction

Multi-tasking during daily life can occur in various environmental contexts (e.g., a dark environment or an environment with an uneven surface) that can challenge one's ability to remain stable and prevent falling. Individuals generally prioritize stability at the expense of other task components (Bloem et al., 2001); however, when young healthy adults are tasked with engaging in a cognitive task and remaining stable under challenging stance conditions, cognitive task engagement tends to remain, and cognitive performance can be maintained relative to less challenging stance conditions (Morelli et al., 2020). In posture-related DT studies, engaging in cognitive tasks can be assumed to increase automatic postural control due to a possible reduction of attention allocated to upright stance (Donker et al., 2007; Nafati & Vuillerme, 2011). Chapter 2 provided some evidence for automatic postural control while completing a cognitive task; the degree of automaticity was not influenced by cognitive task difficulty and was not dependent on a stance condition challenge. Since young healthy adults use automatic postural control mechanisms (Potvin-Desrochers et al., 2017; St-Amant et al., 2020) and remain engaged with a cognitive task despite some postural unsteadiness (Morelli et al., 2020), exploring a DT paradigm with various stance condition manipulations to challenge stability can further explain underlying postural control mechanisms, such as automaticity, while attending to various tasks at once. A greater understanding of postural control mechanisms in DT scenarios can contribute to the development of strategies to help individuals remain stable, safe, and avoid falls.

3.2.1 Automatic Postural Control

Roerdink et al. (2011) modelled postural control automaticity on a continuum of conscious to automatic control. This model hypothesized that automatic postural control contributions increase when attention is withdrawn from stance and throughout recovery from disease or injury (e.g., a stroke); conscious postural control contributions are hypothesized to increase under conditions of postural threat (e.g., standing at a height) and when sources of sensory information are reduced, such as standing with eyes closed (EC) (Roerdink et al., 2011).

As a proposed marker of attentional involvement in postural control, sample entropy (SampEn) is used to represent automatic postural control contributions (Roerdink et al., 2006; Roerdink et al., 2011). SampEn quantifies the degree of randomness or regularity of a time-series signal. A more random or less regular signal (i.e., SampEn increase) can be interpreted as less constrained, on the other hand, a less random or more regular signal (i.e., SampEn decrease) can be interpreted as more constrained (Richman & Moorman, 2000). Directing attentional resources toward stance may lead to more conscious control, which may interfere with the automatic processes regulating upright stance (Roerdink et al., 2011; Wulf et al., 2001). This interference can be understood to constrain and reduce random sway adjustments tightly regulating postural control (Cavanaugh et al., 2007; Stergiou & Decker, 2011).

In posture-related DT studies, completing cognitive tasks can elicit automatic postural control due to a reduction of attention allocated to upright stance (Donker et al., 2007; Nafati & Vuillerme, 2011); however, this assumption is rarely subjectively measured. The perceived contribution of conscious movement control has been quantified using the Movement Specific Reinvestment Scale (MSRS) (Masters & Maxwell, 2008). In posture-related studies, the MSRS has been used to measure state-specific changes in conscious processing (Huffman et al., 2009)

and one's propensity to think about their movements (Zaback et al., 2015). Increases in perceived conscious processing between test trial conditions are evident when standing under threatening conditions (i.e., at a high height) (Huffman et al., 2009). Since engaging in a cognitive task is anticipated to increase SampEn and reduce conscious movement processing (Roerdink et al., 2011), assessing both SampEn along with perceptions of movement control can assist in making inferences about cognitive task engagement and automatic postural control.

3.2.2 Overall task challenge

Overall task difficulty was a phrase used to describe the combined challenge of stance and cognitive task components in this study. Each of these components can vary the relative difficulty of a DT paradigm. A postural task, such as bipedal upright stance, can be challenged by varying the presence and accuracy of sensory information available. Visual, vestibular, and ankle somatosensory inputs help one remain stable by providing the central nervous system with information about the orientation of the body in space (Horak, 2006). The six Sensory Organization Test conditions, which include standing with accurate, absent, and inaccurate visual feedback as well as accurate and inaccurate somatosensory feedback, have been used to manipulate upright stance sensory input (Shumway-Cook & Horak, 1986). While standing with varying amounts or accuracy of sensory information, sensory reweighting is proposed to occur in which a greater weight is placed on present and accurate sensory modalities; absent and inaccurate sensory modalities are thought to be downweighed (Peterka, 2002; Peterka, 2018). Despite a proposed reweighting of sensory inputs, postural steadiness can still be challenged when standing with less present and/or accurate sensory inputs (Riley & Clark, 2003; Shumway-Cook & Horak, 1986).

Remaining upright with less sensory information has been suggested to use a greater amount of attentional resources (Remaud et al., 2012; Roerdink et al., 2011; Teasdale et al., 1993). Given that, upright stance uses some attentional resources (Woollacott & Shumway-Cook, 2002), a distracting cognitive task may interfere with upright stance when upright stance attentional demands increase. In young adult DT studies, posture-cognitive interference—represented as sway amplitude increases under DT conditions—has been shown to be evident when standing with inaccurate visual and somatosensory modalities (Lanzarin et al., 2015; Morelli et al., 2020). Since decreases in sway amplitude while completing a cognitive task, tend to occur in young healthy adult DT studies (Polskaia & Lajoie, 2016; Potvin-Desrochers et al., 2017; Resch et al., 2011; Ross et al., 2011; St-Amant et al., 2020) and because sway amplitude decreases may reflect greater automatic sway control (Polskaia & Lajoie, 2016), the absence of sway amplitude decreases while completing a cognitive task and standing under challenging stance conditions can be interpreted as less automatic postural control contributions (Lajoie et al., 2016). This may show a possible limit to the usage of automatic postural control mechanisms in tasks with greater overall difficulty.

3.2.3 Objective and hypotheses

Exploring the overall difficulty of a DT paradigm, when engaging in a cognitive task under variable stance conditions, can probe the effectiveness and use of automatic postural control in various DT contexts. The combined influence of stance and cognitive task challenge was quantified by calculating dual-task cost (DTC) outcomes. DTC measurements compare DT and single-task (ST) versions of the same stance task to assess the effect of a cognitive task relative to the stance condition. It provides a measure that considers both stance and cognitive

task components, thus, representing the overall difficulty of a task in this Study. For reference, the following research questions and associated hypotheses were considered:

1. Do increases in overall task difficulty continue to elicit a shift from automatic to conscious postural control?

It was hypothesized that the use of automatic control will not remain and a shift to relatively more conscious control will be evident in tasks of a greater overall difficulty (Roerdink et al., 2011). SampEn DTC outcomes were expected to become negative and reduce in magnitude under challenging stance conditions.

2. Is there a sway amplitude cost from potential changes in overall task difficulty, automatic, and conscious control?

It was hypothesized that a sway amplitude decrease, due to more automatic control, will not remain and increases in sway amplitude will be evident in tasks of greater overall difficulty (Lanzarin et al., 2015; Morelli et al., 2020). Root mean square (RMS) DTC outcomes were expected to become positive and reduce in magnitude under challenging stance conditions.

3.3 Methods

3.3.1 Participants

A sample size estimate indicated that a minimum of 18 participants were required for this study. Using the G*Power 3 program (Faul et al., 2007) an Analysis of Variance repeated measures within factor priori analysis was conducted using an alpha of 0.05, power of 0.8, one group, 6 measurements, and an estimated effect size of 0.89 (based on Cohen 1988). The estimated effect size was determined from previous literature that assessed automatic postural

control with and without a cognitive task, while standing upright with feet together, in a young healthy adult population (St-Amant et al., 2020). St-Amant et al. (2020) found a statistically significant cognitive condition main effect in medial-lateral (ML) SampEn outcomes, with $\eta^2=0.440$ (i.e., an effect size of 0.89).

Thirty-three young healthy adults were recruited from York University and the surrounding community. The inclusion criteria required participants to be between the ages of 18–40 years old, have no self-reported history of a concussion or neurologic injury, and have no current muscle or skeletal foot or leg injury. When a self-reported history of concussion or neurologic injury was reported, participation was permitted only if the prospective participant was symptom free for at least one year. Data from these participants (n=2) were closely assessed and, due to contributing to outliers in the data, were removed from the analysis. Previous literature has reported instances of instability post-concussion (Guskiewicz et al., 2003), and not all postural sway measures have been shown to return to baseline post-concussion (Sweeny et al., 2020). Therefore, data from 31 participants were assessed; descriptive characteristics of the analyzed sample are presented in Table 3.1. This research was approved by the York University Research Ethics Board (Certificate #: 2021-373).

