

REAL-TIME FNIRS INVESTIGATION OF DISCRETE AND CONTINUOUS COGNITIVE
DEMANDS DURING DUAL-TASK WALKING

A Thesis

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by

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Abstract

Younger adults who are walking and doing additional tasks at the same time may not realize if their performance suffers, putting some at greater risk for injury and impairment during certain tasks. This thesis has addressed this confound by developing a divided attention paradigm focusing on discrete and continuous demand manipulations. The work assessed in motor-cognitive processing changes with cerebral and behavioral monitoring of over-ground walking with or without cognitive tasks. Participants ($n = 19$, 18-35 years, 13 females) were asked to walk at their usual pace [usual walking condition (SM)], walk at their usual pace while performing a cognitive task [dual-task condition (DT)] as well as conduct a cognitive task while standing [single cognitive condition (SC)]. All participants conducted two discrete [simple response time (SRT) & go-no-go (GNG)] and two continuous cognitive tasks [N-back (NBK) & double number sequence (DNS)] of increasing demand.

The study revealed significant brain and behavior interactions during the most demanding continuous cognitive task, the DNS. The findings demonstrated lower accuracy rates, slower walk speeds as well as greater cerebral oxygenation in DNS DT in comparison to single task conditions. With increasing cognitive demands and tasks, there were longer response times, as well as lower accuracy rates. The behavioral findings were qualified by marginally significant interactions in a 2×4 RM ANOVA between SC-DT task and demand for accuracy rate [$F(3, 54) = 2.66, p = 0.06, \eta^2 = .13$], significant interactions in response time [$F(2, 36) = 4.1, p = 0.026, \eta^2 = .18$] as well as significant SM-DT task and demand findings for walk speed [$F(3, 54) = 5.3, p = 0.003, \eta^2 = .23$]. The $2 \times 2 \times 4$ RM ANOVA revealed significant HbO₂ interactions between walking tasks (single and dual), hemisphere and demand [$F(3, 54) = 5.730, p = 0.002, \eta^2 = .24$] in the DNS only.

The data suggests that greater demand manipulations with continuous cognitive tasks may be sensitive to both prefrontal cortex (PFC) and behavioral assessments in younger adults (YA). Further validation of the discrete-continuous demand paradigm in motor studies may provide a basis for cognitive assessment with applications in motor learning, cognitive training, aging and more.

For Rafi Ansary, my love and partner in all that I do.

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List of Abbreviations

DT	dual task
SM	usual walking
SC	single cognitive
SRT	simple response time
GNG	go-no-go
NBK	n-back
DNS	double number sequence
HbO ₂	cerebral oxygenation
HbR	cerebral deoxygenation
fNIRS	functional near infrared spectroscopy
PFC	prefrontal cortex
DPFC	dorsolateral prefrontal cortex
CNS	central nervous system
YA	younger adults
OA	older adults
ERP	event-related potential
BOLD	blood oxygen level dependent
MR	magnetic resonance

Chapter 1

INTRODUCTION

Walking was often considered a simple, routine, bipedal motor activity. The lack of overt attention dedicated to walking after learning this activity in childhood, led to the notion that walking was largely an automatic task (Schneider & Shiffrin, 1977). As we travel in a largely bipedal manner, we walk at different speeds, patterns or manners depending on the task at hand. While walking, we have a heightened sense of awareness as we look around, survey the environment and take in a large amount of information (Steinicke, Visell, Campos, & Lecuyer, 2013). Studies have demonstrated that walking is in fact susceptible to change with cognitive tasks, revealing an interaction between automatic and executive control processes (Clark, 2015; Dommès, Granié, Cloutier, Coquelet, & Huguenin-Richard, 2015). The involvement of executive control (planning, shifting, updating) during walking suggests that it is not a completely automatic task and several factors might influence the amount of executive control. Shifts between physical and mental demand during walking, make it difficult for us to pinpoint when a task (or tasks) become so laborious that it becomes difficult if not impossible to maintain performance.

Cognitive and motor domains share an interdependent relationship such that compromises in one domain may lead to or be related to decrements in another (Montero-Odasso, Verghese, Beauchet, & Hausdorff, 2012; Woollacott & Shumway-Cook, 2002). Deciphering the task limitations of what is humanely possible can address critical human factors in pedestrian fatalities, fall risk, aviation emergencies, interface

designs, air traffic control and much more (Causse et al., 2017; Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016; Mwakalonge, Siuhi, & White, 2015).

Pedestrians, like drivers, tend to multi-task with their mobile devices, listening to music or reading, distracting their attention while walking. Distracted walking effects are similar to distracted driving (J. Nasar, Hecht, & Wener, 2008; J. L. Nasar & Troyer, 2013; Sarkar, Tay, & Hunt, 2011). Pedestrians are vulnerable road users, along with cyclists and motorcyclists, who are victim to more than half of all traffic deaths (World Health Organization, 2018). Approximately 1.35 million people die annually as a result of traffic crashes that account for nearly 3% of the gross domestic product cost in most countries (World Health Organization, 2018). One of the leading cause of fatalities in children and young adults (YA) is traffic injury (World Health Organization, 2018, *see Figure 1*). Economic losses include treatment cost as well as productivity of those directly and indirectly affected such as family members. Many that suffer non-fatal injuries may suffer from disability. Despite the serious concerns, distracted walking interventions and policies have not been enacted to curb pedestrian safety. Very little research data has been collected for quantification of distracted walking. A Governors Highway and Safety Association report provides subjective evidence that distraction was a factor in pedestrian crashes (Hedlund, 2012).

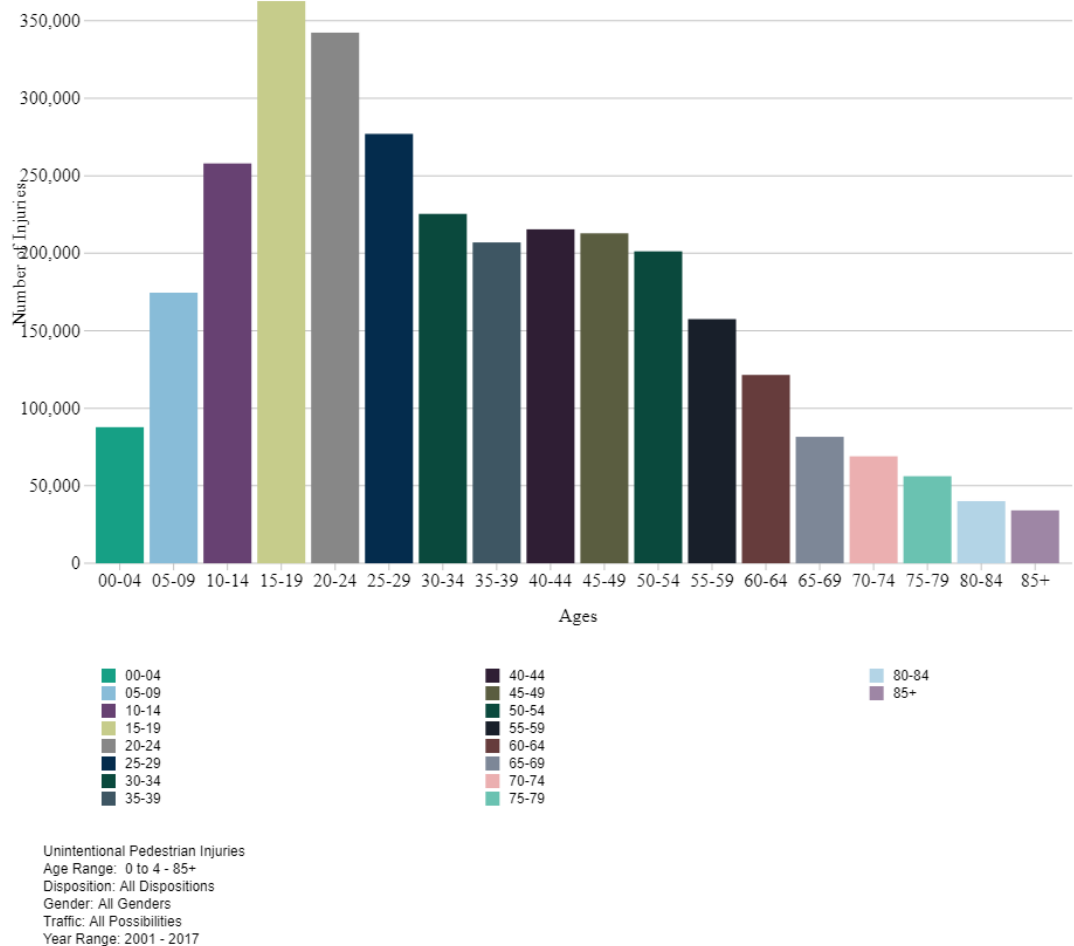


Figure 1: *Pedestrian Injury Distribution by Age (Consumer Product Safety Commission, 2019)*

One way to empirically assess distraction during walking is the dual-task (DT) paradigm. Dual-task (DT) paradigms can demonstrate the association between motor control and cognition while comparing the performance of the two tasks (Woollacott & Shumway-Cook, 2002). However, most DT walk studies report diverse performance findings as a result of variations in experimental design (Beurskens & Bock, 2013; Dommes et al., 2015; Holtzer et al., 2011; Lu, Liu, Yang, Wu, & Wang, 2015; Lu et al.,

2015; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014; Mirelman et al., 2014; Plummer, Apple, Dowd, & Keith, 2015; Schabrun, van den Hoorn, Moorcroft, Greenland, & Hodges, 2014; Srygley, Mirelman, Herman, Giladi, & Hausdorff, 2009; Szturm, Sakhalkar, Kanitkar, & Nankar, 2017, De Sanctis, Butler, Malcolm, & Foxe, 2014; Fraser, Dupuy, Pouliot, Lesage, & Bherer, 2016; Lajoie, Teasdale, Bard, & Fleury, 1993; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014). Studies tend to utilize cognitive tasks that are discrete or continuous with low demand, associated with greater accuracy rates. As a result, researchers have reported DT walk speed measures that were attenuated (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Lu, Liu, Yang, Wu, & Wang, 2015; Lu et al., 2015; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014; Mirelman et al., 2014; Plummer, Apple, Dowd, & Keith, 2015; Schabrun, van den Hoorn, Moorcroft, Greenland, & Hodges, 2014; Srygley, Mirelman, Herman, Giladi, & Hausdorff, 2009; Szturm, Sakhalkar, Kanitkar, & Nankar, 2017) or unaltered (De Sanctis, Butler, Malcolm, & Foxe, 2014; Fraser, Dupuy, Pouliot, Lesage, & Bherer, 2016; Lajoie, Teasdale, Bard, & Fleury, 1993; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014), suggesting that when evaluating performance (i.e., walk speed, cognitive errors), many participants can handle low levels of cognitive load while walking.

Dual-task studies utilize a wide variety of cognitive tasks such as the simple response time, go-no-go, n-back, serial subtracting, just to name a few. Utilizing such varied cognitive tasks, researchers have reported behavioral outcomes (i.e.: walk speed, accuracy) that were improved (S. A. Fraser, Li, DeMont, & Penhune, 2007), attenuated (Lajoie et al., 1993; Srygley et al., 2009; Szturm et al., 2017) or unaltered (De Sanctis et al., 2014; Fraser et al., 2016; Holtzer et al., 2011; Kline, Poggensee, & Ferris, 2014; Lu et

al., 2015; Meester et al., 2014; Mirelman et al., 2014). The cognitive tasks utilized in most YA DT studies had unaltered cognitive outcomes, indicating low levels of cognitive demand that may not have been challenging or a result of participants prioritizing cognitive performance. The complexity of cognitive tasks should be carefully standardized to cater to the target population, in this case, younger adults (Chu, Tang, Peng, & Chen, 2013).

An alternative explanation for such conflicting results may be a result of the components of the cognitive task in relation to the motor task (J. Miller, 1988). Secondary cognitive tasks of lower demand may result in improved motor performance than more demanding cognitive tasks as a result of an external focus of attention, stimulating automatic motor self-organization than would be possible with an explicit focus on the movement itself (Beilock, Bertenthal, Mccoy, & Carr, 2004; S. A. Fraser et al., 2007; Huxhold, Li, Schmiedek, & Lindenberger, 2006; Lövdén, Schaefer, Pohlmeier, & Lindenberger, 2008; Pellecchia, 2003; Rowe, Friston, Frackowiak, & Passingham, 2002; Wulf & Prinz, 2001). Since the usual walking condition in this study entails a self-selected walking pace, an increase in cognitive demand may result in decrements in motor performance as a result of decreasing automaticity and a parallel increase in executive control (Pellecchia, 2003).

Certain motor control studies have addressed the diversity in cognitive tasks by distinguishing them in two categories: discrete and continuous (Lajoie et al., 2017; Lajoie, Richer, Jehu, & Tran, 2016; Polskaia, Richer, Dionne, & Lajoie, 2015; Richer, Polskaia, & Lajoie, 2017). Discrete tasks consist of a probe or stimulus presented at various times during a block followed by a quick response not involving the effector,

legs, from the motor task (Schmidt, Richard A. & Lee, Timothy D., 2011). Furthermore, discrete tasks are situated in a shorter temporal range with a 1-step black box processing mode such as in the simple response time (SRT) or the go-no go (GNG) task (Salthouse, 2000). On the other hand, continuous tasks are performed during the complete duration of the block, situated in a longer temporal range and involve many concurrent overlapping steps such as in the 2-back (NBK)(Fraser et al., 2016) and the double number sequence (DNS)(Polskaia, Richer, Dionne, & Lajoie, 2015) tasks. Although both discrete and continuous properties of a task operate on a gradient, the distinctions between the two not only lay in the temporal range but also in the number of steps associated with the operation when manipulating or updating items in memory(E. K. Miller & Cohen, 2001; J. Miller, 1988).

Depending on the nature of the cognitive task, most studies report an overall high accuracy rate with few studies reporting on response times (De Sanctis et al., 2014; Fraser et al., 2016; Holtzer et al., 2011; Kline, Poggensee, & Ferris, 2014; Lu et al., 2015; Meester et al., 2014; Mirelman et al., 2014). A closer look at the response time facilitates our understanding of whether parallel perceptual processing may be occurring (Klapp, Maslovat, & Jagacinski, 2018). The total time required for a physiological process from the moment stimuli is received to the moment of a reaction, will make up the response time. Response time can also be an index of cerebral cortex activation levels (Li et al., 2009). Further behavioral measures of response time and accuracy can provide evidence for facilitation or slowing or a potential trade-off during the dual task (i.e., walking slower and responding quicker).

The individual demands of executive processes on cognitive control and resources in young adults during over ground walking is little understood. According to a meta-analysis review of cognitive task type complexity in predicting falls in elderly, more research is needed to directly compare the influence of different cognitive tasks (Chu et al., 2013). Few studies have systematically manipulated cognitive demand while gauging cerebral activity during over ground walking. Researchers have reported upregulated PFC measures as a result of dual task or increasing cognitive demand (Ayaz et al., 2013; Coxon et al., 2016; Fraser et al., 2016; Harada, Nashihara, Morozumi, Ota, & Hatakeyama, 2007; Herff et al., 2014; Holtzer et al., 2011; Huppert, Schmidt, Beluk, Furman, & Sparto, 2013; Lu et al., 2015; Meester et al., 2014; Rypma & D'Esposito, 2000), deregulated PFC measures (Izzetoglu, Bunce, Onaral, Pourrezaei, & Chance, 2004; Rypma & D'Esposito, 2000), or unaltered measures (Mirelman et al., 2014).

The combined variation in cerebral findings and cognitive tasks dilute our understanding of whether there may be a turning point of performance from low to greater cognitive demands that is reflected across behavioral and neural capacities. The present thesis will attempt to unravel the diverse range of findings with a graded distinction between discrete and continuous tasks that may be driving the role of attention on executive control. While behavioral performance may not seem altered in some dual-task conditions, the brain may tell us something different: individuals may actually be utilizing executive processes to maintain performance.

1.1 Purpose

This thesis addressed the increasing concern of performance decrements in adults dual tasking as a result of motor and/or cognitive changes. There is some evidence that

fNIRs provide a robust way to study neurological changes in dynamic “real-life” settings (Jahani et al., 2017). It is important to understand how we are able to perform multiple physical and cognitive tasks at the same time and in what conditions we are unable. This activity is integral to our daily functions, and it becomes more difficult as we age without our acute awareness (Woollacott & Shumway-Cook, 2002). Dual-task performance decrements in aging has consequences for the maintenance of social networks, leisure and health (Woollacott & Shumway-Cook, 2002). The main goal was to investigate the automatic or controlled attention mechanisms that guide walking under dual-task conditions in a cognitive demand manipulation with discrete and continuous tasks. We modeled this study after a demand manipulation study with increasing continuous demands utilizing a treadmill (Fraser et al., 2016) and a postural control study with both discrete and continuous demands (Yves Lajoie, Richer, Jehu, & Tran, 2016). This study addressed the following research question: In younger adults, will single-dual over ground walking task performance with continuous tasks be poorer than discrete cognitive task performance?

1.2 Hypotheses

1. Irrespective of the cognitive demand, behavioral performance will be poorer in dual-task conditions than both walking and cognitive single task conditions (i.e.: longer response times, lower accuracy rates and slower walk speed).
2. Irrespective of the cognitive demand, cerebral oxygenation will be greater in dual-task conditions than both walking and cognitive single task conditions (i.e.: greater changes in cerebral oxygenation).

3. Behavioral performance will be poorer in continuous tasks than discrete tasks (i.e.: lower accuracy rates, longer response times and slower walk speed).(Al-Yahya et al., 2011)
4. Neural performance will demonstrate greater change in the continuous tasks when compared to the discrete tasks (i.e.: greater cerebral oxygenation).(Al-Yahya et al., 2011)

Chapter 2

LITERATURE REVIEW

2.1 ATTENTION

Attention is a continuous and graded competing process (Smith & Kosslyn, 2008). When two sensory inputs need to be processed at the same time, the information selected may be imperfect. The integrated competition theory states that when attention is divided as such, the two sources need to compete for limited attentional resources when acting within the same modality (Duncan, Martens, & Ward, 1997). The harder or more tasks there are, the more resources it may require. Failure or performance decrements may occur when the capacity is less than the requirements of the two tasks (Kahneman, 1973). If the demands of the tasks require fewer resources, there is less competition for limited capacity or resources. The input that is analyzed in a simple competition and selection within the brain will go on to take up most of the resources. Since it is not possible for all inputs to be processed at the same time, attention acts as a cognitive bias that resolves the competition involving cerebral regions across the brain (Duncan, 2006; Smith & Kosslyn, 2008).

The earliest study that motivated the integrated competition theory was from monkeys performing visual search tasks as experimenters conducted a single cell recording (Moran & Desimone, 1985). In the study, two targets would compete for the cell's responses when they were in the same receptive field. But when one of the two targets was a distractor, the neuron would block processing of the distractor and just process the target. Since that study, many experiments have gone on to demonstrate that

performance limitations do not just arise from activity between single cells. In addition, when in a dual-task condition, animal research has demonstrated that the stimuli that is selectively less attended to be associated with reduced cerebral activity (Moran & Desimone, 1985). In DT conditions, animals successfully perform simultaneous operations by switching between actions (Moran & Desimone, 1985). Humans plan and control to coordinate the actions, which is a main function of the prefrontal cortex (E. K. Miller & Cohen, 2001). ERP and fMRI studies have demonstrated that increases in PFC activation occur when human participants perform demanding tasks (Ayaz et al., 2013; Coxon et al., 2016; Fraser et al., 2016; Harada et al., 2007; Herff et al., 2014; Holtzer et al., 2011; Huppert et al., 2013; Lu et al., 2015; Meester et al., 2014; Rypma & D'Esposito, 2000).

Competition in attention can be both modality specific (e.g. visual or auditory, vocal or motor) and general. Most of the investigative work in this area was done with auditory and visual domains demonstrating modality specific interference (Duncan, 2006). Greater dual-task costs may result when the information presented in the two tasks is of the same type or modality (i.e., motor-motor) than when they are different or cross modal (i.e., motor-auditory) (Brooks, 1968). Interference may be heavily dependent on the nature of the cross-modal demands. The repercussions of dual-tasking even with cross modal tasks may be incrementally larger when it comes to pedestrian injury, falls or work performance

The byproduct of competition across modalities is not completely understood, especially when it comes to motor and cognitive domains. A combination of top-down and bottom-up interactions between the brain, spinal cord and muscles determine the

strength of the competing stimuli when it comes to dual-task walking (Smith & Kosslyn, 2008). When cognition drives perception from the brain or central nervous system down to the muscles, it is known as top-down processing or goal-driven endogenous attention. At the same time, bottom-up processing or exogenous attention originates from the body and its sensory receptors, taking the information up to the brain which is stimulus driven (Smith & Kosslyn, 2008). Attention, indicated physiologically by cerebral activity, may be directed to whichever stimuli or goal is stronger. A combination of the behavioral measures with cerebral involvement can develop our understanding of how attention alters behavior and brain activity during dual-task walking, if at all. Selection of attention can be driven endogenously by our goals or exogenously by external stimuli. In a divided attention condition, selection is partially controlled endogenously and exogenously when the combined tasks are of equal priority (Smith & Kosslyn, 2008).

Few studies have anchored performance variables with physiological measures of the brain to investigate attention. Functional imaging fMRI studies with mental imagery of locomotion was first compared with real human locomotion in the la Fougère et al. (2010) study. Experimenters qualitatively compare [18F]-FDG PET with the BOLD response during imagined locomotion in a group of sixteen right-handed adults (mean age 61.3 ± 7.8 years). Glucose utilization was determined shortly after walking with FDG-PET, giving us the neural correlates of gait. Subjects walked at self-selected pace over ground 10 minutes before and after FDG injection while PET images were acquired 30 minutes after the administration. The same subjects also underwent an fMRI in which they imagined walking after training over repeated 20s periods over 20 minutes in a visual environment for resting, walking (1 m/s), and running (2 m/s). Seven and fourteen

days later, a baseline resting PET scan was acquired as the subject lay supine with eyes open. Subjects were trained for the resting baseline (lying supine), standing, walking and running conditions. During the MR imaging, subjects were asked to imagine those conditions while supine. Neural activation patterns demonstrated similarities in basic locomotion network activation/deactivation as well as differences. PET imaging findings for real locomotion demonstrate right hemisphere dominance in the primary motor and somatosensory cortex. The primary motor and somatosensory regions were distinctly more active in real locomotion. The differences may be a result of the constant walk speed in the FDG-PET study whereas the fMRI consisted of only 20s periods with gait initiation and speed changes (la Fougère et al., 2010). At the same time, imagined locomotion activated supplementary motor areas and basal ganglia much more than imagined lying or standing (Crémers, Dessoullières, & Garraux, 2012). The findings from this study indicated that imagined locomotion was strongly correlated with real walking. However, this methodology does not completely capture the multifaceted DT gait conditions such as walking while talking or increasing cognitive complexity.

