The influence of cognitive resources on compensatory arm responses

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Abstract

The purpose of this study was to determine the influence of an ongoing cognitive task on an individual's ability to generate a compensatory arm response. Twenty young and 16 older adults recovered their balance from a support surface translation while completing a cognitive (counting) task of varying difficulty. Surface electromyographic (EMG) recordings from the shoulders and kinematics of the right arm were collected to quantify the compensatory arm response. Results indicated that the counting task, regardless of its difficulty as well as the age of the individual, had minimal influence on the onset or magnitude of arm muscle activity that occurred following a loss of balance. In contrast to previous research, this study's findings suggest that the cortical or cognitive resources utilized by the cognitive task are not relied upon for the generation of compensatory arm responses and that older adults are not disproportionately affected by dual-tasking than young adults.

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Table of Contents

List of Tables

List of Figures

1.0 Review of Literature:

1.1 Postural Control in Humans:

Postural control involves maintaining, achieving or restoring a state of balance during an activity or stance (Pollock, Durward, Rowe, & Paul, 2000). Human postural control is a complex process requiring sensory input from the visual, vestibular and somatosensory systems (Melzer, Benjuya, & Kaplanski, 2001) and requires the individual to monitor two parameters: the body's centre of mass (COM) and the base of support (BOS). The body's COM is the weighted average of each body segment's centre of mass represented as a single point in a frame of reference (Winter, 1995). The BOS refers to the area on the supporting surface that is in contact with the body. To maintain balance, an individual must ensure that the position of their COM lies within their BOS.

To compensate for any changes in COM position caused by internal or external perturbations, two types of balance control strategies can be employed: predictive balance control and reactive balance control (Maki & McIlroy, 1997). Predictive balance control strategies, also known as anticipatory balance control, serve to minimize the destabilizing effects of future disturbances, such as a volitional movement (Maki & McIlroy, 1997). This strategy is accomplished by compensatory movements initiated prior to the expected perturbation, such as a weight shift to the left before raising the right arm out to the side (Balasubramaniam & Wing, 2002). In contrast, reactive or compensatory balance control, which is the focus of this thesis, occurs in response to an unexpected external perturbation, such as a slip or a trip (Maki & McIlroy, 1997).

1.2 Reactive Balance Control Strategies:

Researchers have incorporated different external perturbations, such as release from lean (Hsiao-Wecksler & Robinovitch, 2007), cable pulls (Rogers, Hedman, Johnson, Cain, & Hanke, 2001), and support surface translations (Brauer, Woollacott, & Shumway-Cook, 2001; Brown, Shumway-Cook, & Woollacott, 1999; McIlroy & Maki, 1995; Rankin, Woollacott, Shumway-Cook, & Brown, 2000) to examine how individuals react to a loss of balance. In response to an unexpected external perturbation, two forms of balance recovery strategies have been observed. First, a fixed-support balance recovery strategy occurs as an early defence to a loss of balance, where an individual recovers their balance without changing their base of support. This is accomplished by generating compensatory muscle torques at the ankle and hip joints, as well as motion of the arms to slow the COM and to keep it from exceeding the boundary of the BOS (Maki & McIlroy, 1997). However, when an individual allows their COM to exceed the BOS for an extended period of time, a change-in-support balance recovery strategy is required to avoid experiencing a fall. Change-in-support reactions involve alterations to the BOS to maintain stability and have been observed in response to small as well as large balance disturbances (Maki & McIlroy, 1997). Typically, alterations to the BOS through a change-in-support strategy are the result of taking a step. An increased reliance on change-in-support balance recovery strategies has been observed in individuals with poor balance ability (Maki, McIlroy, & Fernie, 2003).

It has been previously suggested that both fixed-support and change-in-support reactions involving the lower limbs require the input and processing of sensory information from the visual, vestibular, somatosensory systems, followed by the output of responses from the reflexive and cortical pathways (Jacobs & Horak, 2007). However, the extent to which cortical pathways utilize sensory information to contribute to balance recovery is not completely understood. It was initially believed that lower limb postural adjustments in response to an external perturbation were strictly controlled by the spinal cord and brainstem of the central nervous system (CNS). This was evidenced in animals, where those with a lesion above the midbrain were still able to activate reflexive movements in response to a loss of balance (Sherrington, 1910). However, both fixed-support and change-in-support balance recovery strategies are now believed to also incorporate a sub-cortical control mechanism because they can be triggered faster and with less variability than voluntary movements (Jacobs & Horak, 2007).

Data obtained using a combination of subthreshold transcranial magnetic stimulation (TMS) and peripheral nerve stimulation on humans indicate that lower limb muscular responses are comprised of three responses: a short latency (SL), a medium latency (ML) and a long latency (LL) response (Taube et al., 2006). SL responses, occurring < 60 ms after perturbation onset, are believed to be controlled through spinal reflex pathways and act to generate non-functional muscle responses that are too small to stabilize balance. ML responses, with a latency of 60-85 ms, are the first of the functional responses and are believed to be a product of brainstem and midbrain outputs, but are also generalized responses such as functionally stabilizing muscle contractions. Finally, LL responses have a latency of > 85 ms and are believed to be cortical responses that influence and modify reactive strategies in order to maintain upright stance (Jacobs & Horak, 2007).