Table 3.1 Study 2 analyzed sample (n=31) descriptive characteristics.

Characteristic	Sample Outcome
Age (years)	23.9 (4.2)
Height (m)	1.7 (0.9)
Weight (kg)	66.4 (12.6)
Years of Education (years)	17.1 (2.4)
Sex	18 female; 13 male

Numeric outcomes presented as mean (SD).

3.3.2 Experimental design

This study consisted of 12 test trials that varied by stance condition and cognitive load as well as two baseline trials. Data was collected in the Sherman Health Science Research Centre at York University. The baseline trials required participants to stand on the firm force plate with their eyes open (EO) and without a head mounted display (HMD; HTC Vive Pro 2, Taiwan); an HMD was used for the 12 test trials. The baseline trials were completed under ST and DT conditions. Due to the focus of this chapter on overall task difficulty that was driven by stance challenges, the baseline trials were not analyzed in this thesis. Summary outcome measurements for the baseline trials are presented in Appendix A.

3.3.2.1 Stance conditions

The test trials included six stance conditions that were used to challenge the postural system by manipulating the availability and accuracy of sensory modalities. Less available and inaccurate sensory modalities can challenge stability (Riley & Clark, 2003; Shumway-Cook & Horak, 1986). The Sensory Organization Test is composed of six stance conditions and various sensory manipulations that are commonly used to assess the visual, vestibular, and somatosensory system contributions (Shumway-Cook & Horak, 1986). The following six conditions, that involve EO, EC, or a sway-referenced visual surround on a firm or unstable surface, are used to assess sensory systems and, in turn, challenge stability (listed from least to most difficult): EO firm surface (EOF), EC firm surface (no vision; ECF), sway-referenced vision firm surface (inaccurate visual cues; SRF), EO unstable surface (inaccurate somatosensory cues; EOS), EC unstable surface (no vision; inaccurate somatosensory cues; ECS), and sway-

referenced vision unstable surface (inaccurate visual cues; inaccurate somatosensory cues; SRS) (Shumway-Cook & Horak, 1986).

With the intention to challenge stability, the above six conditions were mimicked by requiring participants to stand on a force plate, with sensory-specific manipulations, while wearing an HMD (Table 3.2). In all the trials with accurate or inaccurate visual input, participants viewed a virtual real-world environment, programmed in Vizard (WorldViz, USA), with a red fixation point (Figure 3.1). Accurate visual conditions were achieved by programming the HMD to respond (i.e., provide feedback) to all head and body position and orientation movements. The inaccurate visual condition (i.e., sway-referenced) was programmed by linking head orientation, but not head position to the HMD. This allowed the virtual environment to respond to head pitch, roll, and yaw movements and not respond to changes in position (i.e., forward/backward, left/right, up/down body movements); the virtual scene was programmed to move in proportion to each participant's sway, thus, providing inaccurate sway-referenced visual feedback (Nashner, 1982). A real-world environment compared to an abstract environment was programmed since abstract environments are associated with increased sway compared to real-world environments (Assländer & Streuber, 2020). To eliminate vision, participants viewed a blacked-out virtual environment without the fixation point. A 19 x 16 x 2.5 inch high-density foam pad (Airex® Balance-pad, Switzerland) acted as the unstable surface. Standing on a compliant surface challenges stability, compared to standing on a firm surface, and is thought to distort and reduce the use of somatosensory signals used to regulate posture (Alahmari et al., 2014; Schut et al., 2017; Shumway-Cook & Horak, 1986).

Table 3.2 The six stance conditions and the associated present/absent and accurate/inaccurate sensory manipulations.

Condition	Sensory Manipulations				
	Vision		Vestibular	Somatosensory	
EOF	Accurate	EO	Accurate	Accurate	Firm surface
ECF	Absent	EC	Accurate	Accurate	Firm surface
SRF	Inaccurate	EO; SR	Accurate	Accurate	Firm surface
EOS	Accurate	EO	Accurate	Inaccurate	Foam surface
ECS	Absent	EC	Accurate	Inaccurate	Foam surface
SRS	Inaccurate	EO; SR	Accurate	Inaccurate	Foam surface

SR indicates a sway-referenced visual surround; Firm surfaces are indicated by an “F” at the end of the condition codes; Foam surfaces are indicated by a “S” at the end of the condition codes to represent a soft surface.

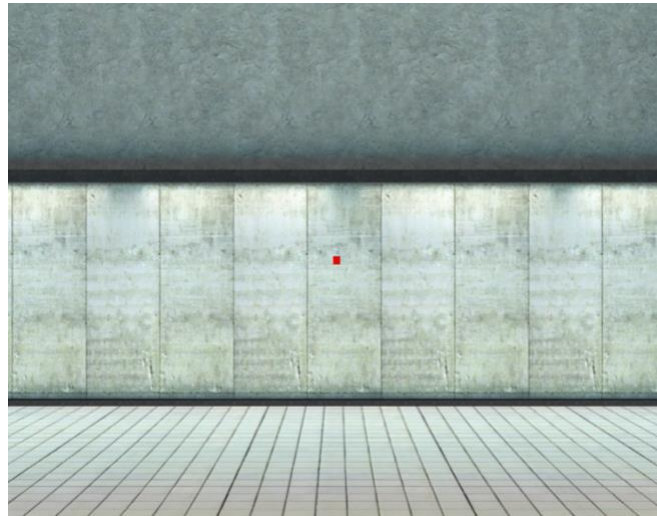


Figure 3.1 The virtual environment viewed for each condition with vision available (i.e., EOF, EOS, SRF, and SRS).

Participants stood on the force plate wearing socks. An upside down “T” was taped onto the force plate to standardize the foot placement. Each participant aligned their heels with the horizontal portion of the “T” (approximately 9.5cm from the posterior edge of the plate) and positioned their feet parallel surrounding the vertical portion of the “T” (approximately 25cm from the lateral edge of the plate). Feet were positioned close together, but not touching, to further challenge stability since a smaller base of support (BOS) creates a smaller area for the

centre of mass to move. Participants stood upright, in an intended comfortable body position, with their hands by their sides and shoulders, neck, and head relaxed.

3.3.2.2 *Cognitive conditions*

Two levels of cognitive load were used. The lowest level of cognitive load was an uncontrolled load condition without explicit cognitive instructions (i.e., QS). Due to the findings of Chapter 2, which identified a general lack of statistically significant differences between arithmetic conditions in the majority of centre of pressure (COP) outcome metrics, serial 7s was the second cognitive condition used.

3.3.3 Experimental procedure

Before participation, participants reviewed and signed a consent form and completed a self-report demographic and medical history form; each form was approved by ethics. Data collection sessions consisted of 14 pseudo-randomized 80 second trials with optional self-selected breaks between each trial. An 80 second trial duration was chosen since it has been shown to be sufficient to provide stable and reliable COP summary measures (Carpenter et al., 2001). Participants also completed two questionnaires immediately after each trial; only one questionnaire was considered for the analysis to help interpret automaticity. Details regarding the questionnaires are outlined further below.

The 14 trials were composed of 12 test trials and two baseline trials. The two baseline trials included an ST and a DT trial that required participants to stand on the firm force plate with their EO without the HMD. The baseline trials were completed before the test trials and were counterbalanced across participants. The HMD was worn for each of the 12 test trials, which

were composed of six stance conditions performed with and without a DT. For all trials with vision available (i.e., accurate and inaccurate vision), participants were instructed to look straight ahead at the red fixation point. For trials without vision, the virtual environment was black, and the fixation point was removed. The experimenter moved the foam pad on and off the force plate for relevant trials. DT trials required participants to subtract by 7s from a three-digit value between 600–700.

At the beginning of each trial, the experimenter told the participants the trial condition. The participants stepped onto the force plate, with an elevated surrounding surface to match the height of the force plate, and took 10 seconds to settle into the stance position. At five seconds the participant was reminded of the trial condition and the start value (if a DT trial). The collection then began. During the collection, the experimenter recorded DT performance on custom data collection sheets. After the collection, the experimenter told the participant the trial was over and asked the participant to step off the plate. The participant then immediately completed the questionnaires. Trials were repeated if the trial was interrupted or the participant aborted a trial, at the end of the initial trial sequence and with a new DT start value (if applicable).