2.2 DIVIDED ATTENTION or DUAL TASK

Processing limitations may be a result of the quantity of information or a by-product of the speed at which information can be processed. The dual-task paradigm has been utilized for a long time in order to elucidate human processing (Kahneman & Daniel, 1973; Pashler, 1994). In one of the earlier divided attention studies, participants indicated whenever they saw a probe letter, while ignoring a stream of letters in white which also contained a target letter (Raymond, 1992). Experimenters recorded the number of correct detections in accordance with how long after target the probe appeared.

In the dual-task condition thereafter, subjects reported the probe and identified the target. Findings indicated that participants were able to identify the probe regardless of how long after the target appeared in the single task condition. However, in the dual-task condition, participants were not able to report the probe when it appeared between 100 and 500 milliseconds after the target. This dual-task effect as a result of temporal constraints is known as attentional blink and aligns with the capacity sharing theory (Kahneman & Daniel, 1973). In this theory, because resources are assumed to be limited, the performance of two or more tasks may cause deterioration in one of the tasks. The processing time for a stimulus may increase if the time between the presentations of stimuli is reduced even if both tasks seem automatic. The capacity sharing theory may also be utilized to investigate the automatic and executive processes during walking.

2.3 AUTOMATIC OR EXECUTIVE CONTROLLED PROCESSES IN DUAL-TASK WALKING

Walking is always on a delicate pendulum, swinging between automatic and executive control processes (Clark, 2015). How the pendulum balances may depend on task demands imposed on the individual (Fraser et al., 2013). The combination of tasks may thereby determine the efficiency or threshold of motor-cognitive performance. Several studies have since demonstrated that both standing and walking utilize spatial attention resources from the fronto-posterior neural networks in the prefrontal cortex (Kerr et al 1985, Malouin et al 2003). Traditionally, automatic processing was conceived as the activation of neural sequences that is automatically instigated in response to a series of inputs (Walter Schneider & Shiffrin, 1977). While under certain conditions motor and cognitive processes may be more automatic, theoretically, it has been argued

that there is a limit to the amount of resources or capacity a person might have and that this may invoke control processes to manage task demands. Controlled processing may also be referred as executive control (Baddeley, Baddeley, Bucks, & Wilcock, 2001). Controlled processes require the active attention of the individual, engaging temporary neural sequence activations (Clark, 2015).

One way to determine the need for executive functioning during walking is to have participants' dual tasking (DT). In a typical DT paradigm, participants are asked to perform each task alone (single task walk, single task cognitive) and then they are asked to perform the two tasks simultaneously (dual task: walk and cognitive task). Dual-task performance is then compared to single-task performance to determine the degree to which participants rely on cognitive processes to control gait. During dual-task, the brain undergoes an internal competition for cortical resources (Fraser, 2015; Fraser et al., 2016; Kahneman & Daniel, 1973; Laguë-Beauvais et al., 2015).

Automaticity is beneficial for the little effort and quick parallel delivery with the spinal reflex processes whereas executive processing may take longer due to its serial processing nature (Clark, 2015). The central nervous system coordinates the neural circuits that make automatic locomotion possible (Nielsen, 2003). The major neural circuits supporting automaticity are in the central pattern generators within the spinal cord, mesencephalic and sub thalamic locomotor regions in the brainstem as well as the cerebellum (Narita et al., 2002). In contrast to automatic processes, executive functioning processes are a key set of cognitive processes vulnerable to decline in the aging (Fraser & Bherer, 2013; Luszcz, 2011). These processes (inhibition, co-ordination, planning) are thought to delegate or control adjacent neurological mechanisms (Wollesen & Voelcker-

Rehage, 2019). Animal and human brain imaging studies demonstrate an association between executive functioning with the PFC (Chudasama, 2011). Executive processing during walking may lead to competition for neural resources during times of increasing demand (Seidler et al 2010). EEG and transcranial magnetic stimulation studies also suggest direct motor cortex involvement in usual walking (Clark, 2015).

Executive processing may be critical in preventing insensitive automatic reflexes from taking over during times of stress. For example, the increased attentional demands of crossing a busy street are associated with younger adults making poorer decisions due to compromised automaticity (Stavrinos, Byington, & Schwebel, 2011). The Dommes et al. (2014) study investigated this phenomenon in three groups of people, young (19-35), younger-old (62-71) and older-old (72-85). Participants walked in a two-way street that was safe and simulated. Visual scenes presented a 5.7 meter wide sidewalk-to-sidewalk consisting of traffic with varied speed (40 or 60km/hr) of motorcycles and cars. The time gaps between the cars were manipulated with 17 different combinations. Participants were tested individually and crossed the street when they decided it was safe. Findings indicated that crossing behavior was slower and less safe in young participants but both older groups made more decisions that resulted in collisions. Younger participants walked faster in the further lane than older adults. Older adults failed to change their gait speed at the same rate as younger adults in challenging traffic conditions, suggesting that OA resources are more limited (Dommes et al., 2015).

The executive control strategies engaged during walking lends insight into the function of the central nervous system (CNS) circuit. The assumption regarding the CNS circuit is that in the absence of automaticity, executive processes hold the primary control

of motor activity(Clark, 2015; Walter Schneider & Shiffrin, 1977) Dual-task experiments are one of the primary methods used to assess changes in automatic and executive control processes. The motor-cognitive performance decrements, or dual-task costs, in a dual-task condition are interpreted as the result of executive control resource competition (Clark, 2015; Ojha, Kern, Lin, & Winstein, 2009). If the dual-task cost is positive, it typically indicates that one of the tasks in the dual task (cognitive or motor) is associated with the need for greater executive control, mediated through serial processing (Clark, 2015; Walter Schneider & Chein, 2003). On the other hand, if the dual-task cost is negative, the single task is attributed to automatic control, a fast and parallel processing mode (Clark, 2015; Walter Schneider & Chein, 2003). The interpretations of dual-task performance are often complex due to many studies targeting an elderly or diseased population (Yogev-Seligmann, Hausdorff, & Giladi, 2008). At the same time, the demands of the motor-cognitive loads are variable in the experiments utilizing dual-task walking making it difficult to compare (Clark, 2015). The differences in task prioritization or cognitive task difficulty all play a part in the shifting demands of the motor-cognitive loads (Clark, 2015). DT experiments in which the experimenter overtly specifies whether one or none of the two tasks need to be prioritized may control for the ‘effort’ component of attention. Despite the complexity in comparing DT findings across studies, the DT paradigm is a unique tool for investigating cognitive-motor domains.

Cognitive and motor domains share an interdependent relationship such that compromises in one domain may lead to or be related to decrements in another (Montero-Odasso et al., 2012; Woollacott & Shumway-Cook, 2002). Scholars unveiled the composite dynamic between motor and executive modalities of attention designating

walking as a complex task (Yogev-Seligmann et al., 2008). Shifts between physical and mental demand during walking, make it difficult for us to pinpoint when a task (or tasks) become so laborious that it becomes difficult if not impossible to maintain performance.

Anxiety is a factor that can shift attention from automaticity to executive control during locomotion. During walking, the form of anxiety that is pertinent to consider is a fear of falling. Poor walk and balance performance have been attributed to this form of anxiety in younger adults (Adkin, Frank, Carpenter, & Peysar, 2002; Brown, Gage, Polych, Sleik, & Winder, 2002; Carpenter, Frank, Adkin, Paton, & Allum, 2004). In the Brown et al. (2002) study, older and younger adults walked at a self-paced speed on a 4 different postural threat conditions altering the width of the walkway as well as the height of the walking surface. Experimenters assessed their gait patterns and joint kinematics with EMG and a camera optoelectronic data collection system. Physiological arousal was assessed with skin conductance measures. Findings indicated that both older and younger adults altered their gait to reflect slower walk speeds and stride lengths, with the slowest walk speed in the condition with the greatest postural threat. This suggests that motor control is strongly influenced by central set mediated by greater anxiety (Brown et al., 2002).

Deciphering the interplay between automaticity and executive control is critical in forming a greater understanding of walking. Most walking studies have investigated this with the use of behavioral performance measures. However, the current state of scientific technology can be utilized to bolster our investigations so that we may also assess the physiological state of the brain, specifically the prefrontal cortex, during walking. The significance of the prefrontal cortex in walking is described in the following section.

2.4 THE PREFRONTAL CORTEX

Beyond performance measures, one way of determining the task limitations of what is humanely possible in a cognitive-motor capacity is to investigate what is occurring in the brain. The human brain is composed of two cerebral hemispheres, consisting of lobes, which support different behavioral functions of an organism (Crémers et al., 2012). The hemispheres control higher cognitive functions such as thought, learning and movement (Herdman & Friedman, 1985). One of the primary roles of the brain is to receive and process sensory information, in return, mediating the response of the organism (Kahneman & Daniel, 1973). While we are aware that there are many areas of the brain involved in dual-task walking (i.e., motor areas, cerebellum, etc.), the current study is targeting executive function processes that have been associated with the prefrontal cortex (PFC).

The prefrontal cortex is actively involved in cognitive-motor situations across various tasks (Basil, 2012; Miller & Cohen, 2001). Humans and other organisms can engage in goal-oriented behavior. Goal directed behavior has been conceptualized by experimental psychologists to primarily involve the working memory system whereas neuropsychologists associate this with executive functioning and the frontal lobe (McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). Studies investigating the cognitive components of the two have demonstrated that the two are very similar but also have some distinct differences (McCabe et al., 2010). Complex cognitive mechanisms have evolved to surpass reflexive behavior by controlling motor and/or lower level sensory memory. The prefrontal cortex has a central role in guiding cognitive control

with neural mechanisms formulated from goal-oriented experiences (E. K. Miller & Cohen, 2001).

The PFC consists of an infrastructure with overlapping sensory and motor systems consisting of various subcortical structures. Ventromedial and dorsolateral regions in the PFC are connected with posterior and subcortical regions (Wood & Grafman, 2003). Emotional processing, memory, higher order temporal visual processing and activity in the dorsolateral prefrontal cortex (DLPFC) are all associated with the ventromedial PFC (VLPFC). Higher order sensory processing, performance monitoring and motor control are all connected with the DLPFC. The DLPFC has a prime role in regulating behavior as well as controlling responses to stimuli (Wood & Grafman, 2003). This wide projection system enables the PFC to enforce a top-down effect with both the VLPFC and the DLPFC executing a role in DT (Laguë-Beauvais et al., 2015). The top down effect is when prior experience drives brain signals instead of sensory stimuli inputs (Narayanan & Laubach, 2006). Anatomical studies of the PFC demonstrate its regional and multimodal convergence from different sensory modalities (Jones & Powell, 1970). PFC neurons can be active over extended time spans and across events as they enable stimulus representation across time while the subject achieves goals (Fuster, Bodner, & Kroger, 2000). Fuster et al. (2000) was one of the first studies to provide evidence that PFC neurons can integrate both visual and auditory stimuli across time. In this study (Fuster et al., 2000), monkeys did a sound-color matching task in which they remembered a beep (240 Hz or 3000Hz) for 10s then chose a color associated with it. During this task, the PFC cells were active when selecting tones and colors. Reaction to the auditory stimuli correlated with the visual stimuli but not for trials that were

inaccurate. This suggests that temporal factors are crucial in the cross-modal PFC network when transferring information. The PFC is also structurally adapted to handle cross-modal sensory inputs. Laboratory studies of the PFC in macaque monkeys reveal that pyramidal cells in the frontal lobe were as much as 16 times more spinous than other lobes such as the occipital parietal and temporal (Elston, 2000). The sheer number of dendritic spine inputs suggest that the PFC can coordinate numerous excitatory inputs.

The prefrontal cortex is one of the prime cerebral regions monitoring executive control (Clark, 2015). Lesion studies have demonstrated changes in executive function associated with lesioned areas of the PFC (Stuss & Alexander, 2000) and the integrity of the PFC is necessary for executive control (Gunning-Dixon & Raz, 2003). The PFC is at the highest level, controlling hierarchy, mediating task planning as well as the physical world with cognitive and motor execution. PFC upregulation, or greater activity, is seen during cognitive task performance, dual tasking, dual-task walking, complex cognitive tasks, complex walking tasks, fine motor task and during gait changes (Ayaz et al., 2013; Coxon et al., 2016; Fraser et al., 2016; Harada et al., 2007; Herff et al., 2014; Holtzer et al., 2011; Huppert et al., 2013; Lu et al., 2015; Meester et al., 2014; Rypma & D'Esposito, 2000). Greater PFC activity may also be a by-product of automaticity processing losses due to neurological or CNS circuit impairment (Seidler et al. 2010, Harada et al. 2009).

Neurons, the individual units of the brain, can have different responses depending on the domain that is dominating attention. The prefrontal cortex may be especially accurate in following task requirements in accordance with attention. Even when other systems mistakenly respond to events, the prefrontal neurons are more accurate and less

likely to respond erroneously (Everling et al. 2005). This functionality lends to the idea that the PFC can maintain cerebral activity in other regions as well as moderating its own (Normal Shallice 1980, Peers). PFC neural cells are flexible to code many different kinds of information or events (E. K. Miller & Cohen, 2001). Attentional competition induced with a broad range of cognitive demands may shed light on the limits of attention (Wollesen & Voelcker-Rehage, 2019).

Dual tasking may activate competition in the multiple demand regions of the PFC (Marois and Ivanoff 2005). Time sharing difficulties are present during concurrent response selection even for tasks that are from different sensory domains (i.e., visual and auditory) as demonstrated in the psychological refractory period (Bourke 1996).

Depending on the task components and their functional associations, in a dual-task condition the tasks may either work together or competitively. Dual-task gait studies that manipulate cognitive load may inform our understanding of whether some tasks have an increasingly differential effect on walking than others (Fraser et al., 2016; Hill, Bohil, Lewis, & Neider, 2013; Mirelman et al., 2014; Van Impe, Coxon, Goble, Wenderoth, & Swinnen, 2011).

Cognitive age-related changes are often subtle and not diagnosable, leading us to question our standards of clinically relevant cognitive impairment. The relationship between attention, executive functioning and motor control may help elucidate changes in cognitive function during everyday tasks such as walking and talking. Gait research demonstrates that executive processes are engaged during walking, designating walking as a complex task (Hausdorff, Yogeve, Springer, Simon, & Giladi, 2005). Deficits in walking and cognition have been independently linked with the compromised capacity

for daily activities and postural instability (Bherer, 2015). Slowed walking has been shown to precede or co-occur cognitive decline in older adults sometimes up to 12 years before diagnosed cognitive change (Montero-Odasso et al., 2012; Wollesen & Voelcker-Rehage, 2019). Physical and cognitive age-related changes augment the challenges of living, even for tasks as simple as walking and talking. The emerging view of cognition appreciates its interrelationship with motor control, so that either changes in cognition and/or motor control can be used to predict pathological cognitive decline (Montero-Odasso et al., 2012). Advances in technology allow us to investigate the physiological changes of the prefrontal cortex in greater detail during gait as described in the following section.

2.5 FUNCTIONAL NEAR INFRARED SPECTROSCOPY

There has been a great interest in the neuromodulation of gait and many imaging studies that had initially tested relationships between imagined gait and over-ground walking parameters (Heuninckx, Wenderoth, & Swinnen, 2008; Holtzer et al., 2015; la Fougère et al., 2010) or supine stepping in a functional magnetic imaging scanner (Burki et al., 2017) in order to better understand the underlying mechanisms. Traditional neuroimaging methods required individuals to be motionless in a supine position while utilizing imagined locomotion with fMRI. Studies found increased PFC activation in imagined walking while talking compared with imagined walking or silent talking tasks consistent with dual-task studies (Blumen, Holtzer, Brown, Gazes, & Verghese, 2014). However, such fMRI studies are limited due to the variance in imagery proficiency. Some studies have utilized radionuclide tracers during motor tasks after which single photon emission computerized tomography (SPECT) or positron-emission-tomography

(PET) was used to examine the radioactive tracers in the brain (la Fougère et al., 2010). However, this method is limited due to its invasive nature permitting only a selective group of subjects for study, deterring real time information about the neural correlates in a dual-task paradigm.

Technological limitations of some of these devices (i.e., must be supine, must minimized movement in a constrained space) have deterred us from investigating the neural basis of over-ground walking in action, in real-time. As such, real-time functional neural correlates of attention demanding walking tasks is limited. In adults, both younger and older, distracted walking effects have been demonstrated to be similar to distracted driving, contributing to pedestrian accidents consisting of more than half of all traffic deaths ((J. Nasar, Hecht, & Wener, 2008; J. L. Nasar & Troyer, 2013; Sarkar, Tay, & Hunt, 2011). World Health Organization, 2018). Investigating the neural biomarkers of gait in naturalistic dual-task settings is crucial to gain a better understanding of cognitive control during walking.

Non-invasive optical imaging methods make it possible for us to study the human brain function in an economic, portable, adaptable and ecological fashion. In order to capture changes in brain activity during task performance, functional near infrared spectroscopy (fNIRS) has become one of the main devices for acquiring ecological neurophysiological evidence in DT gait research issues in ways that other neuroimaging technologies (i.e., fMRI) cannot (Jahani et al., 2017).

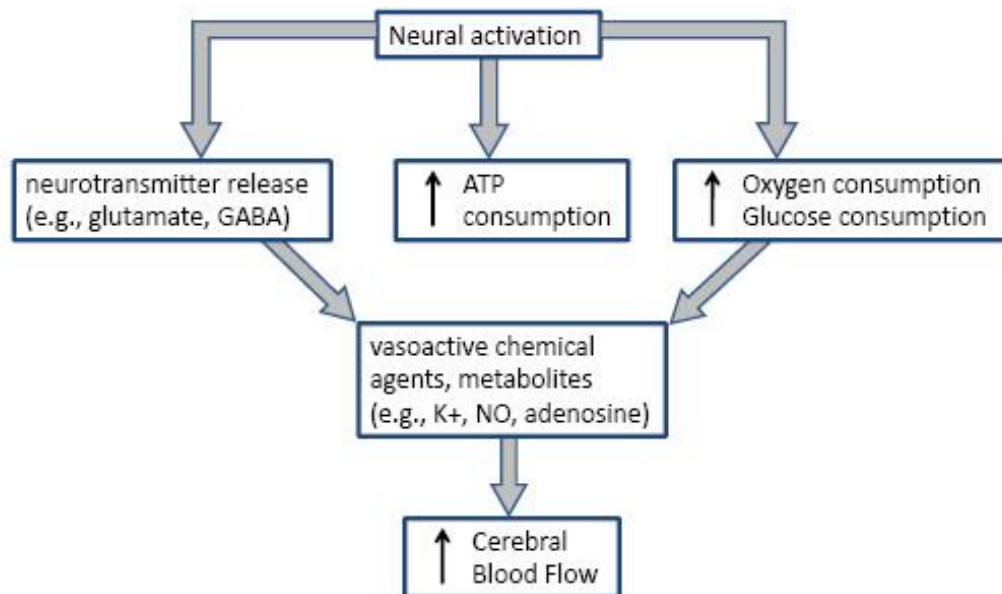
Vascular-based functional brain imaging techniques such as the fNIRS rely on neurovascular coupling to detect neural activity changes (Mackert et al., 2004). Neurovascular coupling is the relationship between cerebral blood flow and neuron

activity. The rise in the level of oxygenated hemoglobin (HbO₂) and a decline in deoxygenation hemoglobin (HbR) in the cerebral cortex is used to infer the active use of neural resources. A series of cellular, metabolic and vascular processes drives this relationship as demonstrated in *Figure 2 (Pasley & Freeman, 2008)*. Cellular processes require energy in the form of adenosine triphosphate (ATP). Approximately 90% of the glucose in the brain is metabolized aerobically, a process requiring oxygen. Both energy substrates, glucose and oxygen, are supplied to the brain through cerebral blood flow. There is a net oversupply of oxygen in the blood since its consumption is much less than cerebral blood flow. Scholars are still unsure about what exactly controls cerebral blood flow. Theories suggest that it may be a result of energy demand (metabolic activity) or neurotransmitters/neural signaling mechanisms (Attwell & Iadecola, 2002; Roy & Sherrington, 1890). Energy demand would dictate increased blood flow to compensate for an absent oxygen reserve in neuronal mitochondria. Regardless of which theory is more viable, the process of neurovascular coupling is indicative of the hemodynamic response such that active brain regions with increased metabolic activity would need an influx of cerebral blood flow containing oxygen (Severinghaus & Astrup, 1986; Villringer & Chance, 1997). Neural activity is mediated by input signals, or synaptic activity in the local electric field potential, as well as output signals, or action potentials branching communication between neurons. Cerebral blood flow positively correlates with synaptic activity and sometimes with action potentials in bottom-up sensory

processes (Hewson-Stoate, Jones, Martindale, Berwick, & Mayhew, 2005; Logothetis & Wandell, 2004).

Figure 2: *Pathway driving cerebral hemodynamics adapted from Pasley & Freeman, 2008.*

fNIRS provides a portable way to record, visualize and infer cortical activity during dynamic movement (Parasuraman & Rizzo, 2008). fNIRS is better than other neuroimaging techniques when it comes to motion artifacts and it has been validated against fMRI blood oxygen level dependent (BOLD) measures (Strangman, Culver, Thompson, & Boas, 2002). The fNIRS neuroimaging technique takes advantage of the distinct spectral absorption properties in the near-infrared region where tissues are more



transparent to assess the changes in light attenuation (Tromberg, Svaasand, Tsay, & Haskell, 1993). Localized points of small sources of laser light are applied on the surface

of the forehead. Light interacts with the brain's deep tissue within a fine wavelength between 680 and 1000 nm, the near-infrared or NIR range (Parasuraman & Rizzo, 2008; Severinghaus & Astrup, 1986). Change in light attenuation is proportional to chromophore concentration changes. The imaging technique was first used by Jöbsis on the human brain approximately 40 years ago (Jöbsis, 1977).

The use of two wavelengths (690 and 830 nm) allows for the inference of the relative hemoglobin component changes (i.e., oxygenated (ΔHbO_2) and deoxygenated (ΔHbR) hemoglobin) with the modified Beer-Lambert law (Delpy et al., 1988). The NIR photons diffuse and scatter in the head as it encounters obstacles like the skull as well as gray and white matter so that light travels in spherical waves, following a semicircular path (Tromberg et al., 1993). Photons will move to penetrate up to 5cm into the tissue capturing changes from the surface of the cortex (Gratton & Corballis, 1995). Intrinsic tissue coloration changes, as a result of oxy or deoxygenation blood content, start within 1 s of cortex stimulation in reflectivity animal studies, reaching a peak 2-3 s later (Grinvald, A., Lieke, E., Frostig, R. D., Gilbert, C. D., & Wiesel, T. N., 1986; Piña-Oviedo, Ortiz-Hidalgo, & Ayala, 2017). The signal consists of a combination of scattering changes due to refractive neuronal tissue properties as well as absorption changes as a result of blood vessel dilation (Frostig, 1994). Measurements of the amount and/or delay of the light that scatters back to the detectors as well as the modified Beer Lambert Law are used to calculate the relative oxygen concentration changes on hemoglobin (Delpy et al., 1988).