1.3 Control of Compensatory Arm Responses:

Previous work examining the influence of cortical involvement in fixed-support balance recovery strategies has focused on those involving the lower limbs (e.g., ankle and hip strategies) (Brauer et al., 2001; Brown et al., 1999; Rankin et al., 2000). While change-in-support strategies such as stepping responses are a primary means of balance recovery, lower limb responses are not always effective for restoring balance. For example, stepping causes lateral instability leading to additional lateral steps, or crossover steps that increase the risk of a foot collision and a fall (Maki & McIlroy, 2006). In such cases, individuals must also rely on the arms to avoid a fall. The use of the arms as a balance recovery strategy is generally referred to as a compensatory arm response.

Compensatory arm responses must be controlled differently than lower limb postural responses because when a perturbation to the trunk or legs results in a compensatory arm response, there is no direct stretch of the arm muscles to initiate a reflex response. While the origin of compensatory arm responses is still not fully understood, several possibilities have been proposed. For example, it was initially believed that compensatory arm responses were activated via a generalized "startle"-like mechanism (Hsiao & Robinovitch, 1999). A startle response is characterized by fast involuntary reflexive contractions followed by a top down activation of upper and lower limb muscles (Allum, Tang, Carpenter, Nijhuis, & Bloem, 2011). However, since compensatory arm responses are known to be scaled to the size of the perturbation, a startle mechanism cannot solely explain how compensatory arm reactions are generated (Maki & McIlroy, 1997). It has also been proposed that the compensatory arm responses may be attributed to a "dynamic multilimb coordinated strategy" that incorporates proprioceptive information from the lower limbs to activate complex neural circuitries that receive cortical input (Marigold, Bethune, & Patla, 2003). However, this strategy cannot be solely responsible for producing compensatory arm reactions because when a perturbation is administered to a seated participant, compensatory arm responses are still elicited even though there is little lower limb proprioceptive feedback (Gage, Zabjek, Hill, & McIlroy, 2007). Thus, there must be other mechanisms, such as vestibular or visual input, that are responsible for and involved in triggering compensatory arm responses following a loss of balance (Guillaud, Gauthier, Vercher, & Blouin, 2006).

Since the control of upper limb responses is not solely reflexive or dependent on lower limb proprioception, it has also been proposed that compensatory arm responses are likely to also be influenced through cortical mechanisms. This was recently examined by Bolton et al. (2011, 2012), when they applied continuous theta burst stimulation (cTBS) to temporarily suppress the area of the primary motor cortex representing the right hand. Using chair tilts to initiate a compensatory reaching response, and an auditory tone for voluntary reach to grasp trials, there was a reduction in the observed amplitude of hand muscle activity in voluntary and a trend toward reductions during compensatory grasping movements (Bolton, Patel, Staines, & McIlroy, 2011). A follow-up study by Bolton, Williams, Staines, and McIlroy (2012) incorporated cTBS to suppress the area of the primary motor cortex representing the right hand but with a fixed-support protocol where the participant grasped handholds with each hand. The authors found an early cortical involvement in fixed support balance reactions, observed by decreases in right hand muscle response amplitude, but no changes were observed in the proximal arm or the left upper limb muscle responses. The results of these studies indicate that there is early primary motor cortex involvement in the production of compensatory grasping responses to a whole-body disturbance for both fixed-support and change-in-support reactions.

1.4 Dual-Tasking:

Although initial work involving TMS has been used to assess the cortical contribution of compensatory arm responses in healthy young adults, limitations of using TMS exist. These include consistency concerns (Sack & Linden, 2003) and potential side-effects (e.g., seizures, discomfort, etc.) (Rossini & Rossi, 2007). The use of TMS during dynamic movements is also difficult as the site of stimulation may be altered with changes in head position. Therefore, an alternate means of indirectly observing and inferring cortical contributions toward the generation of compensatory arm responses is required. This may be achieved through the use of a dual-task paradigm.

Dual-tasking refers to the concurrent performance of two tasks (Pashler, 1994). Examples of dual-tasking are when an individual walks and talks, or drives and talks simultaneously. Research investigating dual-task performance compares an individual's performance on a series of single tasks (e.g., balance task and cognitive task) to when the single tasks are completed together. Interference observed in the simultaneous performance of two tasks has been explained by capacity and bottleneck theories (Pashler, 1994). Capacity theory states that individuals have a finite cognitive processing capability at any given time. If two tasks require more cognitive resources for task processing that what is available for use, there will be an observed slowing in one or both of these processes. Bottleneck theory suggests that when two ongoing tasks require the same cortical area for processing, only one cognitive process can be completed at a time.

This creates a processing bottleneck and leads to a delay in response. When interference between two concurrent tasks leads to a decreased ability to perform one or both of the two tasks, capacity theory assumes that the performance of two tasks requires a sum of attentional or cognitive resources that is greater than what is available to the individual (Woollacott & Shumway-Cook, 2002). Therefore, during a postural control task, the observation of a performance decline in the balance task, cognitive task, or both tasks, infers that attention is required to maintain balance. For the purposes of this thesis, it was assumed that attentional processing involves cortical mechanisms (Gevins, Smith, McEvoy, & Yu, 1997).