3.3.4 Data collection and processing

COP data were collected at 1024Hz using an AMTI force plate (OR6-7-1000-3985) and Power1401-3A analog to digital board (Cambridge Electronic Design, England). Raw COP data were collected using Spike2 (Cambridge Electronic Design, England). Custom LabVIEW (National Instruments, USA) code was used to calibrate data from V/mV to N/Nm. A second-

order low-pass Butterworth filter, with a cut-off frequency of 10Hz, was applied to the COP time-series. The middle 60 seconds of each trial were isolated for analysis.

COP data points, in the anterior-posterior (AP) and ML directions, were determined using the same calculation process as presented in Chapter 2 (section 2.3.4). The equations are presented below for reference:

$$COP_y = \frac{M_x + F_y * Z_o}{F_z}$$
$$COP_x = \frac{-(M_y + F_x * Z_o)}{F_z}$$

Since Z_o , an offset value, is effectively 0, each equation was simplified to the following:

$$COP_y = \frac{M_x}{F_z}$$
$$COP_x = \frac{-M_y}{F_z}$$

F and M represent force and moment outputs, respectively, along the x, y, and z axes.

Custom data collection sheets were used to record cognitive performance. The experimenter also scored the questionnaires.

3.3.5 Data analysis

Objective and subjective data were considered for Study 2. Input data, for objective analyses, was expressed as mean-removed directional COP data points along the time-series and used to calculate SampEn as well as RMS. Subjective data was collected through conscious control and simulator sickness questionnaires. The simulator sickness questionnaire was not included in the analysis due to the primary focus of this chapter on automaticity. A brief explanation and simulator sickness questionnaire outcomes are presented in Appendix B.

Variable explanations and calculation procedures as well as details regarding the conscious control questionnaire are outlined below.

3.3.5.1 Sample entropy

SampEn was used to assess automatic postural control. The same data analysis procedure and interpretation, as outlined in Chapter 2 (section 2.3.5.1), was used. The calculation procedure, which is similarly defined for the ML direction, is presented below for reference:

$$SampEn_{Ap} = -\ln\left(\frac{A}{B}\right)$$

where,

$$B = \frac{(N - m - 1)(N - 1)}{2} B_i$$

$$A = \frac{(N - m - 1)(N - 1)}{2} A_i$$

and,

$$B_i = \frac{\sum C_i^m}{N - m}$$

$$A_i = \frac{\sum C_i^{m+1}}{N - m}$$

SampEn parameters chosen included $m=2$, $r=0.2*SD$, and $N=7680$. Given that SampEn is thought to be positively correlated with the amount of attentional involvement and automaticity in postural control (Roerdink et al., 2006; Roerdink et al., 2011), more automatic postural control can be reflected by an increase in SampEn (i.e., a less regular time-series), and less automatic postural control can be indicated by a decrease in SampEn (i.e., a more regular time-series) (Roerdink et al., 2011).

3.3.5.2 Root mean square

RMS was used to assess possible changes in sway amplitude. The same data analysis procedure and interpretation, as outlined in Chapter 2 (section 2.3.5.3) was used. For reference, the calculation procedure, which is similarly defined for the ML direction, is outlined below:

$$RMS_{AP} = \left(\frac{1}{N} \sum AP[n]^2 \right)^{1/2}$$

$AP[n]$ is the mean-removed COP_{AP} data point and N is the total number of data points (Prieto et al., 1996). A greater RMS value was interpreted as less of an ability to control upright stance around an average position (Palmieri et al., 2002).

3.3.5.3 Conscious Motor Processing sub-scale

To assist with data interpretation, subjective perceptions of the degree of conscious involvement in postural control were considered. A portion of the MSRS (Masters & Maxwell, 2008) was administered after each trial (i.e., 14 times total). The MSRS considers the role of consciousness during movement (Masters & Maxwell, 2008). It has been used in posture-related studies (Huffman et al., 2009; Zaback et al., 2015) and validated in a population that is vulnerable to instability (Kal et al., 2016). The MSRS is composed of two subscales measuring Conscious Motor Processing (CMP) and Movement Self-Consciousness (Masters & Maxwell, 2008). The CMP assesses the role of consciousness in movement and Movement Self-Consciousness considers personal concerns about movement appearance (Masters & Maxwell, 2008). Each subscale of the MSRS is measured separately. Only the CMP was considered for this study. The CMP required participants to rate five statements on a six-point scale from strongly disagree to strongly agree (Masters & Maxwell, 2008). Statements were scored on a scale of one to six (Kal et al., 2016) and compared between scores to assess subjective perceptions of

conscious control. Scores can range from 5 to 30; greater scores are indicative of more conscious control. The CMP used in this study was adapted to increase statement clarity and to specifically apply to trial conditions (see Appendix C for the administered CMP). MSRS statement adaptations have been previously done to better align with experimental protocols (e.g., Cooke et al., 2011; Huffman et al., 2009).

3.3.5.4 Dual-task cost

DTC outcomes assessed the overall difficulty of the trials in this Study. The DTC was quantified using the following equation (Boisgontier et al., 2013; Pavão et al., 2021; Yu & Huang, 2017):

$$DTC = \left(\frac{DT - ST}{ST} \right) * 100\%$$

where DT and ST represent the summary measurement of interest for the respected conditions. DTC interpretations for each summary measure are presented in Table 3.3. Each summary measure was represented and analyzed as a DTC value to highlight overall task difficulty.

Table 3.3 DTC interpretation for SampEn, CMP, and RMS summary measures.

Measure	Sign		Magnitude	
	Negative	Positive	Decrease	Increase
SampEn	Less automatic (more conscious) involvement	More automatic (less conscious) involvement	Less DT and ST condition difference	Greater DT and ST condition difference
CMP	Less perceived conscious processing	More perceived conscious processing		Greater DT and ST condition difference
RMS	Less amplitude sway	More amplitude sway		Greater DT and ST condition difference

Sign comparisons are indicated for the DT condition relative to the ST condition.

3.3.5.5 Cognitive task performance

As a secondary outcome, cognitive task performance was quantified and analyzed as the number of correct responses (within 60 seconds) and response rate across the stance conditions.

3.3.6 Statistical Analysis

To test the hypotheses that the use of automatic control and a sway amplitude decrease will not remain in tasks of greater overall difficulty, DTC outcomes for SampEn, CMP, and RMS were assessed using non-parametric Friedman tests, in SPSS (IBM, USA), since most outcomes were not normally distributed. Prior to conducting the Friedman tests, each variable was assessed for normality using the Shapiro-Wilks test for normality; most tests were significant. These deviations from normality were determined to be from outliers, which were determined by assessing z-scores and identified as values greater than two standard deviations from the mean. Statistically significant Friedman tests were further assessed through Wilcoxon signed-rank tests with a Bonferroni correction applied. The following post-hoc comparisons were made if a Friedman test was statistically significant: EOF-ECF, EOF-SRF, EOF-EOS, EOF-ECS, EOF-SRS, ECF-SRF, ECF-EOS, ECF-ECS, ECF-SRS, SRF-EOS, SRF-ECS, SRF-SES, EOS-ECS, EOS-SRS, and ECS-SRS. Secondary cognitive task performance variables (i.e., the number of correct responses and the response rate) were also analyzed using non-parametric Friedman tests; all tests were not statistically significant. Statistical significance was set at $p < 0.05$.

3.4 Results

3.4.1 Overall task difficulty and automatic postural control

3.4.1.1 Sample entropy

SampEn DTC outcomes appeared to remain positive, on average, indicating DT SampEn was generally greater than ST SampEn for each condition (Table 3.4; Figure 3.2). The magnitude of the DTC seemed to decrease when standing on foam compared to no foam conditions.

SampEn DTC outcomes tended to vary across individual participants for each condition (Figure 3.3). The analyses demonstrated limited statistical significance between each stance conditions.