The calculation of cerebral oxygenation changes (ΔHbO_2 , ΔHbR , & ΔHbT) holds several assumptions listed in Appendix A

In comparison to other cerebral monitoring modalities (fMRI, EEG, PET, SPECT), fNIRS is the only one that provides oxygenation information on deoxygenated and oxygenated hemoglobin. The advantages of fNIRS deems it especially applicable in the development of brain-computer interfaces (BCI) (Hu, Hong, Ge, & Jeong, 2010; Mihara & Miyai, 2016). fNIRS in comparison with fMRI, provides greater temporal resolution in the order of milliseconds, while in comparison with EEG, greater spatial resolution (Mehta & Parasuraman, 2013). A better temporal resolution facilitates filtering out noisy physiological signals (Gratton & Corballis, 1995). This allows for acquisition of changes in brain activity while an individual performs a naturalistic motor task (such as walking).

Custom filtering techniques are applied to gather the intrinsic neural functional signal with the intricacies of the experimental design in mind (Perrey, 2008). fNIRS signals are not only effected by cerebral activation, but also physiological factors such as head movement, facial movement, ambient light, muscle movement as well as respiration (Laguë-Beauvais et al., 2015). In contrast to HbO₂, HbR reveals information about oxygenation in volumes of venous blood rather than cerebral blood flow. Studies have revealed that there is an inverse relationship between HbR and blood oxygenation level dependent (BOLD) fMRI signals (Ekkekakis, 2009; Strangman et al., 2002).

Walk studies suggest that HbO₂ may be the most robust signal to track since it demonstrates the greatest changes in relation to locomotion (Mihara & Miyai, 2016; Mirelman et al., 2014; Miyai et al., 2001; Perrey, 2008). Miyai et al. (2001) was one of the first studies of real-time brain activity with fNIRS that demonstrated this. In that study, participants took part in the following conditions on a treadmill for 32s: walked at

1 *km/h*, alternated arm swinging, sat while alternating dorsiflexion and plantar flexion at 1 *Hz* and watch motor imagery of walking while standing. Experimenters monitored the fNIRS signal and conducted an fMRI with the same conditions but with the participant imagining the acts. The findings demonstrated that walking activities were bilaterally associated with increased cerebral oxygenation levels. This study was the first to suggest that NIRS and ΔHbO_2 may be a critical tool for evaluation of cerebral activation patterns during real time locomotion. The following section will provide an overview of dual task studies that have investigated gait.

2.6 DUAL-TASK GAIT

The variety of cognitive tasks and cerebral tools used in dual-task walk studies have resulted in a complex research environment deterring simple comparisons between studies. Studies reported behavioral measures (i.e.: response time, walk speed, accuracy) that were mostly unaltered (De Sanctis et al., 2014; Fraser et al., 2016; Holtzer et al., 2011; Kline et al., 2014; Lu et al., 2015; Meester et al., 2014; Mirelman et al., 2014) necessitating a physiological component of investigation. In order to attain a complete picture of how attention is orienting motor-cognitive components, investigations must be informed of how attention is being distributed by providing overt instructional cues designating priority to motor, cognitive or both motor and cognitive tasks and by pairing walking with tasks of different cognitive demand.

In order to understand an individual's general ability to process tasks, it is necessary to understand the conditions for the limits of dual-task performance. Dual-task interference or failure does not only occur when tasks are hard or incompatible, interference may be present even when tasks are not apparently difficult. Interference

between tasks may be a result of competition for a limited processing capacity.

Behavioral decrements as a result of the DT condition can be referred to as a dual-task cost or motor-cognitive interference (Abernethy, 1988; Bardy, 1991).

In the cognitive realm decrements may be in the form of accuracy or response time while in the motor, it may be in terms of walk speed or other gait parameters. At times, performance may not be altered but physiological measures such as cerebral hemodynamics may tell us something different (e.g. individuals using executive processes to maintain their performances).

Although dual-task paradigms are primarily aimed to challenge attention and assess associations between neural and behavioral outcomes, it also provides us with a unique insight into the demands of different tasks. Increasing task demands may be associated with depreciating behavioral performance at which point automaticity fails. In walking, failing automaticity may be associated with slower walk speeds. While various studies have demonstrated changes in gait parameters during dual-task (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Lu et al., 2015, 2015; Meester et al., 2014; Mirelman et al., 2014; Plummer et al., 2015; Schabrun et al., 2014; Srygley et al., 2009; Szturm et al., 2017), less is understood about how it changes neural dynamics, especially as it relates to both motor and cognitive tasks. The bottleneck theory (described below) outlines how neural overlaps in processes may result in interference with a consequential decline in performance due to the underlying neurobehavioral mechanisms (Pashler, 1994).

Just as multiple inputs may result in interference, coordinating multiple outputs also result in a dual-task cost that is known as a response bottleneck (Pashler, 1994). In a

bottleneck, if two tasks are processed in the same neural network, the processing of one of the tasks may be delayed. This results in temporal gaps in the form of delays in response times or slowing gait (Pashler, 1994). The studies supporting this theory demonstrated this delay with cognitive tasks consisting of similar inter-stimulus and inter-response intervals such as discrete cognitive tasks. Few studies have investigated DT walking with continuous cognitive tasks consisting of significant differences between inter-stimulus and inter-response intervals. The following sections will review some DT walking studies that have incorporated discrete and/or continuous cognitive tasks.

2.6.1 WALKING WITH DISCRETE COGNITIVE TASKS

The current DT gait literature utilizing cognitive demand is dominated by one cognitive task type: discrete tasks such as reciting alternate letters of the alphabet (Holtzer et al. 2011). Discrete tasks are situated in a shorter temporal range with a 1-step black box processing mode not requiring manipulation or coordination of items in memory (Salthouse, 2000). Discrete tasks typically consist of a probe or stimulus presented at various times during the block followed by a quick response not involving the effector, legs, from the motor task (Schmidt, Richard A. & Lee, Timothy D., 2011), such as in the simple response time (SRT) or the go-no go (GNG) task (Yves Lajoie et al., 2016; Polskaia et al., 2015; Richer, Saunders, Polskaia, & Lajoie, 2017). This section will review some of the cognitive findings from DT walk studies utilizing discrete cognitive tasks.

DT gait studies with discrete cognitive tasks incorporate low demand and/or inadequate control of instructional cues for prioritization (Yogev-Seligmann, Hausdorff, & Giladi, 2008). Inadequate control of effort in attention may have contributed to

contradictory findings with both dual-task facilitation and interference. In a treadmill walking dual-task study, using a discrete semantic judgement task, Fraser et al. (2007) found that younger adults demonstrated better cognitive performance (facilitation) during DT than single task with shorter response times while accuracy was high overall. Dual-task facilitation is described as the condition in which dual-task performance is better than single task performance, indicating that the two tasks may have processing mechanisms that are non-interfering and/or that at low levels of cognitive demand concurrently walking might induce better cognitive responding. In this study, behavioral measures of response time and accuracy provided evidence for improved cognitive performance during dual task (DT: cognitive task and walking) in comparison to single task (cognitive task alone).

Many studies have demonstrated dual-task interference in terms of declining gait speed (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Lu et al., 2015, 2015; Meester et al., 2014; Mirelman et al., 2014; Plummer et al., 2015; Schabrun et al., 2014; Srygley et al., 2009; Szturm et al., 2017). Early DT studies aimed to assess attentional requirements comparing standing with walking. Lajoie et al. (1993), utilized an auditory SRT in which participants had to respond “top” when they heard high pitched beeps that were presented randomly. The SRT is a highly sensitive attention task in which performance is only mediated by top-down processes without any stimulus associated attention increases due to its constant stimulus saliency. In this study, younger participants performed the SRT task in three states: while sitting, broad-support or narrow –support standing and walking. During the walking task, participants were asked to prioritize walking at a constant speed. Findings demonstrate that the DT walking tasks

were associated with slower cognitive response times while successfully maintaining constant walk speed. This suggests that younger adults compensate for the dual-task demand of maintaining walk speed by reducing response time in a discrete cognitive task (Lajoie et al., 1993). Although the findings do not suggest parallel processing, this does provide evidence that having speed (RT) measures for both cognitive and motor tasks (in this case fixed) can provide us some insights on trade-offs to maintain performance. The behavioral findings further demonstrated that walking is more demanding than standing upright and sitting in a chair, respectively. Since there were only DT trade-offs in walking and during standing or sitting, the findings support the notion that altering the motor requirements of the task can also increase the attentional demands.

The go-no-go task is a unique discrete cognitive task consisting of both information processing and decision making processes with inhibition, designating it more demanding than the SRT (Yves Lajoie, Jehu, Richer, & Chan, 2017). Studies have demonstrated that the GNG task strongly involves the medial frontal cortex (Simmonds, Pekar, & Mostofsky, 2008). The Humberstone et al. (1997) study discriminates the cortical responses to the go and no-go stimuli by comparing fMRI activity in the medial frontal cortex. The findings reveal a hierarchical subdivision of the medial premotor cortex in an anterior pre-supplementary motor area, involved in decision making, and the posterior region, involved in motor execution (Humberstone et al., 1997). This indicates that discrete inhibitory tasks like the GNG differentially activates the prefrontal cortex areas involved in both decision making and motor execution.

The GNG task is an executive functioning task that has typical cerebral activation patterns and hemodynamic activation within neural circuit areas associated with

inhibition (Bell et al. 2013). Different versions of this task have been widely used in studies for its dual nature, requiring both response and inhibition (Garavan et al. 2002, Lajoie et al. 2017). In the De Sanctis et al. (2014) study, young adult subjects participated in 3 task conditions: sitting, walking deliberately (1.4 *km/hr*) and walking briskly (5 *km/hr*) on a treadmill while conducting a cognitive inhibition task, go-no-go. When conducting the GNG task, subjects clicked on a computer mouse when they saw a neutral image but had to withhold clicking if the same image was presented twice in a row. Experimenters collected data with the MOBI and found no response time differences between sitting and walking. Although no dual-task performance costs exhibited, the neural findings were consistent with previous inhibition studies demonstrating differences in amplitude, latency and topography of ERP components. This clearly indicates that sitting and walking during GNG execution have different neural processes despite a lack of behavioral differences.

This kind of neural upregulation in GNG tasks is more pronounced in younger adults than older adults. In an fMRI study comparing younger and older adults, an event-related experiment was designed to assess activation differences during the GNG task. Participants manually responded with one hand or both hands as a cue to stop. The stop-task difficulty was then matched across the groups. Other than a significant group by condition interaction in preSMA/supramarginal gyrus/anterior insula and the right inferior frontal cortex, the findings demonstrated neural upregulation in successful Stop versus Go trials only in the younger adults (Coxon et al., 2016). This supports previous studies that also found neural upregulation in the prefrontal cortex regions during the GNG inhibition task associated with improved cognitive performance in younger adults.

2.6.2 WALKING WITH CONTINUOUS TASKS

As reviewed above, executive functioning has demonstrated strong associations with gait performance in dual-task conditions (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014; Plummer, Apple, Dowd, & Keith, 2015; Szturm, Sakhalkar, Kanitkar, & Nankar, 2017). Executive functioning tasks may consist of continuous tasks that are performed during the complete duration of an experimental block, requiring constant monitoring and updating. They are typically situated in a longer temporal range and involve many concurrent overlapping steps such as in the 2-back (NBK) (Fraser et al., 2016) and the double number sequence (DNS) (Polskaia et al., 2015) tasks. Cognitive tasks with working memory or arithmetic components like the NBK and DNS may require executive functions (McCabe et al., 2010). Cognitive tasks with internal interfering factors like arithmetic tasks are prone to disturbing walk performance more than discrete response time tasks that involve external interfering factors (Al-Yahya et al., 2011). Continuous tasks with mental tracking like the DNS are significantly related to predicting falls in elderly as opposed to dual tasks or discrete tasks such as response time, discrimination and verbal fluency (Chu et al., 2013).

DT gait studies have used a variety of continuous cognitive tasks, even tasks that require additional motor regulation such as in the Schabrun et al. (2014) study where participants were walking and typing phrases as they appeared on a smartphone screen, walking while reading text or walking at a self-selected pace over 8.5 meters. The investigation parsed out the behavioral differences between reading and texting while walking in the three conditions. The findings demonstrate slowed gait performance when

texting demonstrating that texting (which involves motor control) imposes greater behavioral costs than reading (Schabrun et al. 2014). However, although representative of real-life situations, the cognitive tasks utilized in the Schabrun et al. (2014) study may have disrupted online-visual feedback mechanisms integral to adaptive human locomotion (Patla & Greig, 2006).

Dual-task walk studies utilizing cognitive tasks with visual components, such as texting, may be differentially affected by instructional cues for prioritization. In the Plummer et al. (2015) counterbalanced block study, the behavior of subjects was assessed as they were texting while standing, walking at their usual pace, walking while texting (no prioritization), walking while texting (gait priority) and walking while texting (texting priority) on a walkway as well as a real-world setting. The study found significant dual-task effects (slower) in gait and texting speed as well as accuracy that were not affected by environmental settings. Interestingly, subjects prioritized the cognitive task (texting) in the no prioritization lab condition but in the real-world condition they were able to equally perform on both tasks. The findings suggest that although DT cost is equally high in both settings, prioritization may be differentially more pronounced in a lab setting than in the real-world setting.

Demanding continuous tasks with arithmetic may be more susceptible to change with gait as opposed to complex cognitive tasks with a verbal component (Srygley et al., 2009). In the Lu et al. (2015) blocked-design fNIRS study, hemodynamic and gait performance was compared as younger adults walked normally, walked with a low-continuous cognitive task (serial subtraction) and walked while carrying a bottle on a walkway. The findings provide evidence for both neural upregulation and slower walk

speeds during the dual-task conditions. Additional motor cortex activation suggests an activated regulatory control mechanism for motor performance during DT. Although the basic activation patterns of walking can be associated with imagined walking in the indirect supplementary pathway, distinct locomotion patterns emerge in real walking that may be a result of gait speed variability in the primary motor cortex's direct pathway.

Although executive function is strongly associated with gait, it is not clear which components of executive function are more strongly affected in both young and elderly healthy adults. The Srygley et al. (2009) study examined motor performance as elderly and young participants did single-and dual tasks consisting of phoneme monitoring, serial 3 subtractions and serial 7 subtractions while walking and sitting. These three tasks can be considered continuous cognitive tasks of low to high demand engaging working memory and arithmetic. Unlike the serial 3 and phoneme tasks, younger adults made significantly more errors during the serial 7 subtractions across walk and sitting conditions. At the same time, both groups had significantly slower gait speed during dual-task conditions than when usual walking. This was one of the first studies utilizing continuous tasks that demonstrated walk performance decrements in young adults. This suggests that continuous tasks with arithmetic may have graded demand effects in YA to alter gait as opposed to less demanding arithmetic tasks like serial 3 subtractions and complex working memory tasks with a verbal component such as the phoneme task (Srygley et al., 2009).

Many studies have been conducted with fMRI and delayed response, or continuous, tasks investigating both physiological and behavioral measures during dual-task conditions. In the Rypma et al. (2000) study investigated working memory changes

in the cortex with continuous cognitive tasks of increasing difficulty in three conditions. Younger and older adults underwent an fMRI in an event-related verbal delayed response task with 2 letters, 6 letters as well as an event related object and spatial match to sample task. The experimenters contrasted the encoding, maintenance and retrieval working memory components with the baseline. Findings demonstrated a positive correlation of reaction time and dorsolateral prefrontal cortex activation during the high load conditions in younger adults (Rypma & D'Esposito, 2000). At the same time, older adults had a negative correlation. The faster YA subjects demonstrated less dorsolateral PFC activation than the slower YA, while the OA demonstrated the opposite. This suggests that continuous tasks may activate the dorsolateral prefrontal cortex differently in YA than OA. Additionally, with YA, expertise differences may also go hand in hand with activation differences.

One of the most frequently used demanding continuous tasks utilized in various clinical and healthy populations has been the NBK task (Fraser et al., 2016; Forn et al., 2007; Jaeggi et al...E. K. Miller & Cohen, 2001; Scheibel et al., 2003). In an auditory version of the NBK developed by Fraser et al. (2014; 2015; 2016) participants hear a series of numbers and say out loud the number they heard 2 numbers back (always keeping two numbers in mind and updating as each new number is presented). Neuroimaging studies with a visual NBK have demonstrated large scale activations in a network including the prefrontal cortex (Cabeza et al., 1997; Jaeggi, Buschkuhl, Perrig, & Meier, 2010; Jaeggi, Schmid, Buschkuhl, & Perrig, 2009; Jaeggi et al., 2003; Rypma & D'Esposito, 2000). The visual NBK is slightly different such that participants are monitoring visually to determine whether the number or picture they saw reappears

(Jaeggi et al., 2003). Since this task has been used in many contexts, implementing this in a manipulation of cognitive demand context would provide a useful comparison to less demanding discrete tasks that do not require monitoring or manipulating of items in memory. The NBK would also be a suitable comparison to a more demanding continuous tasks with greater inter-response intervals (Adrian M. Owen, McMillan, Laird, & Bullmore, 2005).

The NBK task is the one of the few demanding continuous tasks that have been able to cerebrally distinguish cognitive demand differences with functional near infrared spectroscopy (fNIRS) (Herff et al. 2014). In dual-task walking, Fraser et al. (2016) explored DT gait performance differences with continuous cognitive tasks of increasing demand overtly prioritizing motor/cognitive tasks equally. In this study, younger (YA) and older adults (OA) performed an auditory 1-back (low demand) and 2-back (high demand) while walking on the treadmill. Both groups produced more errors in the more difficult 2-back compared to 1-back during DT treadmill walking at a self-selected pace. Overall, YA were more accurate than OA and both groups demonstrated higher PFC HbO2 in DT than usual walking.

The brain plays a critical role in unravelling both motor and cognitive performance measures during dual-task walking. But due to technological limitations, few studies have been able to support their findings with a neural component that has been collected during walking. Holtzer et al. (2011) is an exception, as their study evaluated PFC activity patterns with fNIRS during dual-task walking in younger and older adults. Participants were compared as they walked at their usual pace for 15m and as they were walking while reciting alternate letters of the alphabet, a discrete cognitive

task. Subjects were instructed to give equal importance to both tasks. This was one of the first studies to find PFC neural upregulation and slower walk speed in DT walk conditions for both young and older subjects in a walk condition not utilizing a treadmill. The literature reviewed above indicates that continuous cognitive tasks may be demanding but have differential effects on gait and cognition and are sensitive to prioritization as well as visual and additional motor components.

2.6.3 INCREASING TASK DEMANDS

Manipulation of demand in dual-task walking studies provides a unique gateway into informing our understanding of the executive and automatic components of walking and how that may change with different cognitive demands. But how does the brain respond to increasing cognitive demands independent of motor components? Contrary to expectations, in some cases, higher levels of task demand may not demonstrate increased cerebral oxygenation, but rather a decrease (Izzetoglu et al., 2004). One of the first experiments to demonstrate this was Izzetoglu et al. (2004) in which subjects performed a complex task while a cognitive processing was inferred with fNIRS measurements of the prefrontal cortex. The task was a naval air warfare video game, warship commander task in which difficulty was manipulated with the number of airplanes, as well as an auditory memory task (secondary task). Findings demonstrate a positive correlation with reaction time (incorporated in the game score) and cerebral oxygenation until the highest level of difficulty with 24 airplanes, such that longer reaction times were associated with greater HbO₂. The combination of sustained attention and task engagement resulted in an increase in performance as well as cerebral oxygenation but when it becomes too difficult

(at 24 airplanes), subjects may experience a mental or concentration shift, resulting in a decrease in cerebral oxygenation (Izzetoglu et al., 2004).

Functional task performance differences in motor learning can be effectively captured with the fNIRS in novel tasks to demonstrate increasing automaticity. In the Ayaz et al. (2012) study, subjects transitioned from executive to automatic control with practice. Subjects were tasked with performing a visual identity n-back (from 0 to 3-back) and two types of air traffic control task, (voice or data communication simulations). Task difficulty was varied with 6, 12 or 18 aircraft. As behavioral performance improved, PFC activity also increased indicating both increased effort and executive demand. During the intermediate phase, better behavioral performance could be maintained with less PFC activation. Whereas in the advanced phase, even higher levels of behavior performance were associated with reduced PFC activity. This kind of PFC activation and behavioral pattern coincides with the capacity theory; the decrease in activation at higher loads may indicate capacity is exceeded. Ayaz et al. (2012) findings indicate that large task difficulty measurements are sensitive to PFC activity differences, but finer task difficulty differences would have to be explored further.

Motor demand manipulation may pose a differential effect of on cognitive outcomes. The Beurskens et al. (2013) investigated whether the influence of the difficulty of the walking task in a dual-task study utilizing visual processing or fine motor cognitive tasks. Participants, elderly and young, walked 20m in four conditions: wide (1.8m), narrow (0.3m), obstacle (1.8m) and fast (1.8m) pathway. The following cognitive tasks were performed individually and with the walk task for the dual-task condition: participants held a sheet of paper and drew 65 squares (check task); participants wore a

jacket with five buttons down the front (button task). Participants received no prioritization cues as they did the 14 different task combinations. The experimenter collected gait data with an online tracking system that provided details regarding the steps, walk speed and checking/buttoning speed. Findings demonstrate visually demanding conditions held more dual-task cost than fine motor control tasks. Young participants also reduce their walk speed and increase cognitive variability, but the changes are stronger in the elderly. This study demonstrates the increased dual-task costs associated with greater overlap between visual-motor than motor-motor domains. Although motor demand manipulation studies lend insight into the executive-automatic controls of walking, it is not representative of daily living in which humans generally walk at self-selected pace.

Dual-task experimental designs may also be considered a form of demand manipulation. Many divided attention studies examine brain and behavior associations with the dual-task paradigm in which participants execute two tasks simultaneously and individually (Fraser, 2015; Fraser et al., 2016; Holtzer et al., 2011). Of the few DT walk studies in healthy adults, some do not demonstrate any cognitive decrements (De Sanctis et al., 2014; Fraser et al., 2016; Holtzer et al., 2011; Kline et al., 2014; Lu et al., 2015; Meester et al., 2014; Mirelman et al., 2014) but do demonstrate motor decrements (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Lu et al., 2015, 2015; Meester et al., 2014; Mirelman et al., 2014; Plummer et al., 2015; Schabrun et al., 2014; Srygley et al., 2009; Szturm et al., 2017), but others like the Szturm et al (2013) treadmill study do demonstrate cognitive decrements, as well as, increased variability in gait. However, in line with crosstalk findings, this may be a result

of including a visual-spatial cognitive task in combination with walking. This type of task would likely cause more interference during walking because of its visual-spatial demands. Walking is highly reliant on visual information (Logan et al., 2010) and manipulations involving this type of task may lead to greater decrements in performance.