1.4.1 Dual-Task Interference with Postural Control:

Kerr, Condon, and Mcdonald (1985) were among the first to show that postural control in younger adults was attentionally demanding and required cognitive effort. This was evidenced by decreases in cognitive task (i.e., Brook's Spatial and Non-Spatial Memory Task) performance while individuals stood without visual information. Follow up studies have incorporated a range of cognitive tasks such as memory and visual tasks (e.g., Brooks Spatial Memory Task, forward and backward digit recall, visuomotor tracking as well as silent and verbal counting tasks) and non-visual tasks (e.g., simple and choice reaction time tasks, and sentence completion, etc.) for assessing dual-task performance. Since different tasks stress specific aspects of cognitive functioning, each task uniquely affects dual-task performance. For example, secondary cognitive tasks that require working memory (e.g., the Visuo-Spatial Sketch Pad) tend to interfere with postural control the most because it is believed that the neural pathways used for processing visual information during standing are the same as those required for completing the working memory task (Maylor & Wing, 1996). More recently, Sturnieks, St George, and Lord (2008) showed that visuo-spatial tasks (e.g., Brooks Spatial Memory Task) interfere more with postural control mechanisms than non-spatial tasks (e.g. backward digit rehearsal). To compensate for periods of multiple demands requiring cognitive processing, individuals commonly exhibit decreases in postural sway, reflecting a reliance towards a "stiffening strategy" (Maylor, Allison, & Wing, 2001). However, these postural effects can vary, especially when the difficulty of the cognitive task increases. During these situations, healthy young individuals demonstrate increases in postural sway in the antero-posterior direction (Pellecchia, 2003).

Dual-task performance is also dependent on the type and difficulty of the postural task (Dault, Geurts, Mulder, & Duysens, 2001; Lajoie, Teasdale, Bard, & Fleury, 1993; Marsh & Geel, 2000; Teasdale & Simoneau, 2001). This has been observed through increases in reaction times with greater postural task difficulty (e.g., sitting to standing with a wide BOS to standing with a narrow BOS to walking) (Lajoie et al., 1993). In a similar study, when more attentionally demanding posture requirements such as unreliable supporting surfaces (i.e., foam) and lack of visual information were presented, individuals responded through increases in reaction time (Teasdale & Simoneau, 2001). However, no changes in the amount of standing sway were observed with increasing postural demands. These differences in results could also be a product of instruction to prioritize the postural task. With increased focus on the postural task, participants may not have been able to pre-plan their reaction time response due to more resources being allocated to the postural task.

1.4.2 Dual-Task Performance During Reactive Balance Control:

While many studies have incorporated static balance tasks to assess dual-task performance, few have examined the influence of a secondary cognitive task on balance recovery strategies to an external perturbation (i.e., a support surface translation). Further, this research has been limited to responses of the lower limbs. For example, when older adults lose their balance while performing a math task (i.e., counting backward by 3's) compared to no-math task, they initiate a step earlier, even at a time when the COM is still within the stability limits (Brown et al., 1999). Other researchers have observed that older individuals require more time to control the centre of pressure following a platform perturbation during a dual-task compared to a single-task condition (Brauer et al., 2001). Lower limb muscle responses are also affected during dual-task performance, whereby muscle responses to a platform perturbation are reduced in magnitude when individuals are required to count backward compared to when they are not counting (Rankin et al., 2000). However, these changes in response amplitude are limited to the later phases of the balance recovery response (Burleigh & Horak, 1996; Norrie, Maki, Staines, & McIlroy, 2002; Rankin et al., 2000). This supports previous work involving TMS, which demonstrated that the LLR but not the SLR is controlled via cortical neural loops (Taube et al., 2006).

Based on these previous findings, it is evident that the increased cortical demands associated with dual-tasking affects the timing (Brown et al., 1999) and magnitude (Rankin et al., 2000) of lower limb postural reactions to a loss of balance. The results inferred from dual-task studies correspond with the neurophysiological recordings obtained from peripheral nerve stimulation and TMS (Taube et al., 2006). Accordingly, incorporating a dual-task protocol to establish the mechanisms responsible for generating upper limb balance recovery strategies (i.e., compensatory arm responses) may be warranted.

1.5 Ageing:

Another approach to understanding the mechanisms underlying the generation of compensatory arm responses may be to examine how older adults respond to a loss of balance. This is because older adults initiate and produce compensatory arm responses that are delayed and reduced in magnitude compared to the young (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Maki & McIlroy, 2006; Mansfield & Maki, 2009; Weaver, Hamilton, & Tokuno, 2012). Older adults are also more reliant than young adults on compensatory arm responses when reacting to a loss of balance (Allum et al., 2002). Finally, when older adults do move their arms in response to a loss of balance, they are more likely to reach towards the direction of the impending fall, which is opposite to what has been observed in the young (Allum et al., 2002). This is believed to be a response in order to absorb the forces of a fall with the arms rather than having the hip absorb these forces (Allum et al., 2002).

Changes in the ability of older adults to generate compensatory arm responses may be due to the numerous neuromuscular changes that occur with age. These changes take place within the sensory and motor systems of the nervous system. For example, within the sensory system, older adults experience declines in visual feedback (Collins & De Luca, 1995; Okuzumi, Tanaka, & Nakamura, 1996; Speers, Kuo, & Horak, 2002), declines in vestibular sensitivity due to a loss of nerve and hair cells (Rosenhall & Rubin, 1975) as well as a loss of cutaneous sensitivity and somatosensation of the feet (Maki &

McIlroy, 2006). These changes are believed to influence compensatory stepping responses (Do, Bussel, & Breniere, 1990) through unreliable sensory feedback, which leads to multiple step reactions (Maki, Edmondstone, & McIlroy, 2000). Within the motor system, ageing leads to sarcopenia, a decline in skeletal muscle mass (Rogers & Evans, 1993), that causes changes in strength, flexibility, and range of motion. Together, these deteriorations can influence an individuals' ability to generate an appropriate response to a loss of balance. For example, decreases in muscle strength may result in difficulty controlling body stability (Rogers & Mille, 2003) because the torque requirements of foot-in-place strategies may exceed the strength capabilities of older adults (Maki & McIlroy, 1997). The observed delay in an older adult's response following a loss of balance may also be due to neural cell loss (Era, Jokela, & Heikkinen, 1986). Fewer neurons may result in neural transmission delays within the peripheral nervous system (PNS) (Rivner, Swift, & Malik, 2001) or information processing delays within the CNS (Tanosaki, Ozaki, Shimamura, Baba, & Matsunaga, 1999; Tobimatsu, Sun, Fukui, & Kato, 1998) leading to a delay in initiating a balance correcting response. It is believed that this delay contributes to the 35-40% increase in falls observed in individuals aged 60 and over (Allum et al., 2002; Maki et al., 2000).