ML SampEn DTC Friedman tests showed a statistically significant difference in DTC outcomes between stance conditions ($\chi^2(5) = 23.553$, $p < 0.001$). Post-hoc tests identified EOF ($Z = -3.449$; $p < 0.001$) and SRF ($Z = -2.939$; $p = 0.003$) DTC outcomes to be greater than the ECS DTC outcome. All other post-hoc comparisons were not statistically significant: EOF-ECF ($Z = -0.510$; $p = 0.610$), EOF-SRF ($Z = -0.490$; $p = 0.624$), EOF-EOS ($Z = -2.646$; $p = 0.008$), EOF-SRS ($Z = -2.371$; $p = 0.018$), ECF-SRF ($Z = -0.470$; $p = 0.638$), ECF-EOS ($Z = -2.234$; $p = 0.025$), ECF-ECS ($Z = -2.646$; $p = 0.008$), ECF-SRS ($Z = -1.960$; $p = 0.050$), SRF-EOS ($Z = -2.439$; $p = 0.015$), SRF-SRS ($Z = -2.371$; $p = 0.018$), EOS-ECS ($Z = -0.901$; $p = 0.367$), EOS-SRS ($Z = -0.235$; $p = 0.814$), and ECS-SRS ($Z = -0.549$; $p = 0.583$).

AP SampEn DTC Friedman tests were not statistically significant ($\chi^2(5) = 4.641$, $p = 0.461$).

Table 3.4 Descriptive SampEn outcomes for each DT and ST conditions.

Direction	Condition	DT SampEn	ST SampEn
ML	EOF	0.071 (0.025)	0.051 (0.025)
	ECF	0.074 (0.028)	0.056 (0.023)
	SRF	0.071 (0.040)	0.055 (0.042)
	EOS	0.084 (0.023)	0.071 (0.021)
	ECS	0.086 (0.021)	0.076 (0.019)
	SRS	0.087 (0.026)	0.073 (0.022)
AP	EOF	0.059 (0.022)	0.051 (0.026)
	ECF	0.065 (0.031)	0.049 (0.021)
	SRF	0.065 (0.038)	0.064 (0.055)
	EOS	0.076 (0.026)	0.062 (0.021)
	ECS	0.084 (0.028)	0.072 (0.019)
	SRS	0.079 (0.031)	0.069 (0.020)

Numeric outcomes presented as mean (SD).

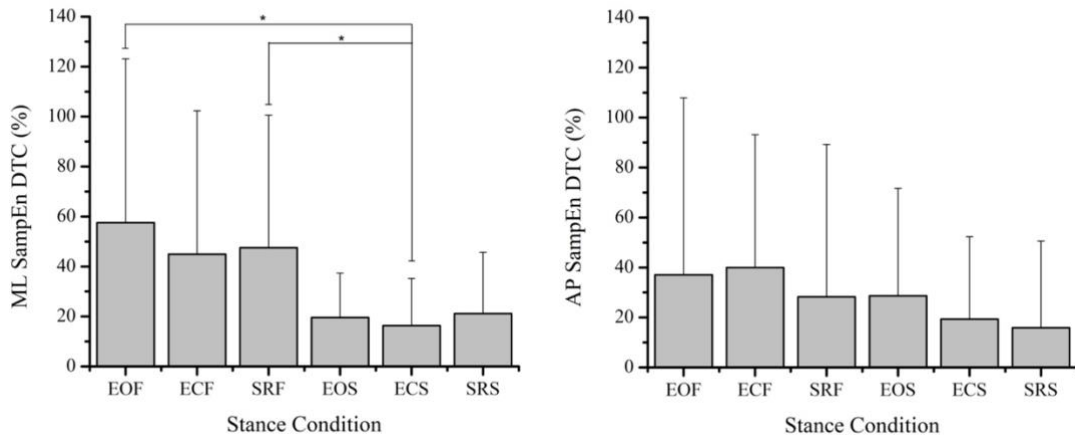


Figure 3.2 Mean and SD of ML SampEn DTC (%) and AP SampEn DTC (%) for each stance condition. Significance (*) is indicated for DTC outcomes that statistically significantly differ after correcting for multiple comparisons ($p < 0.0033$).

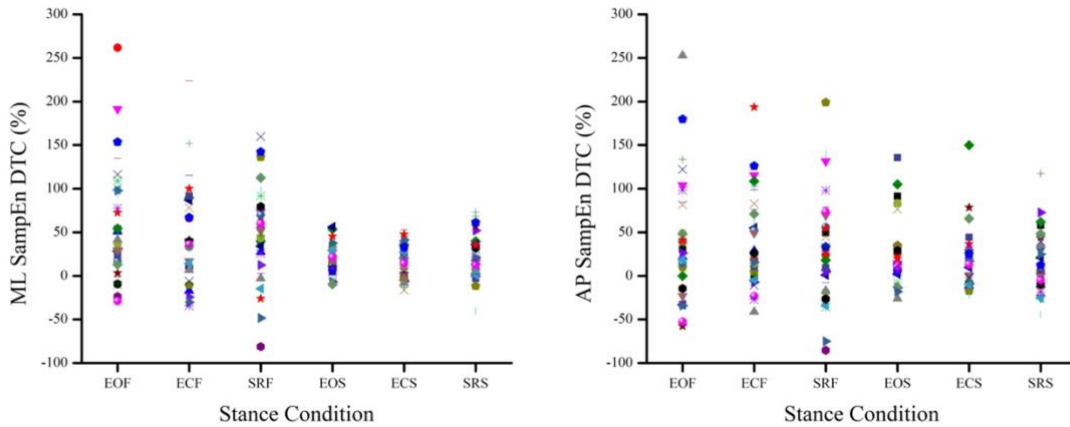


Figure 3.3 Raw ML and AP SampEn DTC (%) outcomes for each stance condition. Each symbol represents individual participants and displays the range of ML and AP SampEn DTC outcomes.

3.4.1.2 Conscious motor processing

CMP DTC outcomes tended to remain negative, on average, based on the observation that DT outcomes were generally smaller than ST outcomes (Table 3.5). Across stance conditions, the majority of participants appeared to use less perceived conscious control when completing the cognitive task, which was indicated by the observation of the concentration of participants with negative CMP DTC outcomes during the test trials in reference to a control (shaded area Figure 3.4). The magnitude of the DTC outcomes appeared to remain relatively consistent between conditions. No CMP DTC statistically significant findings were revealed ($\chi^2(5) = 2.698, p=0.746$).

Table 3.5 CMP scores for each DT and ST condition as well as DTC (%) outcomes. CMP scores range from 5 to 30 with greater scores indicating more perceived conscious processing.

	DT CMP	ST CMP	DTC (%)
EOF	10.81 (5.55)	14.16 (6.77)	-17.67 (30.13)
ECF	10.23 (5.32)	13.13 (6.10)	-17.02 (33.87)
SRF	10.77 (5.77)	12.83 (5.39)	-14.42 (29.35)
EOS	13.25 (6.46)	17.55 (6.81)	-21.51 (29.17)
ECS	14.39 (7.26)	17.84 (7.02)	-18.84 (31.68)
SRS	12.77 (6.19)	16.68 (6.97)	-18.81 (27.36)

Numeric outcomes presented as mean (SD).