The variation in DT findings may have resulted from the nature of the cognitive task or the walking protocol. Studies that have manipulated walk speed during dual-task performances have found that manipulations of walk speed in younger adults do not seem to affect certain working memory tasks in younger adults (Meester et al., 2014; Kline et al., 2014). The Kline et al. (2014) EEG study addresses the variation in walk speed while young adults perform spatial working memory tasks. Findings indicated that walk speed did not affect performance in the spatial working memory task. There is no change in reaction time, accuracy or cerebral activity. This study and others suggest that activity in the executive center of the brain, PFC, isn't significantly affected by walking on a treadmill at different speeds in YA (Kline et al., 2014; Meester et al. 2014). In the Meester et al. (2014) study, YA subjects walked on a treadmill while performing cognitive tasks at a self-selected pace and at a 20% faster pace on the treadmill. Cerebral activation of the PFC, spinal cord reflex activity as well as gait changes measured with an inertial measuring unit were collected. Subjects completed familiarization trials before engaging in the walking and DT walk tasks. The cognitive task consisted of backward counting in serial sevens. Findings indicated that PFC was not affected by walk speed, but it was affected by dual-task condition. At the same time, H-reflex amplitude and gait variables did not change with walk speed or dual-task condition. This suggests that the PFC activation mechanisms in young adults are sensitive to dual-task cognitive load

while motor aspects are maintained/unchanged. Minimal PFC engagement may be due to automaticity processes taking over with brainstem and spinal circuit activation. Increased automaticity processes reduce the need for executive control resources like that of the PFC (Clark, 2015).

Neural upregulation, increased cerebral oxygenation, were observed in DT gait fNIRS studies with little discrimination between whether the upregulation was associated with verbalization, gait or standing. When examining PFC contributions in younger adults during dual-task gait, Mirelman et al. (2014) contrasted the single cognitive task (standing), usual walking and dual task (DT) in a study manipulating cognitive demand with discrete and low continuous cognitive tasks. Participants conducted two auditory cognitive task demands: serial subtractions (Walk+S7) and counting forwards, paired with over-ground self-paced walking/standing. Participants walked on an electronic walkway while their brain activity was monitored with a 2-probe fNIRS. The graded HbO2 findings increase with respect to task: DT (Walk+S7) > walking + counting > SM while no differences were found between SM and standing as well as standing with or without subtraction. This suggests that PFC neural upregulation during walking while talking (DT) were specific to dual-task cognitive demand as opposed to verbalization or motor task demands. Results demonstrated that in comparison to SM: there was a reduction in gait speed, increase in gait variability and HbO2 changes in the DT condition across cognitive tasks. Furthermore, accuracy was high in both single and dual tasks for all conditions, demonstrating that the cognitive tasks were of low difficulty and cognitive demand.

2.7 SUMMARY

Both the Mirelman et al. (2014) and the Fraser et al. (2016) study utilized continuous tasks and found greater PFC HbO₂ during DT, despite discrepancies in cognitive outcome findings with the former study reporting no single-dual accuracy differences while the latter reported marginally significant differences ($p = .06$). At the same time the Fraser et al. (2007) study utilized discrete tasks to report improved cognitive performance (facilitation) in DT than single. The differences between the functional elements of discrete and continuous cognitive tasks may be contributing to the mixed results during cognitive-motor walk situations. Cognitive tasks with internal interfering factors like arithmetic task are prone to disturbing walk performance more than discrete response time tasks that involve external interfering factors (Al-Yahya et al., 2011).

It is unclear from these works whether the differences between continuous and discrete tasks might have a greater or lesser effect on the PFC involvement during DT walking in YA. Overground natural walking is yet to be investigated in younger adults with a cognitive approach utilizing tasks of increasing difficulty across discrete and continuous cognitive tasks and real-time cerebral oxygenation measures during dual-task walking. Although many research studies have investigated cognitive demand and dual-task gait, this is the first study to evaluate over ground walking with discrete and continuous tasks of increasing demand.

Our study aims to add to the current literature on DT PFC involvement by investigating over-ground walking with four cognitive tasks of increasing demand that include discrete and continuous tasks. Given the behavioral findings from Fraser et al.

(2007) and the neural findings from Fraser et al. (2016) and Mirelman et al. (2014), we hypothesized that greater cerebral activation changes and poor performance would be associated with DT (slower walk speed, longer response times and lower accuracy) and no single task conditions (SM and SC). Similarly, we expected continuous task performance to be poorer than discrete task performance to due to the additional cognitive demand of working memory tasks (maintaining/monitoring and updating). We also expected that neural changes in HbO₂ would increase with cognitive demand in both: (1) DT as opposed to usual walking (SM)/single cognitive (SC) conditions and (2) with respects to increasing demand on the cognitive tasks SRT < < GNG, < NBK, < DNS, respectively.

Chapter 3

A REAL-TIME FNIRS INVESTIGATION OF DISCRETE AND CONTINUOUS COGNITIVE DEMANDS DURING DUAL-TASK WALKING

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**A REAL-TIME FNIRS INVESTIGATION OF DISCRETE AND CONTINUOUS
COGNITIVE DEMANDS DURING DUAL-TASK WALKING**

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ABSTRACT

Distracted walking is one of the contributors to increased injury rates in younger adults. The present study used a portable functional near infra-red spectroscopy (fNIRS) device to investigate motor-cognitive processing changes with cerebral and behavioral monitoring of over-ground walking. DT walking in YA with increasing discrete and continuous cognitive task demands has not yet been explored. We hypothesized, that continuous tasks would be associated with greater ΔHbO_2 and performance decrements during DT walking in comparison to discrete tasks. Nineteen younger adults aged 18-35 years were asked to execute a cognitive task while standing [single cognitive condition (SC)], walk at their usual pace [usual walking condition (SM)], and walk while performing a cognitive task [dual-task condition (DT)]. All participants completed two discrete [simple reaction time (SRT) & go-no-go (GNG)] and two continuous cognitive tasks [N-back (NBK) & double number sequence (DNS)], with respectively increasing demand.

Behaviorally repeated measures (RM) ANOVAs between SC-DT tasks and cognitive demand revealed marginally significant interactions for accuracy rate [$F(3, 54) = 2.66, p = 0.06, \eta_p^2 = .13$], such that SC was more accurate than DT only for the continuous tasks: NBK ($p = 0.01$) and the DNS ($p = 0.03$). There was also a significant interaction for response time [$F(2, 36) = 4.1, p = 0.026, \eta_p^2 = .18$], in which response times for SRT ($p = .005$) and NBK ($p = .004$) were significantly slower in DT compared to SC. There was also an interaction for walk speed [$F(3, 54) = 5.3, p = 0.003, \eta_p^2 = .227$], in which only the DNS demonstrated significant slowing from SM to DT ($p = .02$). The $2 \times 2 \times 4$ RM ANOVA revealed significant HbO₂ interactions between walking tasks

(single and dual), hemisphere and demand [$F(3, 54) = 5.730, p = 0.002, \eta_p^2 = .241$] in the DNS only, where the DT ΔHbO_2 was higher than SM ΔHbO_2 with marginal significance in the right hemisphere ($p = .056$).

The data suggests that continuous cognitive tasks may be sensitive to both prefrontal cortex (PFC) and behavioral assessments in younger adults (YA). Further investigation may provide a basis for cognitive assessment with applications in motor learning, cognitive training, aging and more.

Highlights

- Continuous and discrete task demands have differential cerebral and behavioral outcomes
- fNIRS was used to determine real-time cerebral activity during walking in young adults
- DNS, a demanding continuous task, was associated with increased HbO₂ levels

Keywords cognitive demand, continuous cognitive task, discrete cognitive task, dual-task, fNIRS, over-ground, walking, younger adults

1. INTRODUCTION

Initially it was believed that walking is a simple, routine, automatic bipedal motor activity (Schneider & Shiffrin, 1977). Extensive dual-task (DT) research has identified the importance of attentional demand during walking and the dynamic between motor and executive modalities (Wollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). Theoretical and experimental work has demonstrated that cognitive and motor domains share attentional resources and when performing cognitive and motor tasks

simultaneously (dual task), if the resource capacity is exceeded, performance on one or both tasks diminish (Kahneman & Daniel, 1973; Montero-Odasso et al., 2012; Woollacott & Shumway-Cook, 2002). The prefrontal cortex is actively involved in dual task conditions across various tasks (Basil, 2012; Miller & Cohen, 2001). Shifts between physical and mental demand during walking, make it difficult to pinpoint when a task (or tasks) becomes so laborious that it becomes difficult if not impossible to maintain performance.

Many divided attention studies examine cognitive and motor associations with the dual-task paradigm in which participants execute two tasks simultaneously and individually (Fraser et al., 2015; Fraser et al., 2016; Holtzer et al., 2011). Studies that have manipulated cognitive load have revealed differential effects on walking (Fraser et al., 2016; Hill et al., 2013; Mirelman et al., 2014; Van Impe et al., 2011). Some dual task studies report declines in walk performance (Holtzer et al., 2011), or cognitive performance (Fraser et al., 2016; Malcolm et al., 2015), while others report slowed walk speeds with no difference in cognitive performance despite difficulty manipulations (Mirelman et al., 2014). One of the reasons behind such mixed results from the literature may be due to the type of cognitive task and how attention is used to execute them while walking (Fraser & Bherer, 2013; Miller, 1988). Several studies have attempted to address the inconsistency in the literature by separating cognitive tasks into discrete and continuous (Lajoie et al., 2017; Lajoie et al., 2016; Polskaia, et al., 2015; Richer, et al., 2017).

Discrete cognitive tasks consist of a probe or stimulus presented at various times during the block followed by a quick response (Schmidt et al., 2011). Furthermore,

discrete tasks are situated in a shorter temporal range such as in the simple reaction time (SRT) or the go-no go (GNG) task (Salthouse, 2000). During discrete tasks, participants respond instantaneously to each stimuli without the need for them to hold onto the memory of stimuli presented previously. In contrast, continuous tasks are associated with longer inter-response intervals. Continuous tasks have longer temporal ranges involving working memory which requires the maintenance of items (stimuli) in memory and can involve many concurrent overlapping steps such as in the 2-back (NBK) (Fraser et al., 2016) and the double number sequence (DNS) (Polskaia et al., 2015) tasks. Both of these tasks involve continuous updating of auditory stimuli being presented and maintenance of items in memory (i.e., keeping in mind the number heard two numbers before (NBK) or mental tracking of the total number of matching stimuli (DNS)). Although both discrete and continuous properties of a task operate on a gradient, the distinctions between the two not only lay in the temporal range but also in the number of steps associated with the operation when manipulating or updating items in memory (Miller & Cohen, 2001; Miller, 1988). Since continuous tasks tend to have these additional steps, they become more cognitively demanding than discrete tasks which require a quick response.

Functional near infrared spectroscopy (fNIRS) has become the primary tool for acquiring ecological neurophysiological evidence in DT gait research issues in ways that other neuroimaging technologies (i.e., fMRI) cannot. fNIRS provides a portable way to record, visualize and indirectly measure of cortical activation during dynamic movement (Parasuraman & Rizzo, 2008). Due to the optical properties of oxyhemoglobin and deoxyhemoglobin, fNIRS can assess cortical activation by emitting wavelength in the near infrared range into the cerebral cortex and measure its attenuation (Tromberg et al.,

1993). The use of two wavelengths (690 and 830 nm) allows us to infer the relative hemoglobin changes with the modified Beer-Lambert law (Delpy et al., 1988). The rise in the level of oxygenated hemoglobin (HbO₂) is used to infer the active use of neural resources. Walk studies suggest that the change in HbO₂ (Δ HBO₂) may be the most robust signal to track since it demonstrates the greatest changes in relation to locomotion (Mihara & Miyai, 2016; Miyai et al., 2001).

The current DT gait literature utilizing cognitive demand is dominated by studies examining discrete cognitive tasks such as responding “Yes” or “No” based on fixed characteristics of the stimuli presented (Beurkens & Bock, 2012) or studies examining relatively low demand continuous tasks such as reciting alternate letters of the alphabet (Holtzer et al. 2011) or serial subtractions (Mirelman et al. 2014; Lu et al. 2015).

Although results are mixed across different age groups, younger adult DT walk studies with fNIRS imaging have largely found a reduction in gait speed (Lu et al., 2015; Mirelman et al., 2014), high cognitive accuracy rates and increase in prefrontal cortex (PFC) activation (Al-Yahya et al. 2011; Lu et al. 2015) with these cognitive tasks. Few studies report response times of participants to the cognitive task. Further behavioral measures of response time and accuracy can provide evidence for facilitation or slowing during dual-task. For example, during treadmill walking using a discrete semantic judgement task, Fraser et al. (2007) found that younger adults demonstrated better cognitive performance (facilitation) during DT walking than single task, with shorter response times while accuracy was high overall.

The enhanced neural resource recruitment required to perform in demanding conditions is also referred to as ‘neural upregulation’ (REF). Neural upregulation

combined with behavioral dual-task costs may help identify shared processing mechanisms in gait and continuous cognitive tasks. When examining PFC contributions in younger adults during dual-task gait, to our knowledge Mirelman et al. (2014) is the only fNIRS dual-task walk study that has manipulated cognitive demand with discrete and continuous cognitive tasks. Participants performed two cognitive tasks of increasing demand: counting forwards (discrete) serial subtractions (Walk+S7; continuous) with over-ground self-pace walking and standing. Findings demonstrated graded HbO₂ increases with respect to task: DT (Walk+S7) > walking + counting > walking (SM) while no differences were found between SM and standing as well as standing with or without subtraction. This suggests that neural upregulation during walking while talking (DT) is specific to dual-task cognitive demand as opposed to verbalization or motor task demands. Furthermore, accuracy was high in both single and dual-tasks for all conditions, demonstrating that these particular discrete and continuous tasks were at a relatively low level of difficulty and cognitive demand for younger adults (YA).

The NBK task is the one of the few demanding continuous tasks that has been able to distinguish cognitive demand differences in the PFC with functional near infrared spectroscopy (fNIRS) (Herff et al. 2014). Fraser et al. (2016) utilized an auditory NBK to explore DT gait performance differences with continuous cognitive tasks of increasing demand (1-back & 2-back). YA and older adults (OA) walking on the treadmill were asked to prioritize motor/cognitive tasks equally during DT (treadmill walking & NBK). Both groups produced more errors in the more difficult 2-back compared to 1-back. Overall, YA were more accurate than OA and both groups demonstrated greater change in PFC HbO₂ in DT than usual walking. There was a difficulty effect in HbO₂ in the

opposite direction to expectations (1-back > 2-back), but this is likely attributable to practice effects since the 1-back was always presented before the 2-back.

With respects to younger adult dual-task walk findings, both Mirelman et al. (2014) and Fraser et al. (2016) studies utilized continuous tasks and found greater PFC Δ HbO₂ during DT. At the level of performance, there were discrepancies between the studies in cognitive performance findings, with Mirelman et al. (2014) reporting no single-dual accuracy differences while Fraser et al. (2016) reported marginally significant single-dual differences ($p = .06$). In contrast to this research with continuous tasks, earlier research by Fraser et al. (2007) that used discrete tasks reported better cognitive performance in DT than single. The differences between the cognitive demands of discrete and continuous cognitive tasks may be contributing to the mixed results during cognitive-motor walk situations. It is unclear from these works whether the differences between continuous and discrete tasks might have a greater or lesser effect on the PFC involvement during DT walking particularly in a sample of YA. Over-ground walking is yet to be investigated in younger adults with a cognitive approach utilizing tasks of increasing difficulty with multiple discrete and continuous cognitive tasks. Our study aims to add to the current literature on DT PFC involvement by investigating over-ground walking with four cognitive tasks of increasing demand that include discrete (2) and continuous (2) tasks. Given the behavioral findings from Fraser et al. (2007) and the neural findings from Fraser et al. (2016) and Mirelman et al. (2014), we hypothesized that greater cerebral activation changes and poor performance (i.e., slower walk speed, longer response times and lower accuracy rates) would be associated with DT and no single task conditions (SM and SC). Similarly, we expected that continuous cognitive

tasks would be associated with the greatest cerebral activation changes as well as declines in behavioral performance due to the additional cognitive demand of working memory tasks (maintaining and updating). We also expected that neural changes in HbO₂ would increase with cognitive demand in both: (1) DT as opposed to usual walking (SM)/single cognitive (SC) conditions and (2) cognitive tasks DNS, NBK, GNG, SRT, respectively.

2. METHODS

2.1 Participants

Nineteen right handed younger adults (21.5 ± 3.6 years, 68% female) between the ages of 18 and 35 years were recruited via social media and flyers to participate in the experiment. All participants completed a health phone screening, to ensure that they fit the study inclusion criteria: that they were right handed, able to walk 15 meters with or without assistance, have no history of stroke, no hearing impairments, or any motor conditions that might compromise their walking performance. A brief overview of participant demographics is provided (See Table 1). Participants gave their written informed consent. The study was approved by the Office of Research Ethics and Integrity at the University of Ottawa, the local ethics board committee. The study was compliant with the human experimentation regulations. All participants were paid an honorarium of \$40 CDN for their time.

2.2 Apparatus

For the duration of the experiment, participants wore a voice recorder (*Philips*, 2018), headphones (*Sennheiser RS 165*, 2018), personal walking shoes, and a continuous wave non-invasive fNIRS system (*Octamon, Artinis Medical Systems*, 2018a). The

headphones were used to present instructions, start and stop cues as well as cognitive stimuli for each of the cognitive tasks. Experimenters presented instructions over a professional microphone (Audix, 2012). *Supplemental Figure 2* illustrates a fully instrumented participant.

2.3 Experimental Protocol

Participants were given a familiarization phase with each of the conditions: cognitive task (SC), usual walking (SM), and dual-task (DT). To ensure that the participant heard and understood the instructions prior to performing the experimental tasks. Participants performed SC SRT-GNG-NBK-DNS conditions until they scored higher than 70% accuracy prior to the experimental phase for a maximum of 5 blocks. On average, participants performed 1.5 SC and 1.2 DT blocks of familiarization. During the experimental phase of the DNS condition, participants had to have combined error counts of less than 6 or the DNS block was repeated. 5.3% of the DNS data was removed due to excessive error counts that deter our understanding of whether the participant was completing the task as instructed.

Test responses, accuracy rates (number of correct responses and errors) and gait speed (m/sec) were manually recorded by the experimenter while vocal responses were acquired with the voice recorder placed in an arm band on the participant. Cerebral oxy- (ΔHbO_2) and deoxygenation (ΔHbR) were measured with the fNIRS Octamon (Artinis) with 8-channels on the PFC. Only ΔHbO_2 was analyzed in this study for its robust association with real locomotion (Mihara & Miyai, 2016; Mirelman et al., 2014; Miyai et al., 2001; Perrey, 2008).

The experiment consisted of two sessions on two consecutive days: static and dynamic. The present paper will only present the dynamic session in which participants walked or stood in single and dual-task conditions. The session consisted of four runs in which each run contained a different cognitive task. *Supplemental Figure 1* gives an overview of the 12 blocks that made up one run. The type of session, the order of the cognitive tasks and the design of the run are all counterbalanced (Girden, 1992) to control for fatigue, learning (Leff et al., 2011) and practice effects (Keedwell & Dénes, 2015).

At the start of each block, the experimenter gave instructional cues for the task with respect to SC-SM-DT. Participants were told to relax with their arms hanging loosely at their sides, eyes fixed on a 6" circular target placed at eye level on a wall 12 m in front of them. For consistency, participants placed their feet behind a horizontal line marked on the floor. A 10 second standing baseline (B) was collected before each block. The start of all the tasks was indicated by three initial warning beeps, the last of which was a higher pitch, at which point the block would begin with an audio presentation of each task. At the end of the task, participants heard a final warning beep. The warning beeps were at a distinct frequency (*hertz*) from any other sounds presented during the experiment. There was 15s of rest period (R) after each block after which participants were cued for their next task. The rest period ensures that the hemodynamic response reverts to baseline before a new block begins (Miyai et al., 2001; Perrey, 2008). Triggers were inserted to mark the beginning and end of each block for offline analysis purposes.

After the experiment, participants completed neuropsychological and physical assessments: Montreal Cognitive Assessment test (MoCA) (Nasreddine et al., 2005), the shortened Beck Depression Inventory, the Short Physical Performance Test (SPPB)

(Guralnik et al., 1994) as well as the Falls Efficacy Scale International (Delbaere et al., 2010). The MoCA, Beck and SPPB assessments were used to provide global cognitive and physical characteristics of our sample and to ensure that none of the participants were severely depressed as this can influence cognition (Fraser et al., 2016; Gotlib & Joormann, 2010). The Falls Efficacy Scale was used to identify participants with a fear of falling (*See Appendix and Table 1.*)

2.4 Experimental Tasks

2.4.1 Cognitive Tasks

All cognitive tasks were recorded and programmed in E-Prime software (Schneider et al., 2002) and presented through the wireless headphones. Participants were given the option to conduct the experiment in French or English, in accordance with the human experimentation ethical guidelines of the University of Ottawa. The cognitive tasks described below have been used in published dual-task studies (Fraser et al., 2016; Yves Lajoie et al., 2016). All blocks were 33 seconds in duration. While conducting the cognitive tasks, participants adopted their preferred standing position on a standard floor wearing their preferred walking shoes.

The differences between discrete and continuous tasks not only lay in the temporal range but also in the number of steps associated with the operation. The SRT and GNG were categorized as discrete tasks for their shorter temporal range and 1-step processing mode (i.e., hear stimuli and respond; Salthouse, 2000). At the same time the NBK and DNS were considered continuous tasks for the concurrent working memory steps within the task that were conducted in a wider temporal range (i.e., to be remembered item was only responded to two stimuli later).

Simple reaction time task (SRT) (Lajoie et al., 1993): Participants heard random high-pitched beeps through the headphones. Whenever they heard a beep, they had to respond by saying the word “top” as fast as possible. Seven stimuli were presented, at varying inter-stimulus intervals (ISIs) of 1 to 8 *secs* for the duration of the block. The high-pitched signal was administered at a fixed frequency of 2850 Hz at 99 dB for approximately 100 milliseconds. An error is registered after a beep presentation, if the participant does not say “top” before the next beep is presented.

Go/no go inhibition task (GNG) (Lajoie et al., 2017): Participants heard high and low pitch beeps presented at varying ISIs. Whenever they heard a high pitch beep, they were required to respond by saying the word “top” as fast as possible, while inhibiting any response to low pitch beeps that are presented. Six stimuli were presented, at an ISI between 2 to 15 *secs* for the duration of the block. The high-pitched signal was administered at a fixed frequency of 2850 Hz at 99 dB whereas the low-pitched signal was administered at a fixed frequency of 970 Hz at 95 dB for approximately 100 milliseconds (ms).

Errors for this task were considered misses to the Go events (not responding to the high pitch beeps) and false alarm responses (responding to the low pitch beeps).