However, another factor that may explain age-related differences in the ability to generate compensatory arm responses may be the availability of attentional resources. Compared to young adults, older adults are more influenced by the effects of a dual-task because of their increased reliance on cognitive resources for balance recovery (Woollacott & Shumway-Cook, 2002). For example, greater reductions in lower limb muscle response amplitude are observed in older than young adults when performing a verbal subtraction task (Rankin et al., 2000). It is hypothesized that older adults demonstrate greater balance performance declines during dual-task performance than young adults (Maylor et al., 2001; Maylor & Wing, 1996; Rankin et al., 2000; Teasdale & Simoneau, 2001) because they require a larger proportion of their total cognitive resources, or attentional capacity, for postural control in response to a loss of balance (Teasdale & Simoneau, 2001). Therefore, if generating a compensatory arm response requires cognitive resources, as reflected by previous studies involving TMS, these arm responses should not only be negatively influenced by the presence of a dual-task, but should also be disproportionately affected in older compared to young adults.

2.0 Rationale, Purpose, Research Questions and Hypotheses:

2.1 Rationale:

It is predicted that by the year 2036, 24% of the Canadian population will be represented by those aged 65 years or older (Statistics Canada, 2012). This ageing population is likely to result in significant costs to the healthcare system in Canada. This is because among the older adult population, about 40% of hospital admissions are due to falls (Lajoie, 2003; Shumway-Cook, Baldwin, Polissar, & Gruber, 1997). Falls and fall-related injuries lead to severe activity restriction (Tinetti, Speechley, & Ginter, 1988) and subsequently, additional decreases in strength, balance, agility and independence (Lajoie, 2003; Maki, Holliday, & Topper, 1991; Shumway-Cook, Baldwin, et al., 1997). To minimize these effects, it is important to gain a greater understanding regarding how balance control strategies, particularly those involving the upper limbs, are controlled in order to help reduce the frequency, severity and consequences of falls in the older adult population.

One situation in which older adults may be more susceptible to falls is when greater ongoing cognitive activity requiring cortical processing, such as a mental counting task, is required. When older adults perform a concurrent cognitive task, they demonstrate changes in postural sway during standing (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Maylor et al., 2001; Maylor & Wing, 1996; Pellecchia, 2003; Sturnieks et al., 2008) as well as decreases in lower limb reactive balance control responses following a loss of balance (Rankin et al., 2000). However, little is currently known regarding how cognitive demands influence the ability of young and older adults to generate a compensatory arm response following an unexpected loss of balance. This is an important area to examine because not only are the arms fundamental for balance recovery in response to an unexpected slip (Marigold et al., 2003), older adults have a decreased ability to initiate a compensatory arm response as early as the young (Allum et al., 2002; Mansfield & Maki, 2009; Weaver et al., 2012). If age-related changes in compensatory arm responses are further exacerbated when a secondary cognitive task is being performed, this may be one area in which rehabilitation specialists could target in balance training programs.

2.2 Purpose:

The purposes of this thesis are to (i) investigate whether ongoing cognitive activity affects the generation of a compensatory arm response; (ii) determine if the amount of ongoing cognitive activity is associated with an individual's ability to generate a compensatory arm response and (iii) examine whether ageing leads to disproportionate differences in the ability to produce compensatory arm responses during dual-task performance.

2.3 Research Questions:

1) Are compensatory arm responses that occur following a loss of balance influenced by cognitive task performance? If so, are the observed changes in the compensatory arm responses scaled to the difficulty of the cognitive task?

2) Is an older adult's ability to generate a compensatory arm response more affected by the presence of a cognitive task than young adults?

2.4 Hypotheses:

1) Performing a concurrent cognitive task will decrease the magnitude of the compensatory arm response generated.

2) The magnitude of the compensatory arm response will depend on the difficulty of the ongoing cognitive task, with more difficult cognitive tasks resulting in greater decreases to the compensatory arm response.

3) The presence of a cognitive task will have greater influence on the ability to generate a compensatory arm response in older compared to young adults.

3.0 Methods:

3.1 Participants:

Twenty healthy young adults aged between 20-27 years and sixteen healthy older adults aged 62 years or older participated in this study. A summary of participant characteristics and assessments is shown in Table 1.

Table 1: Characteristics and assessment scores of young and older adults. Values represent group means ± one standard deviation. ABC = Activity Specific Balance Confidence scale, TUG= Timed Up and Go, FRQ = Fall Risk Questionnaire, and MoCA = Montreal Cognitive Assessment.