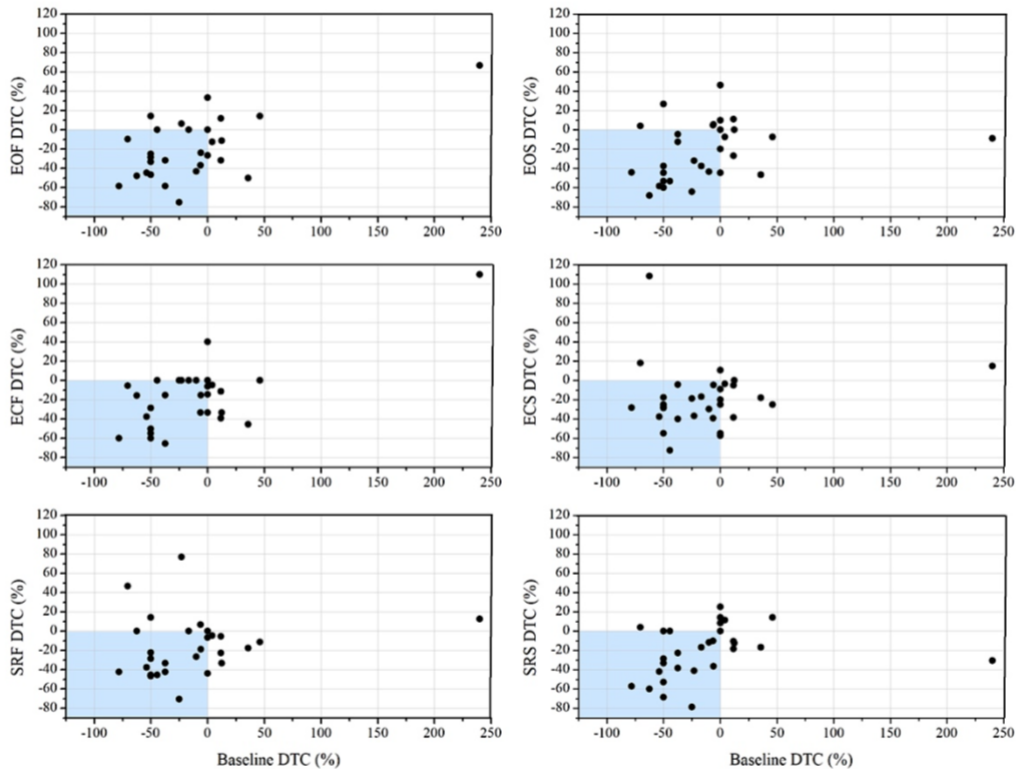


Figure 3.4 Scatter plots of DTC (%) CMP outcomes for each stance condition (y-axis) in reference to a control (i.e., baseline trials; x-axis). Relative to the DT condition, negative values represent instances when less conscious movement control was perceived, conversely, positive values represent instances when more conscious movement control was perceived. The concentration of DTC CMP outcomes in the shaded area illustrates a general perceived engagement with the serial 7s task.

3.4.2 Overall task difficulty and sway amplitude

3.4.2.1 Root mean square

RMS DTC outcomes tended to remain negative, on average, indicating that DT RMS was generally less than ST RMS and the magnitude varied across conditions (Table 3.6, Figure 3.5 (ML); Table 3.7 (AP)). Individual RMS DTC outcomes showed to vary across conditions due to

a large range of DTC outcomes across participants (Figure 3.6). Statistically significant condition DTC outcome differences were not apparent after post-hoc analyses.

ML RMS DTC Friedman tests revealed statistically significant differences between the stance conditions ($\chi^2(5) = 13.525, p=0.019$); however, post-hoc comparisons failed to reveal statistically significant differences after correcting for multiple comparisons. The following DTC post-hoc comparisons were made: EOF-ECF ($Z = -0.745; p=0.456$), EOF-SRF ($Z = -1.627; p=0.104$), EOF-EOS ($Z = -2.058; p=0.040$), EOF-ECS ($Z = -2.841; p= 0.004$), EOF-SRS ($Z = -2.077; p= 0.038$), ECF-SRF ($Z = -0.235; p=0.814$), ECF-EOS ($Z = -0.745; p=0.456$), ECF-ECS ($Z = -1.411; p=0.158$), ECF-SRS ($Z = -1.587 p=0.112$), SRF-EOS ($Z = -0.999; p=0.318$), SRF-ECS ($Z = -1.587; p=0.112$), SRF-SRS ($Z = -1.352; p=0.176$), EOS-ECS ($Z = -0.764; p=0.445$), EOS-SRS ($Z = -0.118 p=0.906$), and ECS-SRS ($Z = -0.353; p=0.724$).

AP RMS DTC Friedman tests did not reveal a statistically significant finding ($\chi^2(5) = 9.710, p=0.084$).

Table 3.6 Descriptive ML RMS (mm) outcomes for each DT and ST conditions.

Condition	DT RMS (mm)	ST RMS (mm)
EOF	4.07 (1.42)	5.20 (2.14)
ECF	4.10 (1.49)	4.93 (1.96)
SRF	4.28 (1.45)	5.14 (1.95)
EOS	7.69 (1.59)	8.60 (2.36)
ECS	8.81 (1.70)	9.43 (1.74)
SRS	8.40 (2.01)	9.05 (1.96)

Numeric outcomes presented as mean (SD).

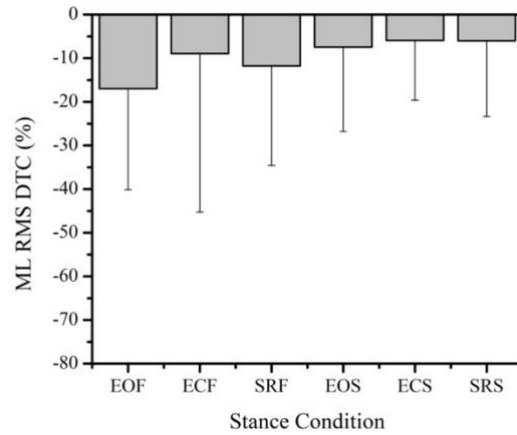


Figure 3.5 Mean and SD of ML RMS DTC (%) for each stance condition.

Table 3.7 Descriptive AP RMS (mm) outcomes for each DT and ST condition as well as DTC (%) outcomes. DTC outcomes were presented in a table, rather than a figure, to optimally present the data.

Condition	DT RMS (mm)	ST RMS (mm)	DTC (%)
EOF	5.41 (3.89)	5.79 (2.51)	-0.02 (74.01)
ECF	4.79 (2.20)	6.04 (2.45)	-15.88 (29.83)
SRF	5.13 (2.54)	5.59 (2.38)	-3.31 (33.56)
EOS	8.78 (2.22)	9.62 (2.42)	-5.84 (22.46)
ECS	9.40 (1.91)	9.84 (2.03)	-3.40 (14.40)
SRS	9.35 (2.35)	9.52 (2.06)	-0.76 (21.23)

Numeric outcomes presented as mean (SD).

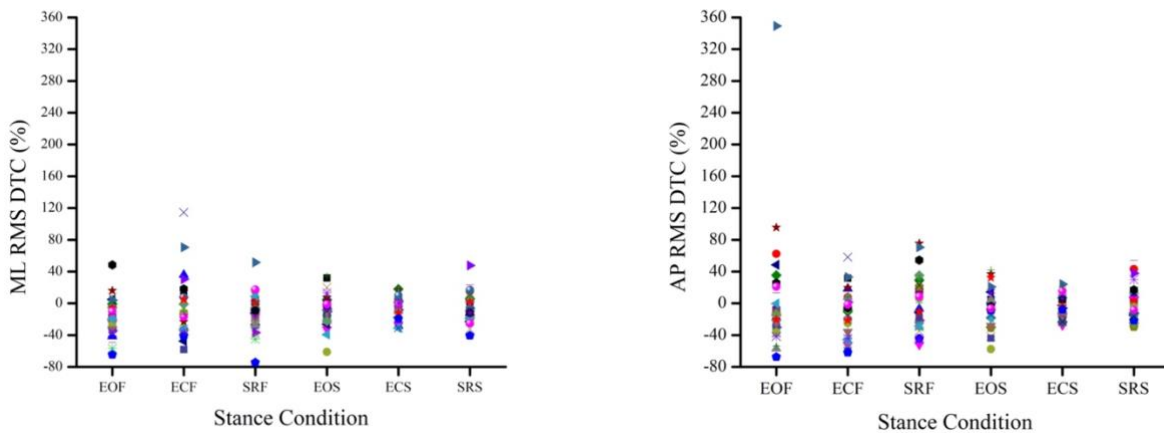


Figure 3.6 Raw ML and AP RMS DTC (%) outcomes for each stance condition. Each symbol represents individual participants and displays the range of ML and AP RMS DTC outcomes.

3.4.3 Cognitive performance

Cognitive performance outcomes (Table 3.7), which included the number of correct responses within 60 seconds and the response rate, tended to remain steady across stance conditions. Friedman tests did not reveal statistically significant findings for the number of correct responses ($\chi^2(5) = 10.764, p=0.056$) as well as response rate ($\chi^2(5) = 8.343, p=0.138$).

Table 3.8 Summary of the cognitive performance outcomes for the number of correct responses (within 60 seconds) and the response rate (response per second) for each stance condition.

	Condition					
	EOF	ECF	SRF	EOS	ECS	SRS
Correct Responses	14.0 (8.0)	15.9 (10.0)	16.0 (8.8)	15.5 (8.8)	15.0 (8.6)	15.6 (7.8)
Response Rate	0.26 (0.12)	0.29 (0.16)	0.28 (0.14)	0.28 (0.14)	0.27 (0.13)	0.28 (0.12)

Numeric outcomes presented as mean (SD).