2-back working memory task (NBK) (Fraser et al., 2016): Participants heard a continuous series of single-digit numbers and were required to indicate the number they heard two numbers back. An auditory sequence of 15 numbers were pseudo-randomly presented without any repeats (9-9) or ordered series (1-2-3), at an inter-stimulus interval of approximately 2.3 *s* for the duration of the block. An error is registered whenever a

participant did not state the accurate number within the response window (prior to the next stimuli), either by saying nothing or by responding with an incorrect number.

Double Number Sequence working memory task (DNS) (Richer et al., 2017): An auditory sequence of 15 three-digit numbers was presented, at an inter-stimulus interval of 2-secs for the duration of the block. In each block, participants were asked to create a running total of two pre-designated target digits by searching and silently counting the number of times the digits are presented in a sequence without using any counting aids. At the end of the block, participants were asked to provide two totals for each number they tracked within the three-digit numbers presented. This cognitive task differs from the other tasks since participants only responded at the end of the block. As a result, we did not derive a response time for this task. The accuracy is a percentage of the participant's answer out of the correct answer.

2.4.2 Motor Tasks

Participants were instructed to walk at their own “comfortable” pace at the start of the block, with instructions “that they were walking to a meeting that they were not late for”. A 10m distance was marked on the floor, with a horizontal line indicating the participant's starting and turning point. At the end of the block, a single beep signaled the participant to stop walking and stand in place. The experimenter quantified the distance covered during each 33 sec walk trial (single and dual).

2.4.3 Dual-tasks

Participants walked at their own pace while simultaneously performing the cognitive task. Participants were instructed to pay equal attention to both the motor and

cognitive tasks with equal priority as previously described (Fraser et al., 2016, Laguë-Beauvais et al. 2015, Holtzer et al., 2015).

2.5 fNIRS Acquisition

fNIRS was used to record changes in brain activity during the experiment with Bluetooth. The fNIRS contained eight temperature stabilized pulsed laser diode channels and two photodiode cooled avalanche receivers (R) with ambient light protection. A combination of eight hundred and thirty and six hundred and ninety nanometers of wavelengths was used to measure ΔHbO_2 , respectively. The Octamon has a NIRS depth of 4 cm with diodes positioned 3-4cms apart.

We collected the raw data at a sampling frequency of 10 Hz, followed by an analysis of the micro-molar chromosphere concentration changes. The raw data was converted to concentrations with the Modified Beer-Lambert law (Villringer & Chance, 1997) and differential path-length factor set to the age of the participant (Cope et al., 1988). Oxysoft (*Artinis Medical Systems*, 2018b) was also used to collect, store and visualize the data. A wavelet analysis was conducted to modify frequency parameters in the bandpass filter, accounting for respiration changes associated with cerebral oxygenation changes during vocalization (Scholkmann, Gerber, Wolf, & Wolf, 2013). The neural data was processed offline on MATLAB (*The Mathworks Inc.*, 2016) with a custom script to filter physiological noise with a bandpass set between 0.5 and 0.01, remove outliers by replacing with a zero value. The change in HbO₂ for all channels was acquired from the difference between the baseline and task conditions as well as the mean of the ΔHbO_2 values for each condition per channel in MATLAB. Note that the variables

of interest, ΔHbO_2 are relative changes in concentration compared to baseline, not the absolute concentrations.

The head circumference was measured for each participant to facilitate fNIRS placement on FP1/FP2 using the modified international EEG 10/20 system (Okamoto et al., 2004). FP1 and FP2 were aligned within 10% of the distance from the nasion to theinion on the midsagittal plane while the position of electrode Cz was fixed at the vertex of the head. The goal was to cover left and right prefrontal cortex. One subject was scanned in an MRI scanner, with fiducial markers placed at the position of the fNIRS optodes for the configuration of the current study. Optodes 1, 2, 3, 4 represented the right PFC while 5, 6, 7, 8 were part of the left PFC (*see Supplemental Figure 3*). Prior to beginning acquisitions, the fNIRS signal was visualized online to ensure a strong signal (with the heartbeat) indicated by a synchronous waveform (Gratton and Corballis 1995; Kirilina et al. 2012) without any software indicators of ambient light contamination. In case of shifting during walking, references were marked on the nasion as well as left/right pre-auricular points to fix the anatomical points. fNIRS data was recorded continuously while the experimenter monitored signal quality for any potential noise or loss of signal. Since continuous wave technology does not provide absolute hemodynamic concentrations, the variables of interest, ΔHbO_2 , represent relative changes in concentration (Laguë-Beauvais et al., 2015).

2.6 Statistical Analyses

2.6.1 Behavioral Data

The behavioral data included accuracy rate (%), gait speed (m/s) and response time (milliseconds). The data was checked for outliers based on 2.5 standard deviations (SDs) from the group mean for each condition. No outliers were found. Pearson r correlations examined whether behavioral and neural outcomes such as walk speed, accuracy, response time, and ΔHbO_2 exhibited speed accuracy tradeoffs with motor-cognitive discrepancies.

Accuracy: The cognitive tasks were assessed with accuracy rates, a percentage representing the number of correct responses out of the total possible responses within a block. The mean accuracy rates were calculated for each cognitive task, both SC and DT conditions. A 2 x 4 repeated measures ANOVA of the two conditions (SC/DT) across the four levels of demand (SRT, GNG, NBK, DNS) was conducted.

Gait: Gait speed was calculated using the distance each participant walked and the time of the trial (33 seconds) in order to derive meters per second. A 2 x 4 repeated measures ANOVA of the two conditions (SM/DT) across the four levels of demand (SRT, GNG, NBK, DNS) was conducted. Alpha was set at $\alpha = 0.05$ for the planned comparisons. All post hoc analyses were Bonferroni corrected.

Response Time: Response times were derived in milliseconds offline with computer software (Audacity, 2014; Microsoft, 2013). The mean response times were calculated for SRT, GNG and NBK task for both SC and DT conditions. A 2 x 3 repeated measures ANOVA of the two conditions (SC/DT) across the three levels of demand (SRT, GNG, NBK) was conducted. Alpha was set at $\alpha = 0.05$ for the planned comparisons. All post hoc analyses were Bonferroni corrected.

2.6.2 Neural Data

The mean cerebral oxygenation data was analyzed with SPSS IBM version 23; we did t-tests within each channel (8) in order to first examine within channel differences between SM and DT for each cognitive task and for HbO₂. Channel specific differences in HbO₂ have been reported in the literature before (Holtzer et al., 2011). Since t-tests revealed differences between the left and right optodes, we then did 2 x 2 x 4 repeated-measures ANOVAs comparing neural changes in SM/DT conditions across two hemispheres (Left/Right) with four levels of demand (SRT, GNG, NBK, DNS) for HbO₂ (Fraser et al., 2016). To address our hypothesis, we then compared the neural changes in SC and DT conditions with t-tests by channel, and the 2 x 2 x 4 ANOVA repeated-measures ANOVAs for HbO₂ for SC/DT conditions.

Please note that when discussing results associated with cerebral hemodynamics the following annotations are used: M_{HbO_2} , cerebral oxygenation. For all the analyses alpha was set at $\alpha = 0.05$ for the comparisons. All post hoc analyses were Bonferroni corrected.

3. RESULTS

3.1. Behavioral Findings

3.1.1 Accuracy Rate

The 2 x 4 repeated measures ANOVA revealed a significant main effect of task [$F(1, 18) = 15.42, p = 0.001, \eta_p^2 = 0.46$], with lower accuracy during dual tasking ($M = 90.8\% \pm 0.79^*$) than when single tasking ($M = 93.65\% \pm 0.6^*$). Participants also exhibited a main effect of demand [$F(3, 54) = 63.82, p < 0.00, \eta_p^2 = 0.78$], with lower accuracy in the DNS ($M = 81.85\% \pm 1.25^*$) than the NBK ($M = 90.02\% \pm 1.3^*$), GNG ($M = 97.08\% \pm 1.14^*$) and SRT ($M = 100\% \pm 0.0^*$), consecutively (See Supplemental Figure 7). These

results were qualified by a marginally significant task x demand interaction [$F(3, 54) = 2.66, p=0.06, \eta_p^2 = 0.13$]. Pairwise comparisons revealed significant differences between SC and DT only during the NBK ($p = 0.01$) and the DNS ($p = 0.03$) (See Supplemental Figure 4).

3.1.2 Response Time

The 2 x 3 ANOVA on response times revealed a main effect of task [$F(1, 18) = 20.65, p < 0.001, \eta_p^2 = .53$] with longer response times during the DT ($M = 477 \pm 21.3$ ms) than the SC conditions ($M = 442 \pm 17.5$ ms). The ANOVA also revealed a main effect of demand [$F(2, 36) = 10.61, p < 0.001, \eta_p^2 = .37$] with longer response times during both GNG ($M = 536 \pm 22.1$ ms) and NBK ($M = 459 \pm 38.5$ ms) than SRT ($M = 386 \pm 13.9$ ms). These results were qualified by significant task x demand interaction [$F(2, 36) = 4.1, p = 0.026, \eta_p^2 = 0.18$]. Response times for SRT and NBK dual-tasks ($M_{\text{SRT DT}} = 398 \pm 14.8$ ms; $M_{\text{NBK DT}} = 493 \pm 41.9$ ms) were significantly slower than single-cognitive tasks ($M_{\text{SRT SC}} = 373 \pm 14.1$ ms, $p = .005$; $M_{\text{NBK SC}} = 424 \pm 37.7$ ms, $p = .004$).

3.1.3 Walk Speed

The 2 x 4 repeated measures ANOVA revealed a main effect of demand [$F(3, 54) = 9.28, p < 0.001, \eta_p^2 = 0.34$]; during both single and DT participants walked slower when performing the DNS ($M = 1.1 \pm 0.04$ m/s*) than the NBK ($M = 1.15 \pm 0.04$ m/s), GNG ($M = 1.15 \pm 0.04$ m/s) and SRT ($M = 1.15 \pm 0.04$ m/s). These results were qualified by a significant task x demand interaction [$F(3, 54) = 5.3, p = 0.003, \eta_p^2 = .227$]. DT walk speeds for DNS ($M = 1.09 \pm 0.04$ m/s, $p = 0.02$) were slower in comparison to SM ($M = 1.14 \pm 0.04$ m/s); while NBK ($M = 1.16 \pm 0.03$ m/s), SRT ($M = 1.14 \pm 0.04$ m/s) and

GNG ($M = 1.13 \pm 0.04$ m/s) DT walk speeds were similar to SM (no significant differences) (See Supplemental Figure 5).

3.2 Cerebral Hemodynamics

3.2.1 Cerebral oxygenation during usual (SM) and dual-task walking (DT)

2 x 2 x 4 repeated measures ANOVA revealed a significant Δ HbO₂ interaction between task (SM; DT), hemisphere and demand [$F(3, 54) = 5.730, p = 0.002, \eta_p^2 = 0.24$]. DT change in HbO₂ ($M = -0.00 \pm 0.08$) was higher than SM ($M = -0.16 \pm 0.08$) with marginal significance in the right hemisphere ($p = .056$) during the DNS condition only.

3.2.2 Cerebral oxygenation during single cognitive (SC) and dual-task walking (DT)

A 2 x 2 x 4 repeated measures ANOVA revealed a significant Δ HbO₂ interaction between task (single cognitive and dual), hemisphere and demand [$F(3, 54) = 4.08, p = .011, \eta_p^2 = 0.19$]. During the NBK-only condition the right ($M = 0.07 \pm 0.06$) hemisphere exhibits significantly ($p = .045$) greater Δ HbO₂ than the left hemisphere ($M = 0.003 \pm 0.07$).

3.2.3 Correlation between brain and behavior

There were no significant correlations between cerebral oxygenation measures (HbO₂) and performance measures (accuracy, response time, walk speed).

4. DISCUSSION

The aims of the current divided attention study were to compare how discrete and continuous cognitive tasks differentially modify neuro-behavioral outcomes of younger

adults during SM, SC and DT over-ground walking conditions. We hypothesized that continuous cognitive tasks would be associated with the greatest cerebral activation changes (ΔHbO_2) as well as diminished behavioral performance (i.e.: lower accuracy and walk speed) in comparison to discrete tasks. Similarly, we expected that dual-task conditions would be associated with the greatest cerebral activation changes (ΔHbO_2) as well as diminished behavioral performance (i.e.: slower response times, lower accuracy and slower walk speed) in comparison to single tasks. Our results partially supported these hypotheses.

As hypothesized, performance in DT performance is poorer than single with lower accuracy rates and longer response times. Gait was affected similarly in SRT-GNG-NBK which aligns with previous studies of younger adult samples (Fraser et al., 2016; Yves Lajoie et al., 2016). HbO_2 levels were similar in single-dual NBK, GNG and SRT. The lack of neural and cerebral task differences in the SRT, GNG, NBK, suggests that younger adults may be able to manage dual-task walking when paired with discrete cognitive tasks like the SRT-GNG as well as continuous tasks like the NBK without significantly engaging the PFC. Indeed, three of the four cognitive tasks in the present study are less demanding discrete (SRT, GNG) or continuous cognitive tasks (NBK), similar to the tasks utilized in previous DT walk studies. But none of the previous studies investigated over ground walking nor have combined the discrete and continuous tasks within the same experiment and varied load even within discrete and continuous tasks.

The divergent nature of discrete and continuous cognitive tasks is utilized to examine which processes may interfere with gait perhaps as a result of competition for the same neural resources. The behavioral findings support earlier reports of DT walking

assessments reporting slower DT walk speeds across low demand continuous and discrete tasks (Mirelman et al. 2014; Holtzer et al. 2011). Discrete cognitive tasks tax processing centers such as speed of processing and inhibition while continuous tasks engage sustained attention centers such as working memory.

The findings partially supported our hypothesis demonstrating poorer continuous task performance than discrete with significant demand effects in walk speed, response time and accuracy rates but not in cerebral hemodynamics. Differences in SC-DT accuracy rates across the DNS-NBK-GNG-SRT tasks align with Lajoie et al. (2017). Since the DNS only required one response at the end of the task, response time measures were not taken into consideration for this task. Similar to information processing, discrete and continuous properties of tasks operate on a graded continuum so that some tasks can be considered more or less continuous, or discrete than others (Miller, 1988).

When comparing the NBK and the DNS cognitive tasks, the DNS encapsulates more continuous properties than the NBK. The NBK, unlike the DNS, requires the participant to hold onto information (up to three numbers) in the working memory for about 7 seconds while they respond to every number, similar to probe stimuli in discrete tasks (Schmidt et al., 2011). The DNS requires the participant to continuously perform mental arithmetic for 33 seconds dynamically updating the memory every 2 seconds. Therefore, the NBK may be considered a less continuous cognitive task than the DNS. The similar single and dual-task findings in cerebral hemodynamics, walk speed and accuracy indicate that younger adults are able to manage the demands of self-paced over-ground walking conditions during SRT-GNG-NBK.

These results were unexpected for the NBK working memory task, a continuous task that has demonstrated significant cerebral oxygenation changes in younger adults walking on a treadmill (Fraser et al., 2016). The different walking conditions (treadmill vs over-ground) may in part account for differences in the younger adult findings for the NBK. Several studies have demonstrated that treadmill walking and over-ground walking do not have the same demands (Lee & Hidler, 2008; Yang & King, 2016). In the Fraser et al. (2016) study, gait speed was fixed for single and dual-tasks on the treadmill, whereas the current study involved over-ground walking and no forced maintenance of gait speed. In younger adults, this change may have minimized demands enough to reduce the need for additional PFC recruitment during dual-task. Alternately, different strategies may have been applied by the younger adults when walking over-ground. YA in this study and Fraser et al. (2016) have accuracy task effects for the NBK (DT less accurate than SC) and the current study also demonstrates significant differences in vocal response time (DT slower than SC) which was not measured in Fraser et al. (2016).

The significant interaction between cognitive tasks, hemisphere and demand reveal right HbO₂ lateralization during the NBK SC condition. This neural correlate corresponds with the right mid-ventrolateral prefrontal cortex, a region that has been previously associated with a fractionation of working memory processes in PET studies (Owen et al., 1999). It is surprising that this difference is not evident during the DT but for the reasons discussed above (strategy, altered walk speed) this may have reduced our ability to detect cerebral oxygenation changes during NBK DT in this same area.

Consistent with our hypothesis, the findings demonstrated that compared with usual walking, younger adults had slower walk speeds and significant change in HbO₂

PFC activation during dual walking with the DNS task, a demanding cognitive task. There were no task differences between all three behavioral and cerebral measures (single versus dual) except in DNS. Taken together, these findings suggest that continuous cognitive tasks, like the DNS, elicit a very different cerebral and behavioral response during DT as opposed to the SRT, GNG and NBK. The results point to a unique relationship between walking and cognitive resources during DT conditions of demanding continuous tasks. The DNS may be unlike other less continuous or discrete tasks since it is a complex cognitive task requiring activation of higher order shared networks (Fuster et al. 2008). These findings are supported by a meta-analysis review demonstrating continuous tasks with mental tracking are significantly related to response time, discrimination and verbal fluency as opposed to dual-tasks or discrete tasks (Chu et al., 2013). Cognitive tasks with internal interfering factors like arithmetic tasks are prone to disturbing walk performance more than tasks that involve external interfering factors (Al-Yahya et al., 2011). The findings support previous studies demonstrating that mental tracking and arithmetic are interlinked with gait control such that demands altered in this region would be enough to disturb gait (Gazzaley and D'Esposito 2006).

Evidence of deteriorating cognitive and motor behavioral measures along with differences in cerebral oxygenation indicate the presence of interference during the DNS (Plummer et al., 2013). The consistent relationship between increased cortical activities (HbO₂) associated with the cognitive task requiring higher executive function is consistent with PFC theories monitoring attention resources (Koechlin, 2003; Watanabe & Funahashi, 2014; Yogeve-Seligmann et al., 2008). The dual-task related activation differences with pronounced costs in the condition with the greatest cognitive demand

(the DNS), align with the capacity sharing model. As hypothesized, cerebral findings indicate greater oxygenation in DT than SM during the DNS, a continuous cognitive task.

Activation increases with demand in the DNS DT condition, demonstrated sensitivity to cognitive manipulation. However, the capacity sharing model postulates that there is a limit to upregulation, after which the PFC cannot be kept sufficiently engaged despite increasing demands, resulting in decreasing activation (Cabeza et al., 2018). Our study utilized graded levels of four demanding tasks, but we did not find evidence of decreasing activation (Cabeza et al., 2018; Mattay et al., 2006; Reuter-Lorenz & Cappell, 2008). The magnitude of dual-task costs in gait parameters and cognitive tasks utilized vary in other studies. However, similar findings demonstrate an inverse relationship between cognitive load and gait was been reported before, with high cognitive load and low gait speed (Agostini et al., 2015; Beurskens & Bock, 2013; Beurskens et al., 2014; Plummer et al., 2015; Schabrun et al., 2014)

Although it seems that YA are able to process the demands of the discrete and one continuous task, the significant response time demand effect suggests that there are still some costs. Response times were faster during SC than DT for SRT and NBK. Response time measures have been utilized to identify parallel processing (Townsend, 1990). Delays in DT response time indicate a processing limitation that prevents adequate preparation of response to a second stimuli until the previous action is completed. The slower DT response times in comparison to SC despite similar cerebral hemodynamics in SRT-NBK indicate a response bottleneck deterring parallel processing in DT gait without increased PFC involvement. This suggests that even at lower levels of cognitive load, parallel processing is not possible in all dual-task walk conditions. Findings demonstrate

that response times were significantly slower during both GNG and NBK than SRT. Fuster et al. (2008) postulates that less dual-task interference occurs with cognitive tasks involving “external interfering factors” like the SRT. Such tasks activate “stimulus driven” lower order networks involving gait control with cerebral activation in areas other than the PFC, such as the motor regions (Stuart et al., 2019).

DT gait study findings may differ across the board due to instructional differences during the experiment. Unlike the Tomporowski et al. (2014) study, the younger adults in this study were explicitly instructed to equally prioritize both motor and cognitive aspects, thereby increasing dual-task demands. Healthy YA and OA may prioritize dual-task conditions differently according to prioritization commands. A smaller prioritization effect was demonstrated in OA specifically in the cognitive priority condition than YA (Yogev-Seligmann et al., 2010). The “naturalistic” approach of not specifying prioritization overlooks the subtleties of attention strategies; further complicating our understanding of DT outcomes that are usually similar to those in cognitive priority condition (Yogev-Seligmann et al. 2010, Laguë-Beauvais et al., 2015). During management of multiple tasks, the prefrontal cortex exhibits different activation patterns indicating differential contributions from specific executive mechanisms (Laguë-Beauvais et al., 2015). Seated DT studies with discrete tasks did not find prioritization differences in younger adults or evidence of increased executive demands during equal priority instructions (Laguë-Beauvais et al. 2015). However, without prioritization cues it is difficult to assess whether neural or behavioral differences are presented as a result of more overt attention towards one domain over another. Yet, most DT motor studies do not explicitly specify prioritization (Lajoie et al., 2017; Mirelman et al., 2014). Younger

adults also show gait differences when prioritization is unspecified or held equal (Plummer et al., 2015).

The participant pool in the present study consists of an unequal gender distribution. However, the sample is too small to test for brain or behavioral differences in relation to gender. While there has been some evidence of differences in gait parameters between older men and women (Holman et al., 2011), behavioral studies have generally not found gender differences in multitasking (Hirnstein et al., 2018; Tschernegg et al., 2017). Imaging evidence suggests some activation differences in men and women, but only in specific tasks (visuospatial & verbal fluency) which have known gender effects (Tschernegg et al., 2017). Further, the literature suggests that motor-cognitive processing differences are more strongly associated with age effects than with gender effects (Sommer et al. 2004, Herrmann et al. 2006). A meta-analysis of functional imaging studies, Sommer et al. (2004), did not reveal language lateralization differences between genders. In the Herrmann et al. (2006) multi-channel fNIRS study, young and elderly subject groups performed a verbal fluency task as experimenters' analyzed age and gender effects on cerebral activation. The findings demonstrated no influence of gender on brain activation patterns. This suggests that controlling for age is more of an important factor than controlling for gender in functional imaging studies (Herrmann et al., 2006) but that studies with larger samples should investigate gender differences further.

It is important to note that the cognitive tasks in this study were purposely chosen to minimize motor-motor or motor-visual interference. Auditory cognitive tasks were paired with gait, in order to reduce domain specific interference (motor/visual) and to create an ecological dual-task walk that mimics as closely as possible everyday walking

and talking. Some studies impose cognitive tasks that require additional motor regulation such as in the Schabrun et al. (2014) study where participants were walking and typing phrases as they appeared on a smartphone screen. Our findings may be distinct from past studies in which the DT behavioral measures are linked with ongoing visual observation tasks (Bock, 2008; Schabrun et al., 2014). The cognitive tasks utilized in this study did not disrupt online-visual feedback mechanisms integral to adaptive human locomotion (Patla & Greig, 2006).