	Young Adults	Older Adults
Sex	14 M, 6 F	5 M, 11 F
Age (y)	23 ± 2 (20-27)	71 ± 4 (62-77)
Height (cm)	175± 9	166 ± 9
Mass (kg)	73± 13	67 ± 14
ABC (%)	95 ± 5	95± 6
FRQ (pts/14)	0.9 ± 1.7	1.6 ± 1.3
MoCA (pts/30)	28.2 ± 1.9	26.7 ± 1.8
TUG (s)	6.4 ± 1.0	7.5 ± 1.3
TUG_{Easy} (s)	6.9 ± 1.2	8.4 ± 1.9
TUG_{Hard} (s)	7.6 ± 1.7	9.7 ± 2.4
Number of Fallers	12	6
Number of Falls	2.3 ± 6.6	0.6 ± 0.9

Participants were free from any neurological, sensory or musculoskeletal disorders (e.g., Parkinson's Disease, stroke, severe pain that limits movement, etc.) that could affect their balance. Participants were recruited from the Niagara region through the means of flyers, word of mouth as well as active recruitment by the primary researcher. All participants provided informed consent prior to participating in this study.

3.2 Questionnaires and Functional Assessments:

First, participant demographic information such as age, height, weight, and sex were collected. Next, four questionnaires/assessments were completed: i) the Activity

Specific Balance Confidence scale (ABC) (Powell & Myers, 1995) to determine the individual's balance confidence during various activities of daily living (Appendix A), ii) the Edinburgh Handedness Inventory (Oldfield, 1971) to determine the participant's dominant hand (Appendix B), iii) the Fall Risk Questionnaire to measure of their risk of experiencing a future fall (adapted from the Optimum Performance Through Movement Physical Therapy Group) (Appendix C) and iv) the Montreal Cognitive Assessment (Nasreddine et al., 2005) to assess cognitive ability and screen for any potential cognitive impairments (Appendix D). Finally, the number of falls that the participant had experienced within the last year was also recorded. For the purposes of this thesis, a fall was defined as "an unexpected event in which the participant came to rest on the ground, floor, or lower level", (Lamb, Jorstad-Stein, Hauer, & Becker, 2005).

To assess functional mobility, participants completed the Timed Up-and-Go (TUG) and the Timed Up-and-Go Cognitive ($TUG_{cognitive}$) tests (Shumway-Cook, Brauer, & Woollacott, 2000). The TUG is a commonly used test to assess an individual's functional mobility and the $TUG_{cognitive}$ allows for the assessment of functional mobility during dual-tasking (Shumway-Cook et al., 2000). For the two variants of the TUG test, participants stood from a seated position, walked out for 3 m as quickly and safely as possible, around a red "X" on the floor and returned 3 m to the seated starting position (Shumway-Cook et al., 2000). The $TUG_{cognitive}$ was modified and required participants to count backward by 2's (TUG_{Easy}) or 7's (TUG_{Hard}) while completing the TUG protocol. Participants began counting from a number provided by the researcher at the start of the trial. For each TUG test, the time from two trials was recorded and the average was taken.

3.3 Experimental Set-up:

Upon completion of the questionnaires and functional assessments, participants wore a safety harness that was attached to a low-friction overhead track. The purpose of the safety harness was to prevent participants from falling to the floor in the event of a total loss of balance. Pairs of surface electrodes (Ag-AgCl, 10mm diameter, 2 cm interelectrode distance, Kendall Meditrace 200, Mansfield, MA, USA) were placed on the left and right anterior, medial and posterior deltoids (AD, MD and PD, respectively), as well as the medial gastrocnemius (MG) and the tibialis anterior (TA) of the right leg. A single reference electrode (Ag-AgCl, 10mm diameter, Kendall Meditrace 200, Mansfield, MA, USA) was placed on the right elbow. Prior to electrode placement, all skin sites were shaved, lightly abraded and cleansed with alcohol. EMG recordings from these electrodes were amplified 350 times (MA-300 Motion Lab Systems Inc., Baton Rouge, LA, USA) and analog-to-digitally converted at a sampling rate of 2 kHz (micro 1401, Cambridge Electronic Design, Cambridge, UK). All EMG signals were band pass filtered from 60-600 Hz, then rectified and low-pass filtered offline at 100 Hz prior to data analysis.

Three-dimensional kinematics were obtained using a motion analysis system (3D Investigator system, Northern Digital Inc., Waterloo, ON. Canada). Clusters of four infra-red (IRED) markers were placed on the left and right upper arms and forearms while a cluster of three markers was placed over the sternum. Fourteen additional points of reference, referred to as imaginary markers, were created on the anterior, medial and posterior deltoid, medial and lateral elbow, as well as the medial and lateral wrist of both the right and left arms. These imaginary markers defined the proximal and distal ends of the upper and lower arm segments and were used to quantify the kinematics of the reaching movement. The imaginary markers were digitized using a four-marker digitizing probe (Northern Digital Inc., Waterloo, Ontario). Kinematic data from the clusters of IRED markers was collected at a frequency of 100 Hz and filtered offline using a Butterworth 4th order low-pass filter at a cut off frequency of 4 Hz.

To quantify standing sway prior to each perturbation, centre of pressure (COP) movements were obtained from a forceplate (AMTI, OR6-7-2000, Watertown, MA, USA). COP movements were analog to digitally converted at a sampling frequency of 2 kHz (micro 1401, Cambridge Electronic Design, Cambridge, UK).