3.5 Discussion

The combined influence of a stance and cognitive challenge (i.e., overall task difficulty) and automaticity as well as sway amplitude were explored through a DT paradigm that consisted of six stance conditions and two levels of cognitive load. Primary findings of DTC outcomes showed that overall task difficulty did not entirely influence the degree of automatic postural control or sway amplitude.

3.5.1 Automaticity and overall task difficulty

The degree of automatic postural control was primarily assessed through SampEn DTC outcomes. The hypothesis that less automatic and relatively more conscious control will become evident in tasks of greater overall difficulty was partially supported since under the ECS condition, ML SampEn statistically showed less of a cost compared to the EOF and SRF

conditions. However, no other statistically significant relationships were found in both the ML and AP directions. In general, it was demonstrated that automaticity has the potential to be elicited under challenging stance conditions.

3.5.1.1 Automaticity and perceptions of conscious control

Observations of the perceptions of conscious control were used to help interpret the SampEn findings since SampEn outcomes are suggested to reflect the amount of attentional involvement in postural control (Roerdink et al., 2006; Roerdink et al., 2011). Completing a cognitive task may require one to divert their attentional resources away from stance and toward the cognitive task (Donker et al., 2007; Nafati & Vuillerme, 2011). This was generally evident by observing the concentration of negative CMP DTC outcomes under each stance condition in comparison to a baseline level; negative CMP DTC outcomes were intended to indicate less perceived conscious involvement in postural control while completing a cognitive task compared to ST conditions. Reducing the attentional resources regulating stance may lead to a more automatic and less constrained postural control system, which can increase random sway adjustments to tightly regulate the postural system (Cavanaugh et al., 2007; Stergiou & Decker, 2011). This was generally reflected under each stance condition since DT SampEn outcomes remained greater than ST SampEn outcomes. In addition, DT RMS outcomes were smaller than ST RMS outcomes resulting in the observation of generally consistent negative RMS DTC outcomes. These findings provide some support demonstrating that the serial 7s cognitive task reduced conscious sway control and helped facilitate automaticity.

3.5.1.2 Automaticity remained with greater overall task difficulty

Roerdink et al. (2011) suggested that less sensory inputs, such as reducing the availability of visual information, may reduce automatic and increase conscious postural control. It can be hypothesized that when completing DT and ST test conditions that manipulate sensory input, less attentional resources directed to a cognitive task may occur due to a possible increase in conscious postural control. A SampEn DTC relationship between DT and ST conditions may decrease in magnitude and become a negative value, yet this relationship was not entirely evident. The only statistically significant SampEn DTC outcome was identified in the ML direction where the ECS condition showed less of a DTC compared to the EOF and SRF conditions.

SampEn findings varied in the ML and AP directions. The foot position used in Study 2 was similar to the Study 1 foot placement. Each participant stood with their feet side-by-side and close together, which narrowed their BOS compared to a shoulder-width stance. Standing with a narrowed BOS has been shown to involve more ML sway compared to standing with feet to the side and apart (Kirby et al., 1987). Changes in the regularity of a COP signal have been suggested to occur in directions of greater sway. For instance, standing with a unipedal stance (i.e., narrowed BOS) showed more changes in COP signal regularity compared to a hip-width bipedal stance (i.e., relatively wider BOS vs. unipedal stance) (Lara et al., 2022). Since the foot placement used in this study could have increased ML sway involvement, ML changes in the regularity of a COP signal show some relevance when interpreting the outcomes.

In the ML direction, each of the EOF, SRF, and ECS conditions elicited some automaticity, indicated by the positive SampEn DTC, with ECS showing less of a difference between the DT and ST conditions. This can be interpreted as ECS being a challenging condition

that required more conscious control, compared to EOF and SRF conditions, thus reducing the degree of automaticity that could be elicited. While dual-tasking, young adults can continue to use automatic mechanisms to remain upright while older adults turn to less automatic control (Yu & Huang, 2017). As individuals age, they may receive less sensory information about the orientation of their body in space (Woollacott, 2000), which may be due to less of an ability to integrate and weigh sensory information (Horak, 1989).

3.5.1.2.1 Automaticity and sensory manipulations

Standing on a foam surface without vision eliminates visual input and reduces the accuracy of somatosensory inputs and leaves only vestibular input to provide accurate sensory information (Shumway-Cook & Horak, 1986). To a degree, this can reduce usable sensory information obtained about the body's orientation in space (Horak, 2006) that may elicit relatively more conscious control (Roerdink et al., 2011); however, this proposed relationship between automaticity, conscious control, and sensory inputs is not always apparent.

Study 1 SampEn outcomes and outcomes from previous literature (Borg & Laxåback, 2010) have shown EC SampEn outcomes to be greater than EO outcomes. The raw SampEn outcomes from this study were observed to partly increase with fewer sensory modalities available, regardless of an added cognitive task. These trends have been explained to reflect a disorganized and noisy control system (Borg & Laxåback, 2010; Stergiou & Decker, 2011). Given that evidence for automaticity tended to remain in each of the ECS, EOF, and SRF conditions despite the potential for greater disorganization in the ECS condition compared to the others, it is possible that the young healthy adult population could tolerate some control system disorganization. Populations described as unhealthy or balance impaired (e.g., post-stroke

patients) appear to employ relatively more conscious movement control compared to healthy controls of a similar age (Roerdink et al., 2006). In addition, younger adults have been shown to continue to use automatic control mechanisms while older adults have not (Yu & Huang, 2017). A smaller SampEn difference between the DT and ST ECS conditions, compared to the EOF and SRF conditions, can be understood to reflect the start of a possible shift toward more conscious control due to the increased stance challenge. This possible shift occurred without the neglect of the cognitive task, which was reflected in the generally consistent cognitive task performance outcomes (i.e., the number of correct responses and the response rate outcomes) and the statistically insignificant CMP DTC outcomes. Overall, these findings show that standing with two less present and/or accurate sensory modalities may be a stance condition challenging enough for young healthy adults to employ relatively less of a degree of automatic mechanisms to remain stable.

3.5.2 The robustness of young healthy adult postural control

The degree of automaticity (SampEn DTC outcomes) involved in postural control did not statistically differ between conditions, other than ML ECS, in both the AP and ML directions despite the consistent observation of automaticity between DT and ST conditions. Similarly, when assessing sway amplitude DTC outcomes, the hypothesis that DT interference, observed as increases in sway amplitude, would become evident in tasks of greater overall difficulty was not supported. Each RMS DTC outcome remained negative meaning that sway amplitude was relatively less while completing a cognitive task, yet the difference between DT and ST conditions did not statistically differ across the stance conditions; no statistically significant findings were evident after a Bonferroni correction was applied in both the ML and AP RMS

DTC outcomes. In general, this shows that sway amplitude can be tightly controlled while completing a cognitive task and that this tight control remains when distracted and while standing under challenging stance conditions. Together, the lack of statistical significance in the remaining SampEn DTC outcomes and all the RMS DTC outcomes highlights the healthy and robust nature of young adult postural control in DT scenarios.

Young healthy adults tend to show an increase in postural sway while engaging in a cognitive task under challenging stance conditions, such as when standing with inaccurate visual and somatosensory modalities (Lanzarin et al., 2015; Morelli et al., 2020). It is possible that despite the stance conditions manipulating sensory inputs, not all sensory manipulations were challenging enough for the population to shift to more conscious control and increase sway amplitude while completing a cognitive task. Sensory reweighting is proposed to occur when individuals remain upright with variable present and accurate sensory modalities (Peterka, 2018). Young healthy adults show evidence for effective sensory reweighting. For example, young healthy adult sway amplitude is not always perturbed when standing under conditions where sensory reweighting is thought to occur, such as when standing without visual input (Winter et al., 1998). The young healthy adult population could have tolerated the sensory challenges to their stability. Populations like this have shown the ability to remain steady in instances when older adults have not (Bernard-Demanze et al., 2009; Potvin-Desrochers et al., 2017; Shumway-Cook & Woollacott, 2000).

Standing on a foam surface without visual input was the only condition that seemed to influence the degree of automaticity compared to the other conditions. This outcome, in the absence of sway amplitude statistical significance, can be attributed to the increased differentiating sensitivity of entropy-related sway measures compared to sway amplitude

outcomes (Cavanaugh et al., 2005). These findings demonstrate that young healthy adults are able to handle DT challenges in various contexts and reinforce the use of various analyses (e.g., linear and non-linear) when studying underlying postural control mechanisms.