The neural compensation model may be utilized to interpret the findings in the present study (Cabeza et al., 2018). The model proposes that greater task demands may necessitate neural upregulation in order to perform the task. However, according to this model cerebral activation levels do not have to correlate with performance. It is possible to have an increase in brain activity without an increase in performance. The neural upregulation highlights the critical role of the PFC in designating neural resources and supporting DT performance in a demanding continuous task. As was found in previous studies, the correlation between gait velocity-cognitive outcomes and cerebral oxygenation was not significant (Holtzer et al., 2015). The lack of association may be a result of a lack of power for this type of analysis or individual level differences in how the subjects are responding to the increased demands of the task.

4.1 Limitations of the current study

The current study has several limitations in assessing motor control and cerebral dynamics. The study does not account for the sitting condition or include additional gait parameters such as stride length, variability and cadence which might have led to different dual-task findings (Lu et al., 2015; Mirelman et al., 2014). Additionally, the

cerebral investigation does not account for other cortical regions such as the parietal lobe or motor regions.

4.5 Conclusions

The findings in this study strengthen the evidence from studies investigating the connection between gait and cognition during walking by highlighting differences when using cognitive tasks with discrete and continuous demands. Both neural and behavioral performance indicates that continuous tasks may have a significant influence on over ground walking. Therefore, continuous tasks may be more strongly associated with distracted walking and injury. Furthermore, a DT test for YA abilities during self-paced walking, may require more difficult continuous tasks in order to sufficiently challenge this age group. The results of this study could be used to develop cognitive training strategies with continuous tasks that are naturally in tune with daily life. Future studies should utilize a similar experimental design to assess healthy older adults and individuals with developmental or neurodegenerative disorders to assess cerebral oxygenation and performance differences in the ability to respond to discrete and continuous tasks during walking.

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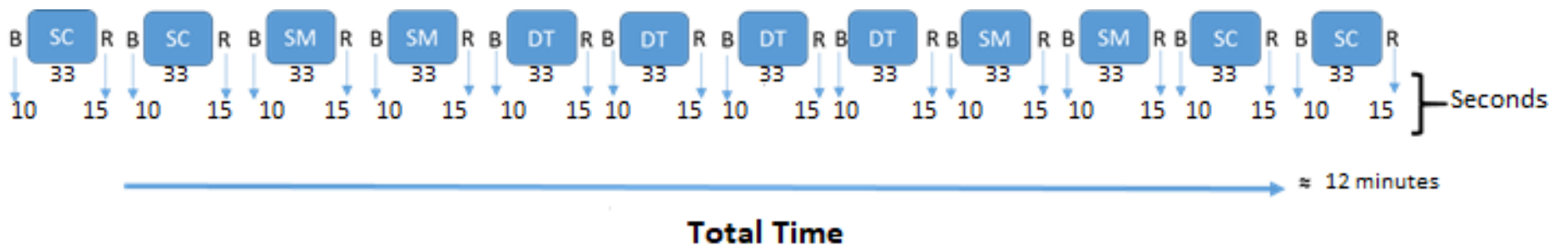
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6. SUPPLEMENTAL FIGURES

Table 1 *Participant Demographics*

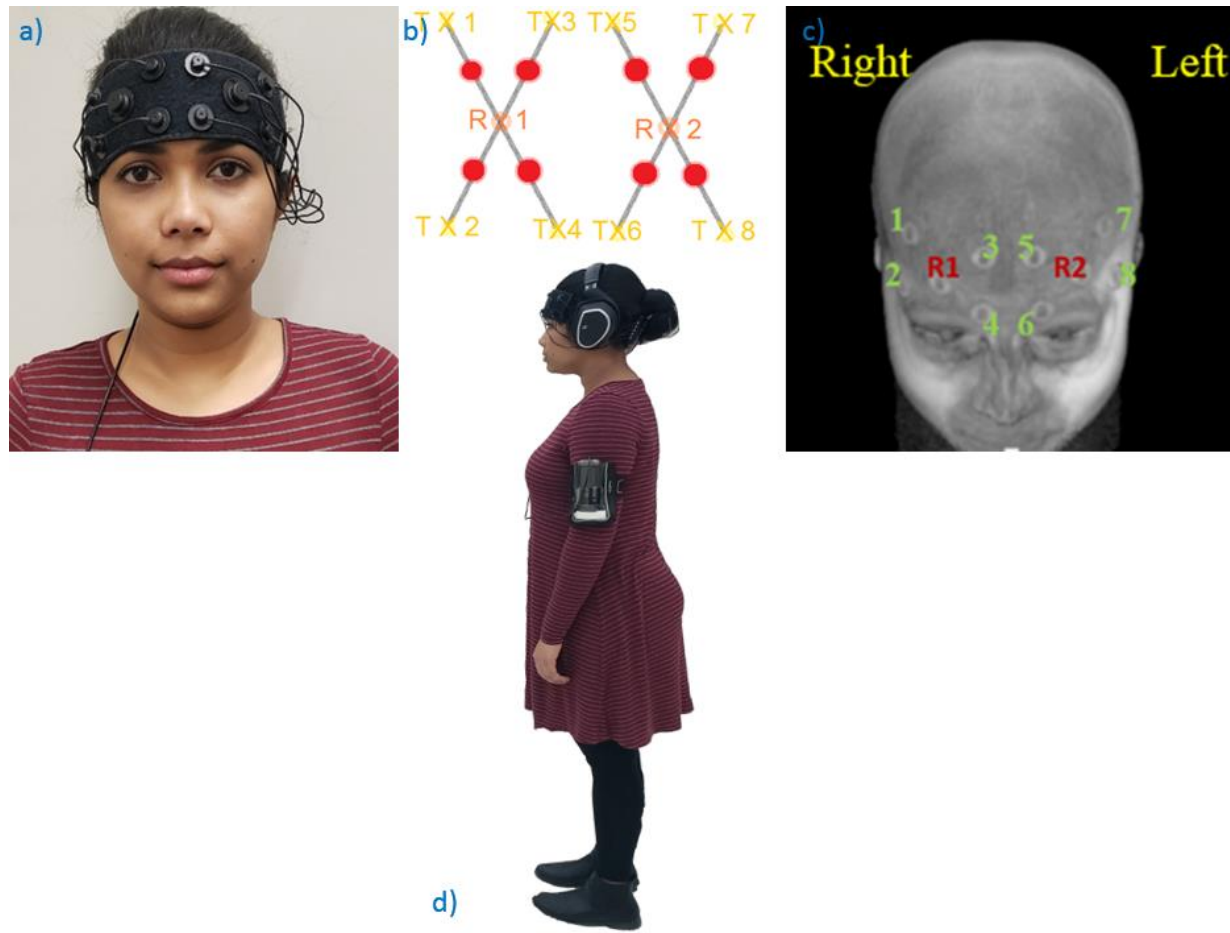
MEASURE	MEAN	(SEM)	Unit
Mean Age	21.6	(± 3.60)	(years)
Females	68.4		(%)
Males	31.6		(%)
Self-selected pace	0.84	(± 0.16)	(m/s)
Depression	2.3	(± 2.80)	(score)
Falls Efficacy Score International	33.8	(± 12.1)	(%)
Montreal Cognitive Assessment	26.7	(± 1.30)	(score)
Short Physical Performance Battery Score	11.6	(± 0.65)	(score)
Education	13.5	(± 1.80)	(years)

Note: Individuals scoring higher than 26 on the MOCA (range: 0 to 30) indicates a participant population of those with healthy cognitive state. The Beck Depression inventory (range: 0 to 30) score of less than 4 indicates healthy mental state. The Short Physical Performance test (range: 0 to 12) is used to identify physical state in which higher values indicate better physical performance. Furthermore, the Falls Efficacy Scale (range: 0 to 100%) is used to identify participants with a fear of falling such that higher values indicate greater concerns. (*See Appendix*)



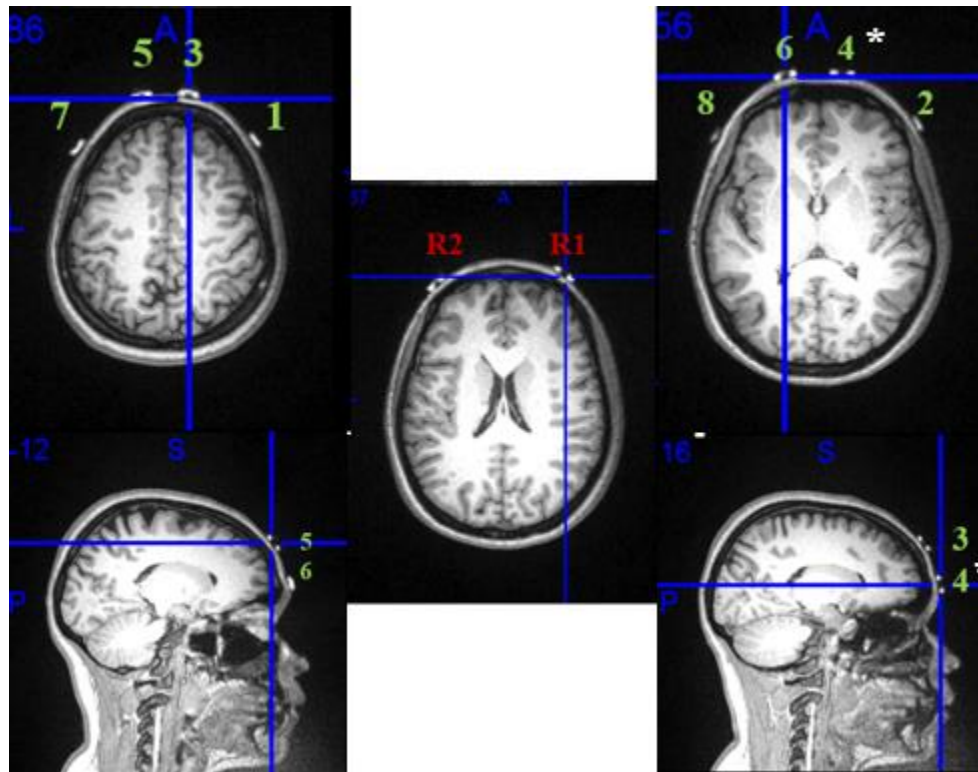
Supplemental Figure 1: *Experimental protocol for one run.*

Note: Abbreviations: B = baseline (fNIRS quiet standing); R = rest, SC = single cognitive (SRT, GNG, 2-back or DNS randomized run order while standing); SM = single motor (usual walking); DT (cognitive task and walking)



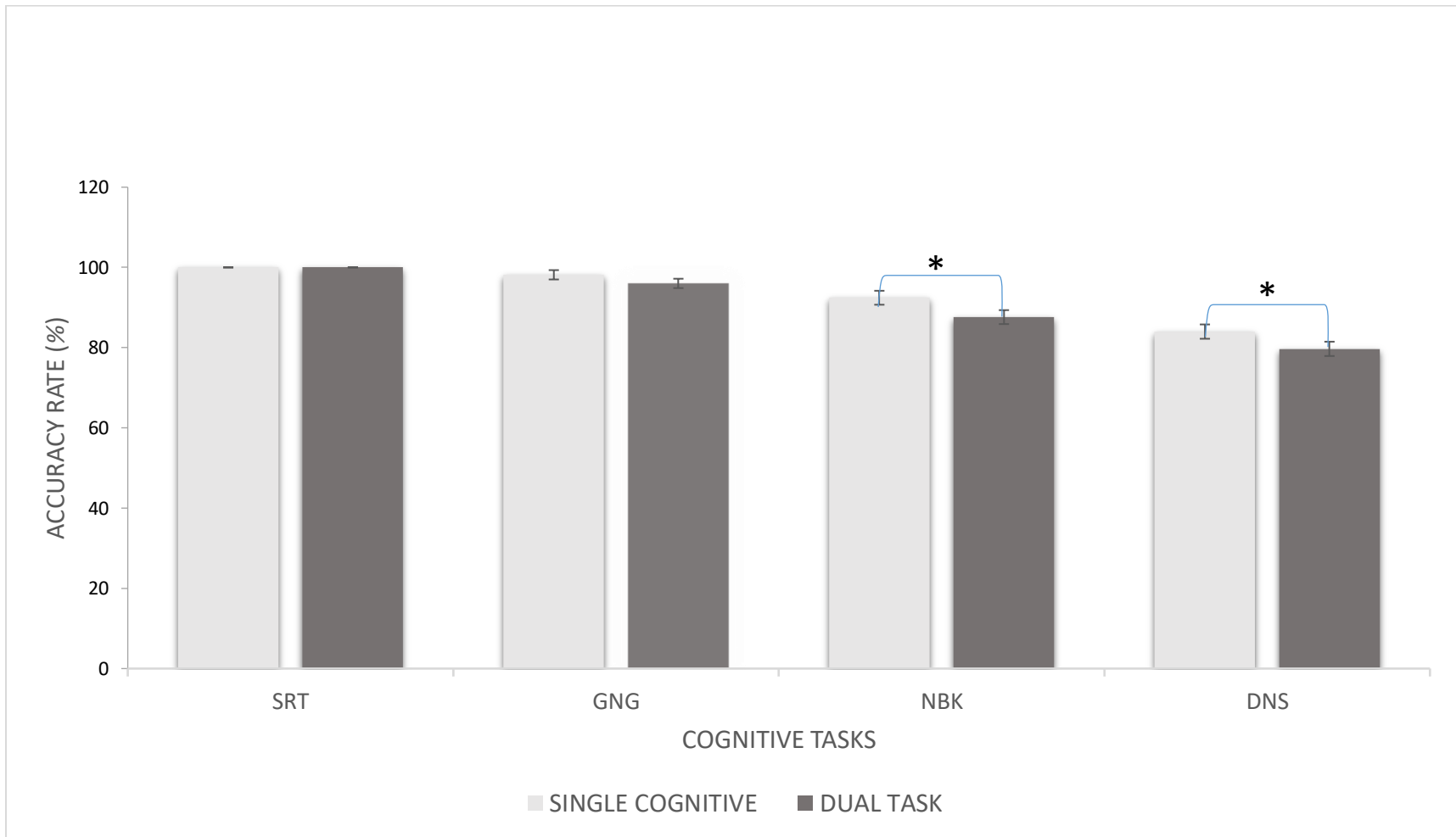
Supplemental Figure 2 (a) Participant with fNIRS. (b) fNIRS optode configuration (c) fNIRS optode configuration mapped onto MRI scan. (d) Fully instrumented participant with fNIRS, headphones and voice recorder.

Note: Abbreviations: Rx1 & Rx2 are detectors; Tx1 through Tx8 are channels.



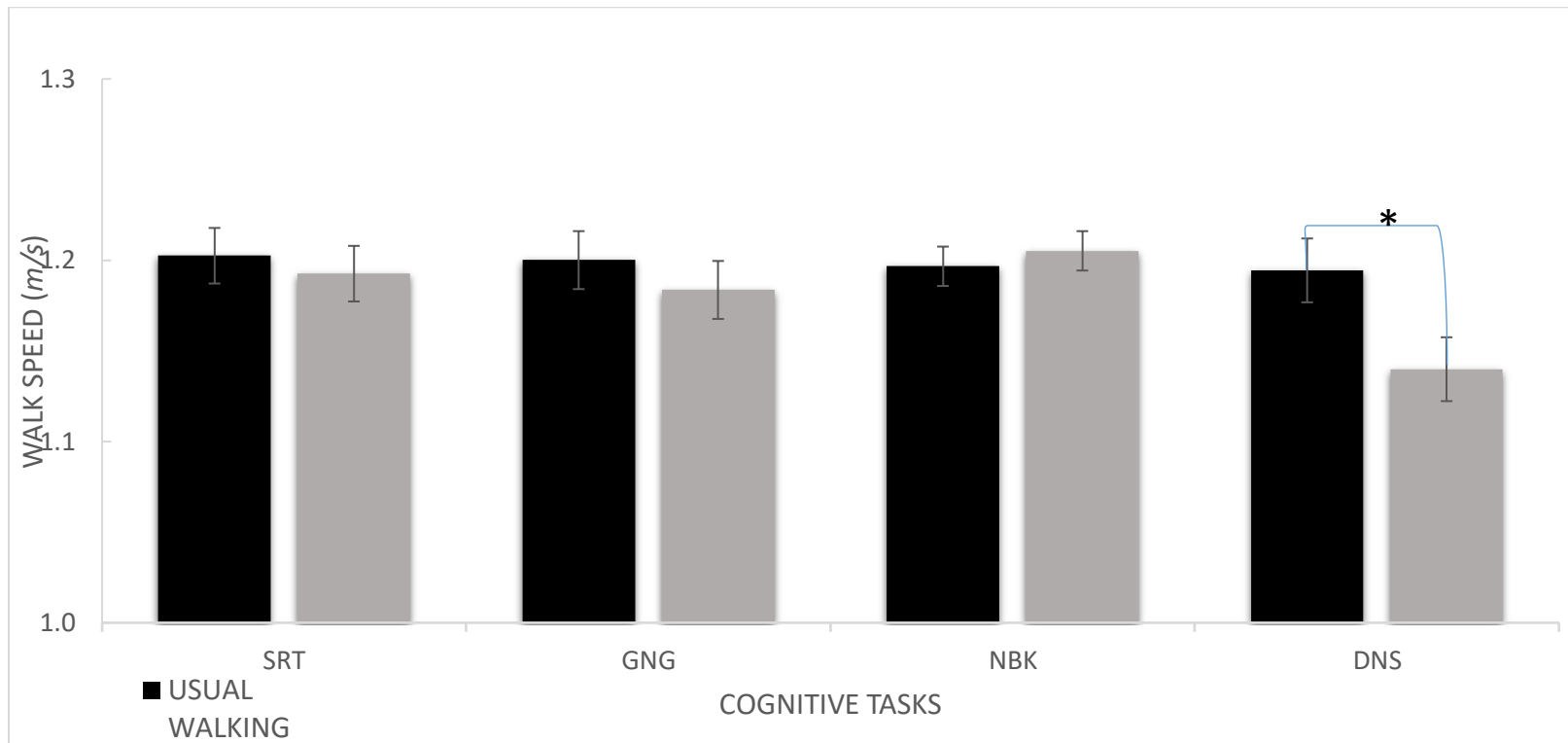
Supplemental Figure 3 *fNIRS optode configuration mapped onto MRI scan.*

Note: MRI demonstrates that all the optodes and receivers on the fNIRS are positioned over the right and left Brodmann area 10(Lacadie, Fulbright, Constable, & Papademetris, 2008) *Abbreviations:* R1 & R2 are detectors; #1 through #8 are channels. * denotes a significant channel difference such that DT HbO₂ is greater than SM HbO₂ ($p = 0.04$)



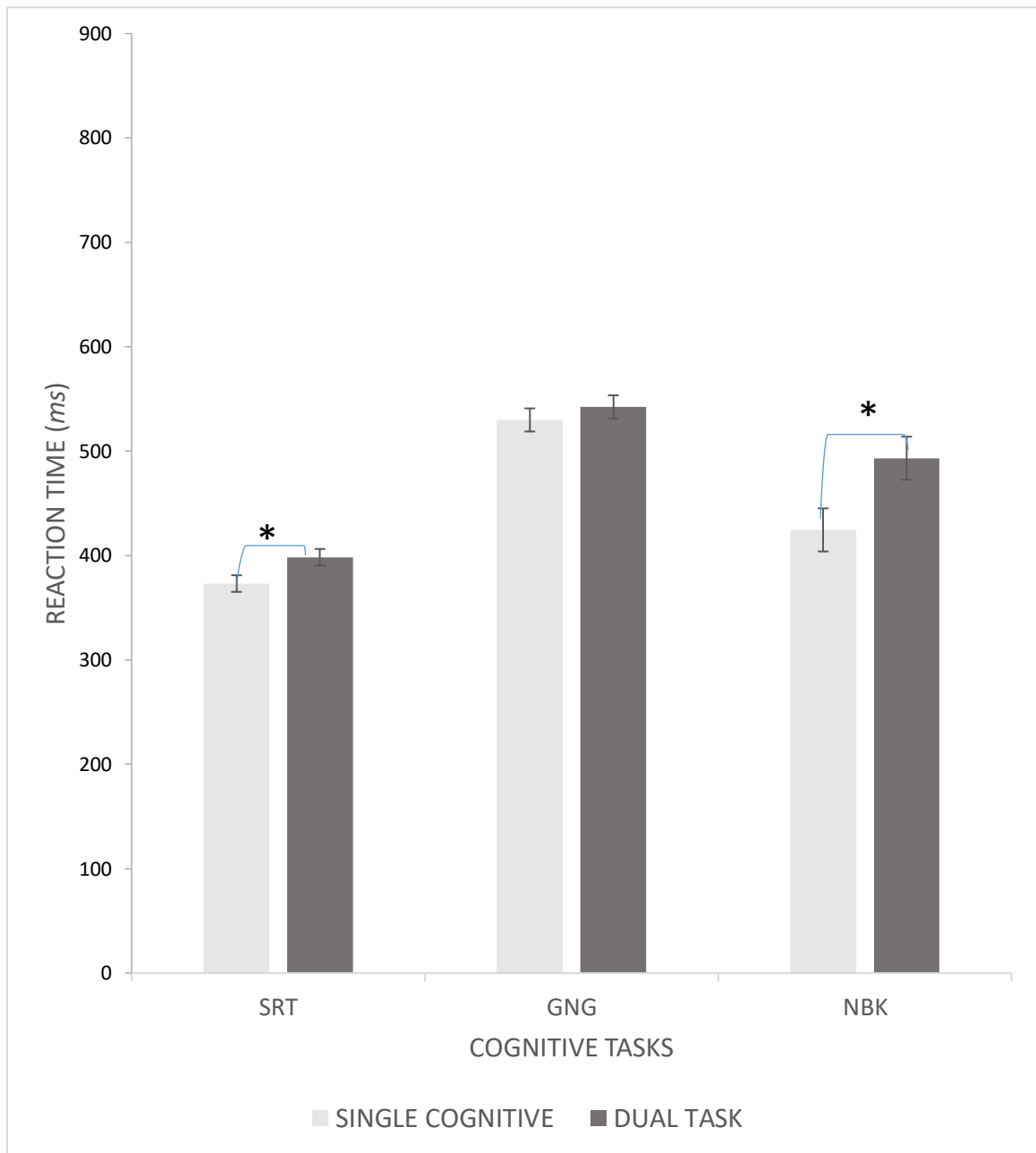
Supplemental Figure 4: *Repeated measures showing mean changes in accuracy rate (\pm SEM) with increasing task and demand.*

Note: $N = 19$; $F(3, 54) = 2.66$, $p = 0.06$, $\eta^2 = 0.13$ * denotes a significant difference



Supplemental Figure 5: Repeated measures showing mean changes in walk speed (\pm SEM) with increasing task and demand.