3.4 Overview of Experimental Protocol:

Participants stood on a 0.46 m x 0.51 m forceplate that was embedded within a (1.83 m x 0.92 m) wooden platform (Figure 1). Participants maintained a relaxed posture while looking straight forward, with their hands at their sides, and feet shoulder-width apart at a self-selected distance. They maintained this position for all future trials. The wooden platform was fixed to a motor driven 4.3 m linear stage (H2W Technologies Inc., Valencia, CA, USA). A minimum of one spotter was located beside the platform and assisted the participant in case of a total loss of balance where the participant was unable to recover their balance effectively. A single handrail (length of 1.98 m, diameter of 4 cm) was located to the participant's right side. Due to the handrail design, all participants who were 183 cm tall and shorter had the handrail placed at its lowest height setting of 101.5 cm above the platform surface. Participants taller than 183 cm had the handrail positioned at a height corresponding to 55% of the participant's height. The handrail was also placed at a lateral distance that was 25% of each participant's height away from the hip (Weaver et al., 2012) (Figure 1).

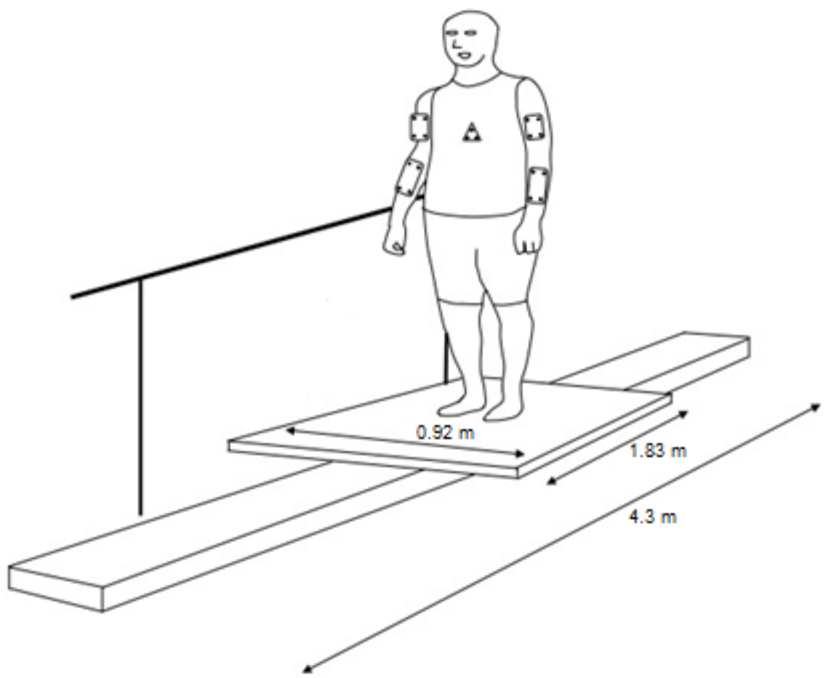

Figure 1: An illustration representing the moveable platform capable of delivering support surface translations in the forward and backward directions. The handrail placement used in this experiment is also shown.

Participants completed a total of 48 trials under three experimental conditions: balance task, cognitive task, or both cognitive and balance tasks (i.e., dual-task) (Table 2). Prior to the experimental trials, participants completed four counting and four balance trials to familiarize themselves with the requirements of the counting and balance tasks. For the practice counting trials, participants completed the two cognitive task conditions (explained in section 3.4.2.) where they counted backward by 2's (easy) or 7's (hard) for a period of 20 seconds. For the practice balance trials, participants experienced two support surface translations in each of the forward and backward directions. Once the practice trials were completed, the experimental trials began. Trials from all conditions were randomly interspersed into three blocks of 16 experimental trials. Each block contained four trials of single-task balance, four trials of single-task counting, and eight dual-task trials, presented in a random order to minimize anticipation effects. A minimum 5 minute break was provided following each block of 16 trials in order to help minimize the effects of fatigue.

Table 2: An overview of the three experimental conditions.

Experimental Condition	Number of Trials	Task	Instruction
Balance Task	12 trials consisting of: - 6 forward translations - 6 backward translations	Recover balance from a horizontal support surface translation in the forward or backward direction	Recover your balance as quickly as possible
Cognitive Task	12 trials consisting of: - 6 trials easy counting - 6 trials hard counting	Count backwards by 2 (or 7) starting from the provided number	When the starting number is given, count backwards as quickly and accurately as possible by 2 (or 7).
Dual Task (Balance and Cognitive Tasks)	24 trials consisting of: - 6 forward translations with easy counting - 6 backward translations with easy counting - 6 forward translations with hard counting - 6 backward translations with hard counting	Count backwards by 2 (or 7) from the provided number and recover balance from a horizontal support surface translation in the forward or backward direction	When the starting number is given, count backwards as quickly and accurately as possible by 2 (or 7). When the platform moves, recover your balance as quickly as possible and continue counting until the platform stops its initial movement.

3.4.1 Balance Task Condition:

For the balance task condition, the platform on which the participants were standing displaced 0.25 m in either the forward or backward direction. It accelerated for 440 ms (peak acceleration of 2.0 m/s^2), reached a peak velocity of velocity of 0.60 m/s and ended with a deceleration for 430 ms (peak deceleration of 2.0 m/s^2). In response to this surface translation, participants were required to recover their balance as quickly as possible without taking a step. Participants were specifically instructed as follows: "In response to the support surface translation, recover your balance as quickly as possible without taking a step". To discourage a stepping response, a foam barrier (external dimensions: length of 56 cm, width of 85 cm, height of 35 cm and internal dimensions: length of 30 cm, width of 70 cm, height of 35 cm) surrounded the participant's feet. The balance task condition was comprised of twelve trials, six in the forward direction and six in the backward direction.