3.5.3 Limitations and future research

Outcomes related to dual-tasking and automaticity as well as interferences regarding multi-tasking in daily life are limited to study conditions that manipulated sensory inputs and imposed a cognitive distraction. While these sensory contexts are characteristic of various environmental constraints in daily life (e.g., navigating a dark environment), they do not account for all environments where multi-tasking may occur. Future research focusing on dual-tasking in additional contexts, such as during dynamic balance or walking tasks, can clarify the generalizability of these findings. Additionally, while outcomes from this study demonstrate the existence of postural control mechanisms (e.g., automatic control) underlying dual-tasking, the outcomes do not fully characterize what automatic postural control is. For example, if automatic control can be conceptualized as a tightly regulated system that permits frequent and random sway adjustments that occur without conscious effort (Cavanaugh et al., 2007; Stergiou & Decker, 2011), it may be understood as a more reactive mode of control (e.g., Habib Perez et al., 2020). Further studying the constructs and analyzing the outcomes can help explain how the postural control system behaves with more automatic control while taking part in various tasks at once.

3.6 Conclusion

Overall task difficulty did not influence the degree of automatic postural control when tasked with remaining stable under various stance conditions. While completing a cognitive task showed evidence for increased automaticity in objective and subjective measurements, the use of automatic control remained despite an increased stance challenge. In general, while dual- or multi-tasking in various environmental contexts that manipulate sensory information available, young healthy adults continue to employ some automatic postural control mechanisms. Further studying and analyzing automaticity in various contexts and with various outcome measurements can refine the characterization of automatic sway adjustments and the use of automatic postural control mechanisms, while multi-tasking, in everyday life.

Chapter 4: General Discussion

This thesis focused on how combined stance and cognitive task manipulations on static postural control influenced postural control strategies in young healthy adults. Specifically, the relative contribution of automatic and conscious postural control mechanisms was considered under various difficult dual-task (DT) conditions. Study 1 (Chapter 2) implemented two stance challenges and six levels of cognitive load to explore how the difficulty of a cognitive task influenced postural control strategies and if a potential influence depended on the stance challenge. While findings suggested a general increase in automatic control mechanisms when engaging in a cognitive task, it was shown that the difficulty of a cognitive task did not influence the degree of automatic postural control. These findings also did not depend on the manipulation of stance challenge through the removal of vision. Study 2 (Chapter 3) consisted of six stance challenges and two levels of cognitive load to increase the relative DT difficulty beyond that of Study 1 and to further explore the use of automatic postural control, elicited from a cognitive task, in various sensory contexts. Findings showed that the overall difficulty of a DT did not entirely influence the degree of automatic postural control. The use of automatic control and a perceived decrease in conscious control tended to remain despite sensory stance challenge manipulations. Together, the findings from both studies provided insight into mechanisms underlying young healthy adult postural control in various contexts while distracted. Young healthy adults tended to employ automatic postural control mechanisms when distracted and continue to use automatic mechanisms when challenged to remain stable.

Previous studies examining posture-cognitive DT conditions in young healthy adults have demonstrated postural sway amplitude to decrease with the addition of a cognitive task (Polskaia & Lajoie, 2016; Potvin-Desrochers et al., 2017; Resch et al., 2011; Ross et al., 2011; St-Amant et

al., 2020). This finding is contrary to predictions of common DT interference models such as the Capacity-Sharing and Bottleneck models, introduced in Chapter 1. Each of these models would predict sway amplitude to increase under DT conditions due to competition for limited shared attentional resources (Capacity-Sharing) or a delay in processing (Bottleneck) (Bayot et al., 2018). The Constrained-Action hypothesis helps explain why sway amplitude decreases when distracted. Externally directing attention away from a stance task is thought to reduce conscious resources regulating one's posture (Roerdink et al., 2011; Wulf et al., 2001). Engaging in a cognitive task can mimic an external focus since attention is thought to be directed away from stance and toward a cognitive task (Donker et al., 2007; Nafati & Vuillerme, 2011). Sway outcome variables, such as sample entropy (SampEn), have reinforced the interpretation of an increase in automatic control while distracted (Roerdink et al., 2006; Roerdink et al., 2011). Given these findings supporting the interpretation of automatic control mechanisms, exploring the use of automatic control in various cognitive and postural contexts allowed for inferences to be made about postural control strategies while completing various tasks at once.

Manipulations of cognitive task difficulty, in Study 1, were intended to thoroughly examine how distractions of various loads influenced postural control strategies and were used to inform the cognitive task for Study 2. Huxhold et al. (2006) described the influence of cognitive task difficulty as a U-shaped relationship with sway amplitude along the y-axis and study conditions along the x-axis. To explain the U-shaped relationship, in the absence of engaging in a cognitive task, such as standing under quiet stance or single-task (ST) conditions, postural sway would be at a baseline level (i.e., the beginning of the U-shape). Relative to this baseline sway level, engaging in a cognitive task that is relatively easier or of a comfortable challenge, can continuously distract an individual and result in postural sway decreases (i.e., the downward

portion of the U-shape). Then, when cognitive tasks become too challenging, postural sway can start to increase, relative to the previously mentioned sway decrease (i.e., the upward portion of the U-shape) (Huxhold et al., 2006). The decreases in sway from ST conditions could be explained by individuals engaging in demanding cognitive tasks (Swan et al., 2007) that continuously direct attention away from stance (Lajoie et al., 2016; Potvin-Desrochers et al., 2017). The increases in sway relative to easier cognitive tasks could be explained by a difficult cognitive task that overloads one's attentional resources (Rizzato et al., 2021). Given that postural sway has shown to behave differently with cognitive tasks of varying difficulty, manipulating cognitive task load was a way to probe the usage of certain postural control strategies. While Study 1 showed the general use of automatic control when distracted, automaticity did not completely vary between cognitive tasks. When completing variations of the same cognitive task, individuals can adjust their engagement with the task. For example, while completing subtraction tasks, individuals can successfully engage in the task but show to adjust their response rate when calculations become more challenging (Masson & Pesenti, 2014). Varying the type of cognitive tasks, which creates cognitive challenges that cannot be compensated for, in future studies, can allow for a refined assessment of how distractions influence postural control strategies.

Common to both Study 1 and Study 2 was the general lack of evidence showing that DT interference depended on the postural task. DT interference that leads to less postural steadiness, which can be interpreted as the use of less automatic mechanisms, has been shown when young healthy adults engage in a cognitive task with inaccurate sensory information from the visual and ankle somatosensory sensory systems (Lanzarin et al., 2015; Morelli et al., 2020). Study 1 showed that SampEn, sway amplitude, and total power outcomes did not depend on a stance

manipulation that included standing with and without vision. Eyes open and eyes closed visual manipulations have not always been shown to perturb stance (Winter et al., 1998). While it was thought that the visual-based stance challenge was not challenging enough to show an interaction in Study 1 and led Study 2 to consider sensory-based stance challenges beyond that of Study 1, Study 2 provided limited evidence for the combined influence of a stance and cognitive task playing a role in postural control strategies elicited. Only standing without vision on a foam surface provided evidence for relatively less a degree of automatic control used, compared to standing with accurate and inaccurate visual inputs on a firm surface. Together, these findings highlight the healthiness of young adult postural control systems. Since this thesis contributes to the literature showing evidence for the continued use of automatic control mechanisms in DT scenarios, future studies specifically characterizing automaticity can provide more insight into the underlying control mechanisms of a healthy postural control system while multi-tasking.

4.1 Revisiting the conceptual model

This thesis was specifically designed to probe postural control strategies and underlying mechanisms in various DT contexts and was constructed from the conceptual model presented in Chapter 1 (Figure 4.1a). This model showed that the stance and cognitive task components of a DT paradigm can be varied by the relative difficulty of each; the combined influence of each task component, considering the relative difficulty, was termed overall task difficulty. Due to general evidence for a shift between automatic and conscious postural control strategies, exploring how DT paradigm components, individually (cognitive only) and together, influence automatic and conscious control contributions provides insight into mechanisms underlying young adult postural control.