Note: $N = 19$, $F(3, 54) = 5.3$, $p = 0.003$, $\eta^2 = .227$ * denotes a significant difference



Supplemental Figure 6: Mean changes in response time with increasing task and demand ($\pm SEM$)

Note: $N = 19$, $F(2, 36) = 4.1$, $p = 0.026$, $\eta^2 = .18$ * denotes a significant difference

Chapter 4

MOTOR COGNITIVE PROCESSING IN YOUNG ADULTS

IMPLICATIONS AND CONCLUSIONS

The objective of this thesis was to evaluate whether dual-task walking and continuous cognitive tasks would be associated with greater cerebral activation changes and poorer performance than over-ground walking and discrete tasks in young adults. We hypothesized that continuous cognitive tasks would be associated with the greatest cerebral activation changes (ΔHbO_2) as well as diminished behavioral performance (i.e.: lower accuracy rates and slower walk speed) in comparison to discrete tasks. Similarly, dual-task conditions would be associated with the greatest cerebral activation changes (ΔHbO_2) as well as diminished behavioral performance (i.e.: slower response times, lower accuracy rates and slower walk speed) in comparison with single task performances. Our findings partially supported the hypotheses. The implications of our findings in relation to the hypotheses will be discussed in the following sections.

4.1 Modifications to cognitive-motor performance as a function of dual-task condition

Generally, the findings suggest that there are greater cerebral oxygenation changes as demand increases, demonstrating sensitivity to cognitive manipulation in younger adults during the DNS. The enhanced neural resource recruitment required to perform in demanding dual-task conditions is also referred to as ‘neural upregulation’. As hypothesized, greater cerebral oxygenation changes in the right PFC during DNS DT in comparison with SM along with significantly slower walk speeds indicate shared

processing mechanisms in gait and the DNS, a continuous cognitive task. These findings are in line with previous over ground-walking studies that have found greater HbO₂ during dual-task than single task conditions (Hill et al., 2013, Meester et al., 2014, Holtzer et al. 2011, Mirelman et al. 2014, Fraser et al. 2016), but only for the DNS task. Right hemisphere dominance has also been demonstrated in real locomotion PET imaging studies (la Fougère et al., 2010). Unlike previous studies, our findings were the first to demonstrate behavioral decrements along with neural upregulation in younger adults' dual-task walking. Right hemisphere lateralization is consistent with arithmetic tasks in fNIRS and fMRI studies (Kawashima et al., 2004; Tanida, Sakatani, Takano, & Tagai, 2004). Al-Yahya et al., (2011) claims that cognitive tasks with internal interfering factors like arithmetic tasks are prone to disturbing walk performance more than discrete response time tasks that involve external interfering factors. Also supporting our hypotheses, DNS DT and SC comparison reveal a lower accuracy rate in the DT condition, further supporting the strong influence of demand with the continuous task.

The combination of a decline in gait speed, DT neural correlates and decrease in cognitive behavior indicate mutual cognitive-motor interference (Leone et al., 2017) during DNS. This finding is supported by a review and meta-analysis demonstrating continuous tasks with mental tracking are significantly related to predicting falls in elderly as opposed to dual tasks or discrete tasks such as response time, discrimination and verbal fluency (Chu et al., 2013). The findings also support previous studies demonstrating that mental tracking and arithmetic are interlinked with gait control such that demands altered in this region would be enough to disturb gait (Gazzaley and D'Esposito 2006)

The increased dual-task cost in the DNS DT condition may indicate greater executive control resource competition (Clark, 2015). Since both cognitive and motor behavioral outcomes were associated with dual-tasking, there is no evidence of automatic processing in the DNS DT condition. PFC upregulation also supports the increased executive activity during the DNS DT condition. In line with the capacity theory, the neural compensation model may be utilized to interpret the findings in the present study (Cabeza et al., 2018). This model proposes that greater task demands may necessitate neural upregulation in order to complete the task(s). However, cerebral activation levels do not have to correlate with performance (i.e., there can be an increase in cerebral activity that is not associated with improved performance outcomes). In the present study, younger adults demonstrated significant increase in HbO₂ levels in DNS DT compared with DNS SM, however this increase did not aid performance. This finding highlights the critical role of the PFC in designating neural resources and supporting DT performance in a demanding continuous task. Many studies have demonstrated a lack of correlation between behavioral task performance and cerebral activity (Heuninckx et al., 2008; Holtzer et al., 2015). The lack of association may be a result of individual level differences in how the participants are responding to the increased demands of the task. In other words, some participants may be trying really hard while others may be giving up.

The magnitude of dual-task costs behaviorally, in gait parameters and cognitive tasks, utilized vary in other studies, but similar findings demonstrating an inverse relationship between cognitive demand and gait has been reported before (Agostini et al., 2015; Beurskens & Bock, 2013; Beurskens et al., 2014; Plummer et al., 2015; Schabrun et al.,

2014). Most DT walk studies have reported attenuated speed measures (Beurskens & Bock, 2013; Dommès et al., 2015; Holtzer et al., 2011; Lu et al., 2015, 2015; Meester et al., 2014; Mirelman et al., 2014; Plummer et al., 2015; Schabrun et al., 2014; Srygley et al., 2009; Szturm et al., 2017). Motor performance declines in a dual-task condition may be attributed to diminished resource availability (Hall, Echt, Wolf, & Rogers, 2011; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). DT studies have also reported walk speed measures that were unaltered, indicating that the combined cognitive-motor demand may not have been significant enough to alter gait (De Sanctis, Butler, Malcolm, & Foxe, 2014; Fraser, Dupuy, Pouliot, Lesage, & Bherer, 2016; Lajoie, Teasdale, Bard, & Fleury, 1993; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014)

The finding may be described as a “compensation attempt, but not success” which has been demonstrated in cognitive studies with a demand component without dual-task gait (Bauer, Sammer, & Toepper, 2018; Cabeza et al., 2018; Turner & Spreng, 2012). The increase in neural resources with an accompanying stability in behavioral performance would be described as compensatory. However, neural upregulation in the present study may indicate the use of less effective cognitive strategies. This has been demonstrated before in Causse et al.,(2017) where increased cerebral hemodynamics were associated with greater errors and difficulty in an fNIRS study assessing mental effort in both ecological and laboratory contexts. The relationship between increased cortical activity (HbO₂) associated with the cognitive task requiring higher executive function (EF) is consistent with PFC theories that argue that EF is monitoring attention resources (Koechlin, 2003; Watanabe & Funahashi, 2014; Yogev-Seligmann et al., 2008).

Slowing gait in DT conditions has been demonstrated in the past with a younger adult study manipulating motor demand (Beurskens & Bock, 2012). The findings demonstrated that dual-task costs were greater in visually demanding conditions than fine motor control tasks. When walking in visually demanding conditions, young participants reduced their walk speed and increased cognitive variability in the DT condition. Similar to the costs of motor demand, cognitive demands may also have greater performance costs that cannot be met even with a diffuse increase brain activity.

Cognitive-motor performance degradation can also occur in a fatigued state, leading to greater errors and slower response times. Fatigue may have origins in either or both central and peripheral domains. Central fatigue occurs when the CNS inadequately stimulates the neurons whereas peripheral fatigue is more related to metabolic factors on the surface membrane or excitation-contraction coupling. Since the CNS is very sensitive to oxygenation changes, insufficient oxygen delivery or diffusion as a result of fatigue can be a significant factor in increasing the perception of workload. The mechanism of central fatigue is unknown, but cerebral oxygenation levels may vary during fatigue development (Chuang et al., 2018; Li et al., 2009).

Fatigue studies demonstrate significant correlations between response time decrements and cerebral oxygenation. Even subjective fatigue is inversely correlated with PFC cerebral oxygenation decrements when conducting executive cognitive tasks (Chuang et al., 2018). The brain, much like muscles, may demonstrate insufficient oxygenation if it is not allowed adequate time to recover to normal HbO₂ concentrations during rest or sleep (Chuang et al., 2018). In our study response time decrements have a significant demand effect behaviorally, but they do not correlate with cerebral activity or

a reduced activity pattern. Hence, counterbalancing the blocks may have successfully accounted for potential fatigue effects in our study. In the Li et al. (2009) study, subjects were randomly divided into control and experimental groups before being subjected to prolonged driving conditions to investigate fatigue. Subjects performed a simulated driving task for 3 hours. Experimenters monitored frontal lobe activity with fNIRS and obtained response time measures before and after the driving task. Findings demonstrate significant response time differences in the post-task period as well as significantly lower cerebral oxygenation. This suggests that lower cerebral activity, as opposed to higher, may be closely related to central fatigue development (Li et al., 2009). This finding was further corroborated in a GNG aging study of the PFC with similar cerebral hemodynamic and behavioral findings (Terentjeviene et al., 2018).

Partially supporting our hypothesis, NBK DT conditions demonstrated diminished behavioral performance (i.e.: slower response times and accuracy rates) in comparison to single tasks but were not associated with greater PFC activation changes or walk speed differences. Main task effects were found in SC-DT (response time and accuracy rate) but not in SM-DT (walk speed). In other words, subjects were able to maintain their usual walk speed and cerebral activity during dual-task gait conditions. This suggests that younger adults can manage dual-task walking when paired with discrete cognitive tasks like the SRT-GNG as well as low continuous tasks like the NBK without significantly engaging the PFC. DT studies have reported walk speed measures that were unaltered in the past, indicating that the combined cognitive-motor demand may not have been significant enough to alter gait (De Sanctis, Butler, Malcolm, & Foxe, 2014; Fraser, Dupuy, Pouliot, Lesage, & Bherer, 2016; Lajoie, Teasdale, Bard, & Fleury, 1993;

Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014). This supports the idea that healthy young adults have an adequate capacity to adjust to subtle changes in walking so that the peripheral changes are either minimal or mediated differently.

The cerebral NBK findings did not support our hypothesis, and are distinct from past DT walk studies with younger adults that found significant bilateral PFC activity during this task (Fraser et al., 2016). This is likely due to methodological differences. Our methodology allowed participants to dual task while walking at their own pace in an over-ground walk design. This is distinct from Fraser et al. (2016) that required participants to walk at a fixed pace on a treadmill. As a result, participants in the current study may have been able to manage the dual tasks differently as a result of differential needs or demands for executive function. Participants had the option to change their pace or gait slightly or slow their vocal responses which may account for these differences. Studies have demonstrated in the past that over-ground walking is significantly different from treadmill walking (Lee & Hidler, 2008; Yang & King, 2016).

The insignificant single-dual cerebral findings across SRT-GNG-NBK may also be a result of our acute focus on the prefrontal cortex or because the activation in the DT trials were similar to SC, leading to undetectable PFC differences. While the PFC has been associated with EF and dual-task, there is literature that demonstrates dual-tasking may involve a larger cerebral network beyond the PFC (Collette et al., 2005; Schubert & Szameitat, 2003; Wong et al., 2015). The functional coordination between systems active in the single-task conditions may collaboratively determine DT coordination (Collette et al., 2005). This is supported by the bottleneck interference model that posits the physiological basis of cognitive-motor interference as a byproduct of two cerebral

regions being activated at the same time as a result of two tasks may result in overlapping cerebral activity (Schubert & Szameitat, 2003). YA seem to be able to manage low-medium levels of demands with no significant increase in cerebral oxygenation (SRT, GNG, NBK) and some decrease in behavioral performances. But at some point, even in the YA the demands are too high and although there is an attempt to meet the demands as indicated by the changes in cerebral oxygenation. However, performance decrements suggest that this cerebral changes were not sufficient to aid performance.

Response time differences are associated with variations in neural processing as opposed to motor preparation or response since temporally we would be capturing something that occurs later (Miller and Low, 2001). Very few DT walk studies have investigated and reported on both SC and SM conditions in comparison to DT, with even fewer reporting DT cost (Fraser et al., 2016; Holtzer et al., 2011; Lajoie et al., 1996; Mirelman et al., 2014; Oliveira et al., 2018). Without the SC measure the cognitive interpretations regarding the DT outcomes are very limited. Decrements in response time without cognitive accuracy or walk speed differences support the cascade model of information theory that the sum of cumulative cognitive control contributions result in additive effects on behavioral response times. Findings demonstrate that response times were significantly faster during the SRT than GNG or NBK. Cognitive behavioral measures in DT gait studies mostly indicate high accuracy rates across conditions along with some differences in response time (when this is reported) since the tasks selected were typically of lower demand. Fuster et al. (2008) postulates that less dual-task interference occurs with cognitive tasks involving “external interfering factors” like the SRT. Such tasks activate “stimulus driven” lower order networks involving gait control

with cerebral activation in areas other than the PFC, such as the motor regions (Stuart et al., 2019). Visuo-sensorimotor coordination is required for locomotion, necessitating the integrated work of cerebral regions beyond the PFC (Holtzer et al., 2011). At the same time, the PFC is intertwined with subcortical and parietal cerebral regions (Alexander, DeLong, & Strick, 1986). Therefore, findings with robust task-oriented hemodynamic changes only provide a glimpse of how the PFC may be working with the extended cerebral networks controlling walking (Yogev-Seligmann et al., 2008).

A key factor in distinguishing our findings from past studies was also associated with experimental design differences. We specifically chose to pair walking with a task that would interfere the least with walking. An auditory task which ideally draws minimally on visual and motor systems required for successful gait (Wellner, Schaufelberger, Zitzewitz, & Riener, 2008). For example in the study by Bock (2008) it is not surprising that the DT cognitive and motor behavioral measures were associated with ongoing visual observation tasks as vision is crucial to locomotion. The cognitive tasks utilized in this study did not disrupt online-visual feedback mechanisms integral to adaptive human locomotion (Patla & Greig, 2006). Further although our three of our cognitive tasks required a vocal response, we aimed to minimize the motor requirements of our cognitive task. Some studies impose cognitive tasks that require additional motor regulation such as in the Schabrun et al. (2014) study where participants were walking and typing phrases as they appeared on a smartphone screen. This type of cognitive task that requires a great deal of motor control will likely increase the overlap and interference in the cognitive-motor dual tasks. Although the lack of a vocal component in the DNS minimizes speech and its associated motor requirements, we have cerebral findings in this task. Our findings

further support the study, Mirelman et al., (2014), which also demonstrated that cerebral findings are not driven by vocal responses in a dual-task gait experiment but rather the dual-task demands.

An additional factor unique in our study distinguished from past studies is the utilization of instructional cues. Instructional cues or prioritization have a significant control in mediating attention in dual-task conditions. Explicit instruction for equal prioritization of both motor and cognitive aspects collaboratively increases dual-task demands (Tomprowski & Audiffren, 2014). Age comparison studies demonstrate smaller prioritization effects in OA specifically in the cognitive priority condition than YA (Yogev-Seligmann et al., 2010). This “naturalistic” approach overlooks the subtleties of attention strategies, further complicating our understanding of the DT outcomes that are usually similar to those in cognitive priority condition (Yogev-Seligmann et al. 2010, Laguë-Beauvais et al., 2015). During management of multiple tasks, the prefrontal cortex exhibits different activation patterns indicating differential contributions from specific executive mechanisms (Laguë-Beauvais et al., 2015). DT studies have utilized different baseline measures for the single task condition when it came to walking. Some studies have used a seated control while others have utilized a standing control. Studies have demonstrated that standing is more closely related to walking than sitting. Seated DT studies with discrete tasks did not find prioritization differences in younger adults (Laguë-Beauvais et al. 2015). Without prioritization cues it is difficult to assess whether neural or behavioral differences are presented as a result of more overt attention towards one domain over another. Yet, most DT motor studies do not explicitly specify prioritization (Lajoie, Jehu, Richer, & Chan, 2017; Mirelman et al.,

2014). Studies have demonstrated behavioral differences between prioritization of motor and cognitive tasks in healthy older adults (Verghese et al., 2007). Younger adults also show gait differences when prioritization is unspecified or held equal (Plummer, Apple, Dowd, & Keith, 2015).

The present dual-task walk protocol consisted of participants turning, as opposed to other studies which only consisted of participants walking on a straight path. Whether the demands of turn walking are unique from usual walking is investigated in some DT studies. The Faulkner et al. (2006) study investigates some walking factors and how they may be associated with poor dual-task performance. Older adults participated in three conditions: seated, walk 20 *m*, turn walk 10 *m* while conducting three cognitive tests: no reaction time, push button reaction time and visual spatial decision reaction time. Here the push button reaction time test pertained to pushing a button as quickly as possible in response to an auditory beep at 1000 *Hz*, delivered randomly. The visual spatial decision task was asked to visualize the time after being told the time of the day and say out loud "same" or "different" after determining whether the hands of the clock were situation on the same side or different sides of the face. Experimenters calculated the reaction time and the walking time separately for the experimental condition of the two trials. Poor dual-task walking reaction times correlated with slower walk speed and muscle strength. The findings suggest that walking may require significantly more cognitive resources in older adults. Furthermore, there was no significant reaction time or visual spatial reaction time difference between straight and turn walks. At the same time, during the turn walk, walk time was faster during the push button task than the visual spatial task in comparison to usual walking condition. Reaction times varied during turn walking with

respect to whether subjects did the seated trial first. Taken together, these findings suggest that turn walking may be similar to usual walking at least for behavioral outcomes (England, Verghese, Mahoney, Trantzas, & Holtzer, 2015; Faulkner et al., 2006). It is unknown how including turns in the protocol affected the cerebral oxygenation of our participants, but since their gait speed was similar between single and dual task, participants would have had a similar number of turns in the 10m distance during a 33 *second* block. So it is unlikely that the turns have influenced our SM- DT comparisons. Future studies should test if cerebral oxygenation in the PFC changes during turns in comparison to walking, as it is likely that motor areas are more active during turns than straight walking.

The significant interaction between cognitive tasks, hemisphere and demand reveal right HbO₂ lateralization during the NBK SC condition. This neural correlate corresponds with the right mid-ventrolateral prefrontal cortex, a region that has been previously associated with a fractionation of working memory processes in PET studies (A. M. Owen et al., 1999). This finding is also in line with Fraser et al. (2016) in which t-tests comparing hemispheric differences revealed greater HbO₂ changes in the right than the left regions of interest in younger adults conducting the NBK. Although this difference is not present cerebrally in a single-dual comparison the behavioral differences cognitively in accuracy and response time suggest that YA may have strategized. YA may have maintained their walk speed in lower demand conditions while altering their walk speed in greater demands (DNS), thereby reducing our ability to detect cerebral oxygenation changes.

Neural upregulation in DNS is not associated with performance stability like most previous studies with continuous tasks in younger adults. This unique finding may be a result of the nature of the DNS, a continuous task with arithmetic requiring many more processing steps than the NBK. The capacity overload in younger adults during DT DNS may have been a result of the greater demand, but the diffuse PFC activation was not efficient in meeting the demands. This study demonstrates that even younger adults may fail to meet demands of a continuous dual-task condition even with neural upregulation.

4.2 Modifications to cognitive-motor performance as a function of increasing cognitive demand

The divergent nature of discrete and continuous cognitive tasks is utilized to examine which processes may interfere with gait perhaps as a result of competition for the same neural resources. The findings partially supported our hypothesis demonstrating significant demand effects in slower walk speed (SRT;GNG;NBK>DNS), lower accuracy rates (SRT>GNG>NBK>DNS*), and longer response time (SRT< GNG< NBK*); but, the DNS & NBK findings were not associated with greater cerebral activation changes than GNG & SRT. The findings are further qualified by main task effects in SC-DT (accuracy rates and response time).

The behavioral findings support earlier reports of DT walking assessments reporting faster usual walk speeds across low demand continuous and discrete tasks despite insignificant single-dual main task effects (Mirelman et al. 2014; Holtzer et al. 2011). Discrete cognitive tasks utilized in the present study tax processing centers such as speed of processing and inhibition while continuous tasks engage sustained attention centers such as working memory. Therefore, the collaborative findings from these studies

suggest that continuous cognitive tasks are more closely related to real locomotion in terms of dual task interference.

The temporal findings in response time measures indicated that the GNG and NBK were significantly more demanding than the SRT. Our findings are unique from Mirelman et al. (2014) and the Holtzer et al. (2011) DT walk studies, the latter did not account for accuracy differences in the continuous tasks while the former was not associated with accuracy rate differences. Differences in SC-DT accuracy rates across the DNS-GNG-SRT tasks align with Lajoie et al. (2017). Since the DNS only required one response at the end of the task, response time measures were not taken into consideration for this task.

Similar to information processing, discrete and continuous properties of tasks operate on a graded continuum so that some tasks can be considered more or less continuous, or discrete than others (J. Miller, 1988). When comparing the NBK and the DNS cognitive tasks, the DNS encapsulates more continuous properties than the NBK. The NBK, unlike the DNS, requires the participant to hold onto information in the working memory for about 7 seconds while they respond to every number, similar to probe stimuli in discrete tasks. At the same time, the NBK only requires the participant to hold onto 2 digits their memory at a time. The average memory span can hold up to seven numbers at a time (G. A. Miller, 1956). DNS requires the participant to continuously perform mental arithmetic for 33 seconds. During the DNS, the participant must mentally perform arithmetic with four numbers, updating every two seconds, while tracking two more numbers so that they are actually holding a maximum of six numbers at a time in their memory span. The demands of the DNS may involve greater use of the visuospatial

sketchpad than the NBK, resulting in greater motor-cognitive interference in walking since it would fall under similar domains (Simmons, Singleton, & Horne, 2008; Woollacott & Shumway-Cook, 2002). Therefore, the NBK may be considered a less continuous cognitive task than the DNS, attributing to its similar single-dual task findings in cerebral hemodynamics, walk speed and accuracy.

As the capacity-sharing theory suggests, attempting to simultaneously perform two tasks may cause performance to suffer due to limits in information processing. Based on the results in our study, it seems that in young adults, the limit of attention capacity falls between the NBK and DNS task. The precipice delineating attention capacity to manage continuous demand loads is between our low and high continuous task similar to Srygley et al. (2009). In the Srygley et al. (2009) study, young adults performed better in the serial 3 subtraction task, a low continuous task, than the serial 7 subtraction task, a higher continuous task. This finding lends further support to the fact that gait is attention-demanding during continuous tasks even for younger adults as was similarly demonstrated in Mirelman et al. (2014), it remains to be investigated whether the statistically significant gait decrements are clinically significant. Clinically significant gait decrements would be consistent with the “posture first” hypothesis (Bloem, Grimbergen, Cramer, Willemsen, & Zwinderman, 2001; Hausdorff et al., 2005).

The present thesis strengthens the evidence from studies investigating the connection between gait and cognition during walking by highlighting the sensitivity of dual-task performance to discrete and continuous cognitive tasks even in young adults. The temporal timing and steps required to perform a cognitive task determines the discrete or continuous nature of the task. The study in this thesis strengthens the

connection between gait and demanding continuous cognitive tasks, adding a novel dual-task component to the literature. This thesis unravels the task limitations in younger adults that are often overlooked even though it contributes to pedestrian fatalities, fall risk, aviation emergencies, interface designs, air traffic control and much more (Causse et al., 2017; Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016; Mwakalonge, Siuhi, & White, 2015). Although young adults and children are the primary victims of fatalities in accidents that make up more than half of all traffic deaths, little research has been conducted on distracted walking. Studies have demonstrated that distracted walking effects are similar to distracted driving (J. Nasar, Hecht, & Wener, 2008; J. L. Nasar & Troyer, 2013; Sarkar, Tay, & Hunt, 2011). Therefore, inadequate awareness of human limitations in pedestrians may also have a critical role in the fatalities and debilitating injuries from traffic accidents. Even younger adults, with generally intact prefrontal cortices, have dual-task limitations that they may not be overtly aware of.