3.4.2 Cognitive Task Condition:

The cognitive task condition required participants to complete a verbal arithmetic task at one of two difficulty levels. Participants completed the easy (count backwards by 2's) and hard (count backwards by 7's) counting difficulty conditions from a starting number provided by the experimenter at the beginning of the trial. Participants continued counting until they were instructed to stop by the experimenter. The total counting time was 20 seconds (Figure 2). Participants were specifically instructed as follows: "When the number is given, count backwards as quickly and accurately as possible by 2's (or 7's) until instructed to stop counting." A total of twelve trials of the cognitive task condition were performed. Six of these trials required participants to perform the easy counting difficulty condition and the remaining six trials required participants to perform the hard counting difficulty condition.

Figure 2: Timeline representing the sequence of events during the cognitive task (counting) condition.

3.4.3 Dual-Task Condition:

During the dual-task condition, participants simultaneously completed the cognitive task and the balance task. Participants began each trial with the easy or hard cognitive task (as described in the cognitive task condition). After a 20-25 second period, the support surface translation was initiated (Figure 3). The platform moved at the same acceleration, velocity and displacement as in the balance task condition. Participants were required to continue counting throughout the support surface translation until the platform ceased its initial movement while recovering their balance as quickly as possible without taking a step. Specifically, participants were instructed as follows: "When the starting number is given, count backwards as quickly and accurately as possible by 2's (or 7's). When the platform moves, recover your balance as quickly as possible without stepping and continue counting until the platform stops its initial movement." Participants completed a total of 24 dual-task trials. These 24 trials were evenly divided into four balance-cognitive task combinations: backward translation while performing the easy counting difficulty, forward translation while performing the easy counting difficulty, backward translation while performing the hard counting difficulty, forward translation while performing the hard counting difficulty.

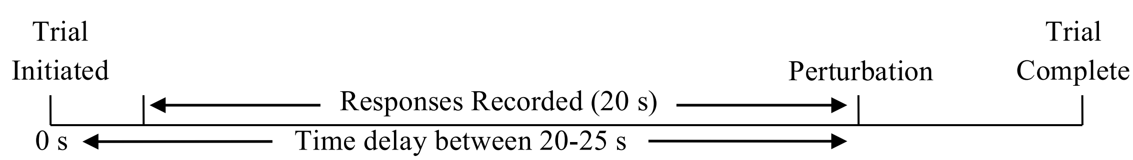

Figure 3: Timeline representing the sequence of events during a dual-task trial.

3.5 Data Analysis:

Counting performance was determined through manual participant response recordings collected by the experimenter. A response was considered correct if the provided answer was less than the previously given response by the required integer (i.e., 2 and 7 for the easy and hard counting difficulty conditions, respectively). Participant counting performance during the cognitive task condition was compared to the participant's counting performance during the 20 seconds pre-perturbation interval for the dual-task condition.

In order to assess how focused participants were on the counting task during the dual-task condition, participants were asked to report how focused they were on the counting task prior to the platform movement. The question was asked following three of the easy counting trials and three of the hard counting trials. Participants rated their focus of attention on a 0-100 % scale with 0% being not focused at all on the counting task and 100% being completely focused on the counting task.

Movement of the COP was assessed by calculating the RMS error of the COP signal in the anterior-posterior (AP) and medial-lateral (ML) directions during the initial 20 s of each trial for all single- and dual-task conditions.

Compensatory arm responses to each support surface translation were quantified through a variety of EMG and kinematic measures. EMG onset latencies for each muscle were determined as the time when the rectified EMG signal exceeded one standard deviation above the mean baseline activity for a minimum of 25 ms (Tokuno, Carpenter, Thorstensson, & Cresswell, 2006). Baseline activity was considered from the time interval one second prior to platform movement. All EMG onset latencies were determined using a custom algorithm written within a commercially available software program (Spike2, Cambridge Electronic Designs, Cambridge, UK) and confirmed through visual inspection (Figure 4).

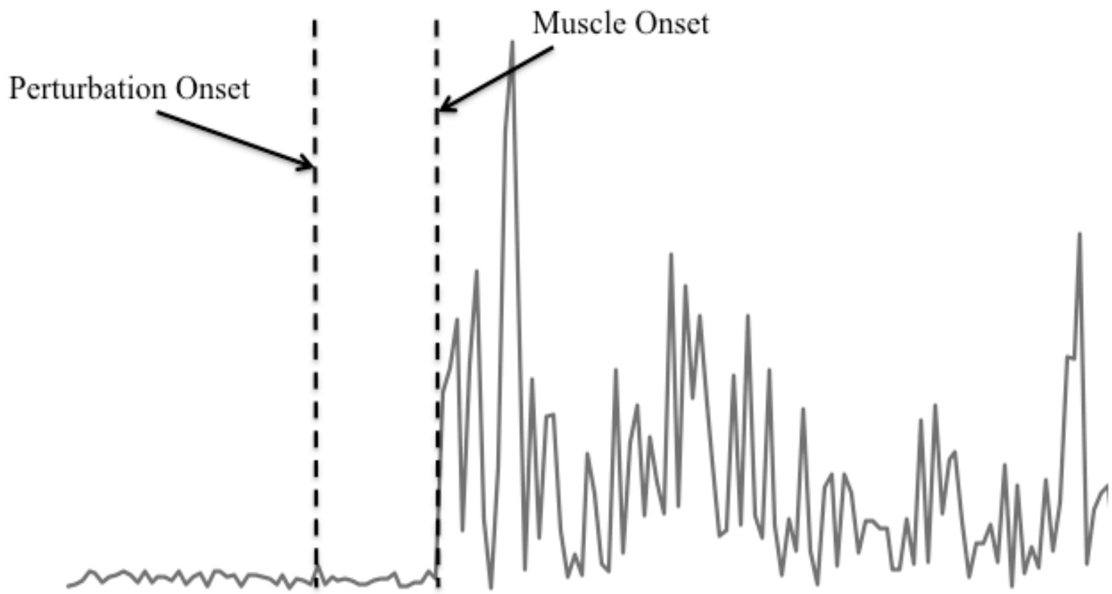

Figure 4: An example EMG trace representing the calculation of muscle onset latency in relation to the time of perturbation. The presented EMG data is not specific to the current project.