Based on the findings from Study 1 and Study 2 as well as future directions of research, a revised conceptual model is presented below (Figure 4.1b). Beginning at the top, the solid black lines represent DT paradigms and how DT paradigms can be composed of various stance and cognitive tasks, which can impose different levels of difficulty. The relative contributions of automatic and conscious control were represented as a gradient to show how the underlying mechanisms of control can shift along a continuum depending on the combined influence of a stance and cognitive task. This relationship was highlighted in Study 2 since relatively less of a degree of automatic control may have been used when standing without vision on a foam surface. The solid blue lines highlight findings from this thesis. Looking to the right of the model, Study 1 findings generally provided evidence for automatic control regardless of the intended difficulty of a cognitive task. In the middle, Study 2 showed that relatively more automatic control remained when the overall difficulty of a DT paradigm increased. Each of these findings demonstrated that young adults use some automatic mechanisms to remain upright and control their posture. Lastly, the dashed blue lines incorporate some of the suggested future research directions. While these concepts are outside of the scope of this thesis (starting on the right) studying cognitive task difficulty, driven by varying cognitive task types rather than cognitive load, can allow for a cognitive challenge to be studied that cannot be compensated for. For example, studying a serial 7s task compared to an n-back recall task allows for two tasks to be studied that offer different baseline levels of challenge. To the left, since the general usage of automatic control in various DT contexts has been identified, further analyzing automaticity and attempting to characterize the nature of automatic sway adjustments (e.g., a reactive mode of control) can help specify the behaviour of underlying mechanisms controlling posture while dual-tasking.

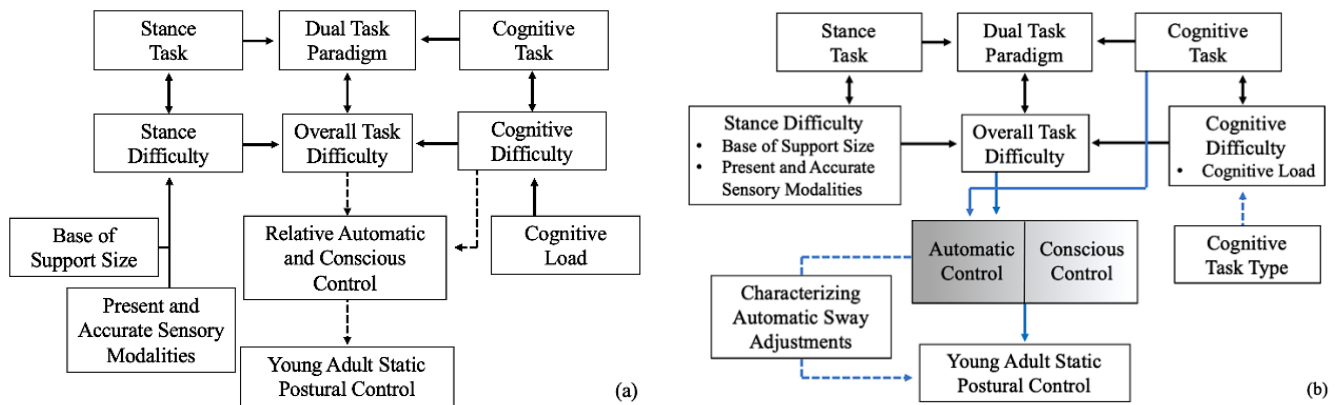


Figure 4.1 (a) The conceptual model used to frame this thesis. Solid lines represent relationships that helped establish the initial framework for the thesis. Dashed lines represent relationships that were probed throughout the thesis. **(b)** A revised conceptual model that incorporated the findings and future research directions identified. Solid black lines represent relationships that were upheld from the original model. Solid blue lines represent the findings identified from this thesis. Dashed blue lines represent suggested future research directions.

4.2 Final conclusion

This thesis primarily aimed to explain how manipulating overall static postural task difficulty, in various stance and cognitive contexts, influenced underlying mechanisms controlling posture. The outcomes from this thesis add to the literature related to postural control mechanisms underlying DT interactions. Specifically, in a young healthy adult population, some use of automatic control mechanisms underlies postural control when one is distracted, regardless of the difficulty imposed by a cognitive and postural task. In everyday life activities that include various task components, young healthy adults may be able to successfully partake in multi-task scenarios due to relying on automatic mechanisms to ensure steadiness and stability. Individuals who are known to be challenged to remain stable may benefit from thinking less internally about movements and directing attention to other task components.

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Appendices

Appendix A: Baseline Trial Outcomes

Table A 1 SampEn, RMS, and CMP summary outcomes for the baseline trial outcomes.

Direction	Measure	DT	ST	DTC (%)
ML	SampEn	0.074 (0.042)	0.051 (0.021)	50.19 (67.79)
	RMS (mm)	4.71 (3.31)	4.55 (2.23)	5.83 (43.86)
AP	SampEn	0.074 (0.055)	0.054 (0.028)	47.25 (78.37)
	RMS (mm)	3.76 (1.65)	4.06 (1.54)	-3.75 (34.67)
n/a	CMP	10.03 (5.90)	12.55 (5.68)	-11.61 (56.00)

Numeric outcomes presented as mean (SD).

Appendix B: Simulator Sickness Questionnaire

B.1 Brief explanation

Cybersickness is motion sickness induced by virtual technology. Sway-referencing vision creates inaccurate visual feedback and a sensory mismatch, which may induce motion sickness (Caserman et al., 2021). Cybersickness has also been shown to correlate with increases in sway (Litleskare, 2021).

Participants completed the simulator sickness questionnaire after each trial; data were presented only for test trials with visual input. Each participant rated the symptoms listed as “none” (i.e., non-existent), “slight”, “moderate”, and “severe.” Each rating was associated with a score of 0, 1, 2, and 3, respectively (Kennedy et al., 1993). These scores were totaled and multiplied by 3.74 to obtain a total score (Kennedy et al., 1993). A greater score provided more evidence of cybersickness.

B.2 Administered Simulator Sickness Questionnaire

Please rate each item on a scale of none (i.e., non-existent), slight, moderate, and severe.

Symptom	Rating			
	None	Slight	Moderate	Severe
General discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eye strain	None	Slight	Moderate	Severe
Difficulty focusing	None	Slight	Moderate	Severe
Increased salivation	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty concentrating	None	Slight	Moderate	Severe
Fullness of head	None	Slight	Moderate	Severe
Blurred vision	None	Slight	Moderate	Severe
Dizzy (eyes open)	None	Slight	Moderate	Severe
Dizzy (eyes closed)	None	Slight	Moderate	Severe
Vertigo	None	Slight	Moderate	Severe
Stomach awareness	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

Condition (circle): single-task dual-task

Trial (circle): Baseline EOF ECF SRF EOS ECS SRS

B.3 Simulator Sickness Questionnaire outcomes

Table B 1 Simulator Sickness Questionnaire outcomes for each test trial with accurate and inaccurate visual sensory input.

		EOF	SRF	EOS	SRS
Total Score	DT	10.83 (13.08)	7.60 (9.44)	11.59 (12.89)	12.38 (11.27)
	ST	6.86 (8.90)	8.73 (10.73)	9.10 (10.79)	11.59 (11.43)

Numeric outcomes presented as mean (SD); DT_EOF and DT_SRF include data from 29 participants and the rest include data from 30 participants.

Appendix C: Adapted Conscious Motor Processing Questionnaire

All these statements are related to the past trial. Please rate each item on a scale of strongly disagree to strongly agree to best reflect how you felt.

Statement	Rating					
I was always trying to think about my movements when I carried them out during this trial	Strongly Disagree	Moderately Disagree	Weakly Disagree	Weakly Agree	Moderately Agree	Strongly Agree
I reflected about my movement a lot during this trial.	Strongly Disagree	Moderately Disagree	Weakly Disagree	Weakly Agree	Moderately Agree	Strongly Agree
I was always trying to figure out why my actions failed during this trial.	Strongly Disagree	Moderately Disagree	Weakly Disagree	Weakly Agree	Moderately Agree	Strongly Agree
I was aware of the way my body worked when I was carrying out a movement during this trial.	Strongly Disagree	Moderately Disagree	Weakly Disagree	Weakly Agree	Moderately Agree	Strongly Agree
I rarely forgot the times when my movements failed me during this trial.	Strongly Disagree	Moderately Disagree	Weakly Disagree	Weakly Agree	Moderately Agree	Strongly Agree

Condition (circle): single-task dual-task

Trial (circle): Baseline EOF ECF SRF EOS ECS SRS