It remains to be determined how demanding discrete and continuous tasks may impact older adult performance. Will older adults demonstrate similar behavioral performance, but earlier neural upregulation as suggested in Cabeza et al. (2018)? Or will older adults demonstrate differences in difficult discrete tasks as well, such as the GNG, in which inhibition plays a central role? This thesis could inform the investigation of discrete and continuous tasks older adults. It could also be used to develop cognitive training strategies with continuous tasks that are naturally in tune with daily life. This may also be utilized to address the increasing risk of pedestrian fatalities in younger adults with the new age of technology. Future studies should utilize a similar

experimental design to assess healthy older adults and individuals with developmental or neurodegenerative disorders to assess cognitive differences.

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APPENDIX

APPENDIX A – FNIRS ASSUMPTIONS

1. The chromophore concentrations are time-dependent.
2. The optical path length is not straight, but it is equal to the distance between the source and the detector in a banana-shape. This shape is corrected with the Differential Pathlength Factor (DPF) (Gramann, Fairclough, Zander, & Ayaz, 2017).
3. The DPF can be held constant at some wavelengths since the change in photon scattering is small in comparison to the absorption (Obrig & Villringer, 2003).
4. The medium is homogenous. NOTE: Since the brain is actually non-homogenous we see the partial volume effect, describing the resulting concentration changes as an underestimation. This also leads to cross talk and separability between chromophores such that the attenuation of HbO₂ would affect HbR, particularly, its magnitude and the time-course. The low spatial resolution of fNIRS is a result of this systematic error. However, studies have derived the optimal wavelength to analyze the chromophores so that the errors are minimized (Uludağ, Steinbrink, Villringer, & Obrig, 2004).
5. The sampling volume is homogenous with the change in chromophore concentration. NOTE: The signal stems from a sampling volume consisting of not only the cortex but also the scalp and skull.

APPENDIX B – HEALTH PHONE SCREENING

1. In the last year have you participated in a cognitive study? (If yes, at least 6 months should have passed between the ending of the previous study and this study)
2. What is your mother tongue?
3. What is your age?
4. What is your date of birth?
5. What is your highest level of education? (Degree and number of years)
6. Are you right or left handed? Right handed ___ Left Handed ___
7. In the last 6 months did you have surgery (or another medical intervention) that required general anesthesia? (If yes, write the date of the anesthesia and we will see them after the delay)
8. Do you have vision or hearing problems that have not been corrected or an abnormal loss for your age?
9. Have you ever had frequent or requiring migraines?
10. Have you ever had neurological or psychiatric problems? If so which ones?
11. Have you ever had a head injury? When?
12. Have you ever lost consciousness?
13. Have you had tremors or involuntary movements?
14. Have you ever had motor problems (walking or manipulating objects) (If severe, exclusion)?
15. Have you ever had dizziness or problems with maintaining your balance (If yes, ask more questions: of what nature, when, frequency, etc.)?
16. Have you ever had and injury to your lower extremities (hip, knee, ankle)?

17. Do you have a cardiovascular condition?
18. Do you have high blood pressure?
19. Do you have diabetes?
20. Do you have arthritis?
21. Do you have epilepsy?
22. Do you have a thyroid condition?
23. Have you ever fallen while walking?
24. What is your weekly consumption of alcohol?
25. Have you ever had alcohol or drug abuse problems?
26. Do you smoke?
27. Do you have problems with concentration or attention?
28. Do you have problems with your memory?
29. Do you have problems finding your words while talking?
30. Have the people close to you noticed a significant difference in these three areas:
attention, memory, trouble finding words?
31. Are you physically active regularly (more than 2 times per week) besides activities of
daily living? What are these activities?
32. Do you take medication? If yes, do these medications make you feel drowsy or effect
your mental state? (List the medications, name and dosage, that are taken regularly)

APPENDIX C – MOCA

MONTREAL COGNITIVE ASSESSMENT (MOCA)

Administration and Scoring Instructions

The Montreal Cognitive Assessment (MoCA) was designed as a rapid screening instrument for mild cognitive dysfunction. It assesses different cognitive domains: attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. Time to administer the MoCA is approximately 10 minutes. The total possible score is 30 points; a score of 26 or above is considered normal.

1. Alternating trail making:

Administration: The examiner instructs the subject: *"Please draw a line, going from a number to a letter in ascending order. Begin here [point to (1)] and draw a line from 1 then to A then to 2 and so on. End here [point to (E)]."*

Scoring: Allocate one point if the subject successfully draws the following pattern: 1 –A- 2- B- 3- C- 4- D- 5- E, without drawing any lines that cross. Any error that is not immediately self-corrected earns a score of 0.

2. Visuoconstructional skills (Cube):

Administration: The examiner gives the following instructions, pointing to the **cube**:

"Copy this drawing as accurately as you can, in the space below".

Scoring: One point is allocated for a correctly executed drawing.

- Drawing must be three-dimensional
- All lines are drawn
- No line is added

- Lines are relatively parallel and their length is similar (rectangular prisms are accepted)

A point is not assigned if any of the above-criteria are not met.

3. Visuoconstructional skills (Clock):

Administration: Indicate the right third of the space and give the following instructions:

*“Draw a **clock**. Put in all the numbers and set the time to 10 past 11”.*

Scoring: One point is allocated for each of the following three criteria:

- Contour (1 pt.): the clock face must be a circle with only minor distortion acceptable (e.g., slight imperfection on closing the circle);
- Numbers (1 pt.): all clock numbers must be present with no additional numbers; numbers must be in the correct order and placed in the approximate quadrants on the clock face; Roman numerals are acceptable; numbers can be placed outside the circle contour;
- Hands (1 pt.): there must be two hands jointly indicating the correct time; the hour hand must be clearly shorter than the minute hand; hands must be centered within the clock face with their junction close to the clock center.

A point is not assigned for a given element if any of the above-criteria are not met.

4. Naming:

Administration: Beginning on the left, point to each figure and say: *“Tell me the name of this animal”.*

Scoring: One point each is given for the following responses: (1) lion (2) rhinoceros or rhino (3) camel or dromedary.

5. Memory:

Administration: The examiner reads a list of 5 words at a rate of one per second, giving the following instructions: *“This is a memory test. I am going to read a list of words that you will have to remember now and later on. Listen carefully. When I am through, tell me as many words as you can remember. It doesn’t matter in what order you say them”*.

Mark a check in the allocated space for each word the subject produces on this first trial.

When the subject indicates that (s)he has finished (has recalled all words), or can recall no more words, read the list a second time with the following instructions: *“I am going to read the same list for a second time. Try to remember and tell me as many words as you can, including words you said the first time.”* Put a check in the allocated space for each word the subject recalls after the second trial. At the end of the second trial, inform the subject that (s)he will be asked to recall these words again by saying, *“I will ask you to recall those words again at the end of the test.”*

Scoring: No points are given for Trials One and Two.

6. Attention:

Forward Digit Span: Administration: Give the following instruction: *“I am going to say some numbers and when I am through, repeat them to me exactly as I said them”*. Read the five number sequence at a rate of one digit per second.

Backward Digit Span: Administration: Give the following instruction: *“Now I am going to say some more numbers, but when I am through you must repeat them to me in the backwards order.”* Read the three number sequence at a rate of one digit per second.

Scoring: Allocate one point for each sequence correctly repeated, (*N.B.*: the correct response for the backwards trial is 2-4-7).

Vigilance: Administration: The examiner reads the list of letters at a rate of one per second, after giving the following instruction: *“I am going to read a sequence of letters. Every time I say the letter A, tap your hand once. If I say a different letter, do not tap your hand”*.

Scoring: Give one point if there is zero to one errors (an error is a tap on a wrong letter or a failure to tap on letter A).

Serial 7s: Administration: The examiner gives the following instruction: *“Now, I will ask you to count by subtracting seven from 100, and then, keep subtracting seven from your answer until I tell you to stop.”* Give this instruction twice if necessary.

Scoring: This item is scored out of 3 points. Give no (0) points for no correct subtractions, 1 point for one correction subtraction, 2 points for two-to-three correct subtractions, and 3 points if the participant successfully makes four or five correct subtractions. Count each correct subtraction of 7 beginning at 100. Each subtraction is evaluated independently; that is, if the participant responds with an incorrect number but continues to correctly subtract 7 from it, give a point for each correct subtraction. For example, a participant may respond “92 – 85 – 78 – 71 – 64” where the “92” is incorrect, but all subsequent numbers are subtracted correctly. This is one error and the item would be given a score of 3.

7. Sentence repetition:

Administration: The examiner gives the following instructions: *“I am going to read you a sentence. Repeat it after me, exactly as I say it [pause]: **I only know that John is the one to help today.**”* Following the response, say: *“Now I am going to read you another*

sentence. Repeat it after me, exactly as I say it [pause]: ***The cat always hid under the couch when dogs were in the room.***”

Scoring: Allocate 1 point for each sentence correctly repeated. Repetition must be exact.

Be alert for errors that are omissions (e.g., omitting "only", "always") and substitutions/additions (e.g., "John is the one who helped today;" substituting "hides" for "hid", altering plurals, etc.).

8. Verbal fluency:

Administration: The examiner gives the following instruction: *“Tell me as many words as you can think of that begin with a certain letter of the alphabet that I will tell you in a moment. You can say any kind of word you want, except for proper nouns (like Bob or Boston), numbers, or words that begin with the same sound but have a different suffix, for example, love, lover, loving. I will tell you to stop after one minute. Are you ready?”*

[Pause] *Now, tell me as many words as you can think of that begin with the letter F.* [time for 60 sec]. *Stop.*”

Scoring: Allocate one point if the subject generates 11 words or more in 60 sec. Record the subject’s response in the bottom or side margins.

9. Abstraction:

Administration: The examiner asks the subject to explain what each pair of words has in common, starting with the example: *“Tell me how an orange and a banana are alike”*. If the subject answers in a concrete manner, then say only one additional time: *“Tell me another way in which those items are alike”*. If the subject does not give the appropriate response (*fruit*), say, *“Yes, and they are also both fruit.”* Do not give any additional instructions or clarification. After the practice trial, say: *“Now, tell me how a train and a*

bicycle are alike". Following the response, administer the second trial, saying: "*Now tell me how a ruler and a watch are alike*". Do not give any additional instructions or prompts.

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Scoring: Only the last two item pairs are scored. Give 1 point to each item pair correctly answered. The following responses are acceptable: Train-bicycle = means of transportation, means of travelling, you take trips in both;

Ruler-watch = measuring instruments, used to measure. The following responses are **not** acceptable: Train-bicycle = they have wheels; Ruler- watch = they have numbers.

10. Delayed recall:

Administration: The examiner gives the following instruction: "*I read some words to you earlier, which I asked you to remember. Tell me as many of those words as you can remember.*" Make a check mark (✓) for each of the words correctly recalled spontaneously without any cues, in the allocated space.

Scoring: **Allocate 1 point for each word recalled freely without any cues.**

Optional: Following the delayed free recall trial, prompt the subject with the semantic category cue provided below for any word not recalled. Make a check mark (✓) in the allocated space if the subject remembered the word with the help of a category or multiple-choice cue. Prompt all non-recalled words in this manner. If the subject does not recall the word after the category cue, give him/her a multiple choice trial, using the following example instruction, "*Which of the following words do you think it was, NOSE, FACE, or HAND?*" Use the following category and/or multiple-choice cues for each word, when appropriate:

FACE: category cue: part of the body multiple choice: nose, face, hand VELVET:
category cue: type of fabric multiple choice: denim, cotton, velvet CHURCH: category
cue: type of building multiple choice: church, school, hospital DAISY: category cue: type
of flower multiple choice: rose, daisy, tulip RED: category cue: a color multiple choice:
red, blue, and green

Scoring: **No points are allocated for words recalled with a cue.** A cue is used for
clinical information purposes only and can give the test interpreter additional information
about the type of memory disorder. For memory deficits due to retrieval failures,
performance can be improved with a cue. For memory deficits due to encoding failures,
performance does not improve with a cue.

11. Orientation:

Administration: The examiner gives the following instructions: "Tell me the date today".
If the subject does not give a complete answer, then prompt accordingly by saying: "*Tell
me the [year, month, exact date, and day of the week].*" Then say: "*Now, tell me the
name of this place, and which city it is in.*"

Scoring: Give one point for each item correctly answered. The subject must tell the exact
date and the exact place (name of hospital, clinic, office). No points are allocated if
subject makes an error of one day for the day and date.

TOTAL SCORE: Sum all sub scores listed on the right-hand side. Add one point for an
individual who has 12 years or fewer of formal education, for a possible maximum of 30
points. A final total score of 26 and above is considered normal.

APPENDIX D – SPPB

SHORT PHYSICAL PERFORMANCE BATTERY

1. Repeated Chair Stands

Instructions: Do you think it is safe for you to try and stand up from a chair five times without using your arms? Please stand up straight as quickly as you can five times, without stopping in between. After standing up each time, sit down and then stand up again. Keep your arms folded across your chest. Please watch while I demonstrate. I'll be timing you with a stopwatch. Are you ready? Begin Grading: Begin stop watch when subject begins to stand up. Count aloud each time subject arises. Stop the stopwatch when subject has straightened up completely for the fifth time.

Also stop if the subject uses arms, or after 1 minute, if subject has not completed rises, and if concerned about the subject's safety.. Record the number of seconds and the presence of imbalance. Then complete ordinal scoring.

Time: _____sec (if five stands are completed)

Number of Stands Completed: 1 2 3 4 5

Chair Stand Ordinal Score: _____

0 = unable

1 = > 16.7 sec

2 = 16.6-13.7 sec

3 = 13.6-11.2 sec

4 = < 11.1 sec

2. Balance Testing

Begin with a semi-tandem stand (heel of one foot placed by the big toe of the other foot).

Individuals unable to hold this position should try the side-by-side position. Those able to stand in the semi-tandem position should be tested in the full tandem position. Once you have completed time measures, complete ordinal scoring.

a. Semi-tandem Stand

Instructions: Now I want you to try to stand with the side of the heel of one foot touching the big toe of the other foot for about 10 seconds. You may put either foot in front, whichever is more comfortable for you. Please watch while I demonstrate.

Grading: Stand next to the participant to help him or her into semi-tandem position.

Allow participant to hold onto your arms to get balance. Begin timing when participant has the feet in position and lets go.

Circle one number

2. Held for 10 sec

1. Held for less than 10 sec; number of seconds held _____

0. Not attempted

b. Side-by-Side stand

Instructions: I want you to try to stand with your feet together, side by side, for about 10 sec. Please watch while I demonstrate. You may use your arms, bend your knees, or move your body to maintain your balance, but try not to move your feet. Try to hold this position until I tell you to stop.

Grading: Stand next to the participant to help him or her into the side-by-side position.

Allow participant to hold onto your arms to get balance. Begin timing when participant has feet together and lets go.

Grading

2. Held of 10 sec

1. Held for less than 10 sec; number of seconds held_____

0. Not attempted

c. Tandem Stand

Instructions: Now I want you to try to stand with the heel of one foot in front of and touching the toes of the other foot for 10 sec. You may put either foot in front, whichever is more comfortable for you. Please watch while I demonstrate.

Grading: Stand next to the participant to help him or her into the side-by-side position.

Allow participant to hold onto your arms to get balance. Begin timing when participant has feet together and lets go.

Grading

2. Held of 10 sec

1. Held for less than 10 sec; number of seconds held_____

0. Not attempted

Balance Ordinal Score: _____

0 = side by side 0-9 sec or unable

1 = side by side 10, <10 sec semitandem

2 = semitandem 10 sec, tandem 0-2 sec

3 = semitandem 10 sec, tandem 3-9 sec

4 = tandem 10 sec

3. 8' Walk (2.44 meters)

Instructions: This is our walking course. If you use a cane or other walking aid when walking outside your home, please use it for this test. I want you to walk at your usual pace to the other end of this course (a distance of 8'). Walk all the way past the other end of the tape before you stop. I will walk with you. Are you ready?

Grading: Press the start button to start the stopwatch as the participant begins walking.

Measure the time take to walk 8'. Then complete ordinal scoring.

Time: _____ sec

Gait Ordinal Score: _____

0 = could not do

1 = >5.7 sec (<0.43 m/sec)

2 = 4.1-6.5 sec (0.44-0.60 m/sec)

3 = 3.2-4.0 (0.61-0.77 m/sec)

4 = <3.1 sec (>0.78 m/sec)

Summary Ordinal Score: _____

Range: 0 (worst performance) to 12 (best performance). Shown to have predictive validity showing a gradient of risk for mortality, nursing home admission, and disability.

APPENDIX E – DEPRESSION SCALE

Beck's Depression Inventory

This depression inventory can be self-scored. The scoring scale is at the end of the questionnaire.

1.
 - 0 I do not feel sad.
 - 1 I feel sad
 - 2 I am sad all the time and I can't snap out of it.
 - 3 I am so sad and unhappy that I can't stand it.
2.
 - 0 I am not particularly discouraged about the future.
 - 1 I feel discouraged about the future.
 - 2 I feel I have nothing to look forward to.
 - 3 I feel the future is hopeless and that things cannot improve.
3.
 - 0 I do not feel like a failure.
 - 1 I feel I have failed more than the average person.
 - 2 As I look back on my life, all I can see is a lot of failures.
 - 3 I feel I am a complete failure as a person.
4.
 - 0 I get as much satisfaction out of things as I used to.
 - 1 I don't enjoy things the way I used to.
 - 2 I don't get real satisfaction out of anything anymore.
 - 3 I am dissatisfied or bored with everything.
5.
 - 0 I don't feel particularly guilty
 - 1 I feel guilty a good part of the time.
 - 2 I feel quite guilty most of the time.
 - 3 I feel guilty all of the time.
6.
 - 0 I don't feel I am being punished.
 - 1 I feel I may be punished.
 - 2 I expect to be punished.
 - 3 I feel I am being punished.
7.
 - 0 I don't feel disappointed in myself.
 - 1 I am disappointed in myself.
 - 2 I am disgusted with myself.
 - 3 I hate myself.
8.
 - 0 I don't feel I am any worse than anybody else.
 - 1 I am critical of myself for my weaknesses or mistakes.
 - 2 I blame myself all the time for my faults.
 - 3 I blame myself for everything bad that happens.
9.
 - 0 I don't have any thoughts of killing myself.
 - 1 I have thoughts of killing myself, but I would not carry them out.
 - 2 I would like to kill myself.
 - 3 I would kill myself if I had the chance.
10.
 - 0 I don't cry any more than usual.
 - 1 I cry more now than I used to.
 - 2 I cry all the time now.
 - 3 I used to be able to cry, but now I can't cry even though I want to.

APPENDIX F – FALLS EFFICACY SCALE

SUPPLEMENTARY DATA

Translators'/Interviewers' notes for FES-I

The text of the FES-I below is the final version agreed by the authors on completion of the development study, prior to subsequent translation and validation in different languages. It became clear during the process of translation that there was no wording of the questionnaire that would translate easily into every EC language using exactly the same words and phrases. Consequently, these notes are intended to assist translators of the FES-I to express the same meaning of items, even if they cannot use quite the same words in their language. They may also assist interviewers who are asked for clarification of the meaning of items when the FES-I is administered by interview.

Instructions

Participants should answer items thinking about how they usually do the activity – for example, if they usually walk with an aid they should answer items about walking to show how concerned they would be about falling when using that aid. Some translators may find it helpful to clarify in the instructions (after the sentence on circling an opinion). 'The opinions you can choose from are: 1 = not at all concerned 2 = somewhat concerned 3 = fairly concerned 4 = very concerned.' In some languages it is better to translate the word 'opinion' as 'statement'.

Response categories

The word 'concerned' expresses a cognitive or rational disquiet about the possibility of falling, but does not express the emotional distress that would be expressed by terms such as 'worried', 'anxious' or 'fearful'. It is important to use a similar unemotional term, as

respondents may be less willing to admit to emotions, which might be viewed as signs of weakness.

Item 3. In some EC languages ‘simple’ meals are best translated as ‘everyday’ meals, but the intention is to refer to a meal that does not require complex preparation, rather than one that is prepared every day.

Item 5. This item is intended to refer to shopping that is not extensive or recreational. In some languages the best translation is ‘shopping for groceries’.

Item 7. This item refers to *any* stairs, not necessarily the flight of stairs in one’s own house.

Item 8. In some languages ‘neighborhood’ may be difficult to translate, and so ‘walking around outside’ can be used instead.

Item 12. In some languages it is necessary to add the term ‘acquaintances’ to friends and relatives, since this is a more common and casual category of relationship than friends.

(see also comment on items 12, 13 and 16 below)

Item 13. ‘Crowds’ can be translated as ‘many people’ if necessary. (see also comment on items 12,13 and 16 below)

Item 14. It was found to be necessary to give examples of what is meant by uneven ground, but no examples could be found that were appropriate for all countries.

Consequently, translators should choose any TWO examples from the following:

cobblestones; poorly maintained pavement; rocky ground; unpaved surface.

Items 12, 13, 16. These items contain a greater element of ambiguity than many of the items assessing functional capabilities, because the physical activities involved in these social events may differ greatly for different respondents. However, it was decided that

this ambiguity was acceptable because it is important to assess effects of fear of falling on social activities.

Now we would like to ask some questions about how concerned you are about the possibility of falling. For each of the following activities, please circle the opinion closest to your own to show how concerned you are that you might fall if you did this activity. Please reply thinking about how you usually do the activity. If you currently don't do the activity (e.g. if someone does your shopping for you), please answer to show whether you think you would be concerned about falling IF you did the activity.

		<i>Not at all concerned</i> 1	<i>Somewhat concerned</i> 2	<i>Fairly concerned</i> 3	<i>Very concerned</i> 4
1	Cleaning the house (e.g. sweep, vacuum or dust)	1	2	3	4
2	Getting dressed or undressed	1	2	3	4
3	Preparing simple meals	1	2	3	4
4	Taking a bath or shower	1	2	3	4
5	Going to the shop	1	2	3	4
6	Getting in or out of a chair	1	2	3	4
7	Going up or down stairs	1	2	3	4
8	Walking around in the neighbourhood	1	2	3	4
9	Reaching for something above your head or on the ground	1	2	3	4
10	Going to answer the telephone before it stops ringing	1	2	3	4
11	Walking on a slippery surface (e.g. wet or icy)	1	2	3	4
12	Visiting a friend or relative	1	2	3	4
13	Walking in a place with crowds	1	2	3	4
14	Walking on an uneven surface (e.g. rocky ground, poorly maintained pavement)	1	2	3	4
15	Walking up or down a slope	1	2	3	4
16	Going out to a social event (e.g. religious service, family gathering or club meeting)	1	2	3	4