The EMG amplitude of each muscle was calculated as the area of the rectified EMG signal for five 100 ms time intervals: the 100 ms immediately prior to perturbation onset to measure background muscle activity, as well as four consecutive 100 ms intervals starting from muscle onset. To facilitate comparison between individuals, EMG areas were normalized as a percentage of the individual's maximal voluntary contraction (%MVC). MVC values were obtained at the end of the experiment by asking participants to perform a maximal isometric contraction of each muscle against resistance applied by the experimenter. The contractions were performed with the participant standing upright and with the arms at the sides of the body. Two contractions lasting 5-6 seconds in duration were obtained for each muscle, and the largest recorded EMG area over a 100 ms window was recorded as 100% MVC. All EMG response amplitudes were determined using a custom algorithm written within commercially available software program (Spike2, Cambridge Electronic Designs, Cambridge, UK) (Figure 5).

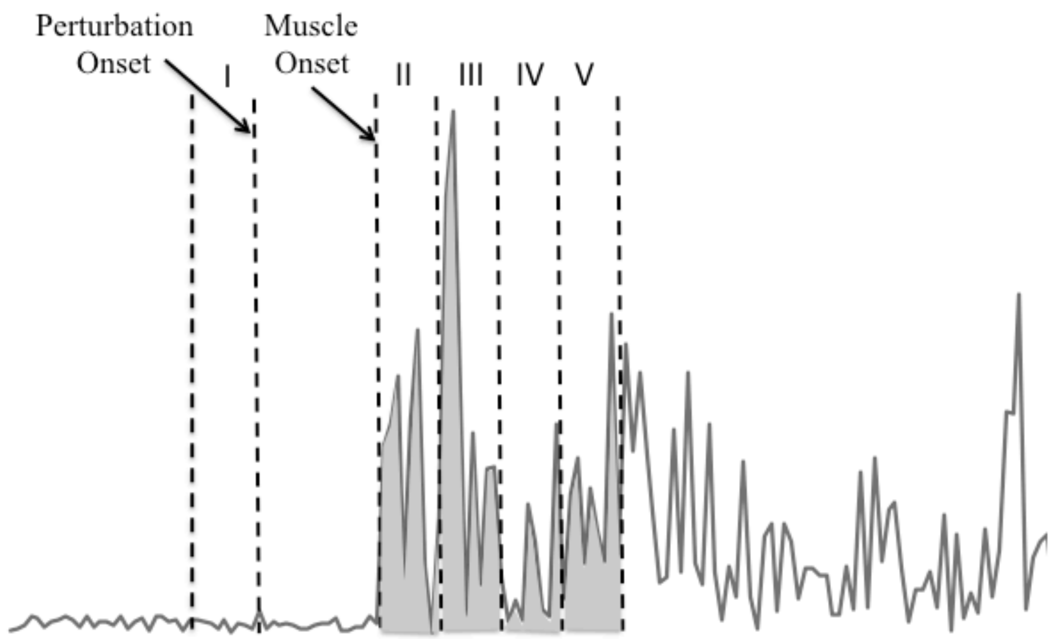

Figure 5: An example EMG trace representing the EMG amplitude calculation as the area under the rectified and filtered EMG tracing and the associated time intervals. The first interval was the 100 ms immediately prior to perturbation, and four 100 ms intervals that followed muscle onset. The presented EMG data is not specific to the current project.

Finally, the kinematics of the compensatory arm response during the balance task and the dual-task conditions were assessed by determining the onset of limb movement, the time of movement termination (i.e., cessation of wrist movement for a duration of 500 ms) and the displacement of the arm movement to handrail grasp. For trials where the participant did not grasp the handrail, displacement of the reaching movement over a 600 ms time period after onset was determined.

3.6 Statistical Analyses:

Walking time results of the TUG walking tests were assessed with a 2 (age category) x 3 (TUG type) mixed-model analysis of variance (ANOVA) that was carried out with age (young vs. older adults) as the randomized factor and TUG type ($TUG_{Original}$ vs. TUG_{Easy} vs TUG_{Hard}) as the repeated factors. For any significant interactions independent and paired samples t-tests were performed to assess differences amongst young and older adults during and/or across each walking condition.

Counting performance, in terms of the number of total and correct responses, was assessed by performing separate 2 (age category) x 2 (counting difficulty condition) x 2 (counting task) mixed-model ANOVAs with age (young vs. older adults) as the randomized factor, and counting difficulty condition (easy vs. hard) and counting task (single-task counting vs. dual-task counting) as the repeated factors.

Changes in attention focus on the counting task were assessed by a 2 (age category) x 2 (counting difficulty condition) mixed-model ANOVA with age (young vs. older adults) as the randomized factor and counting difficulty condition (easy vs. hard) as the repeated factor.

To assess for changes in the RMS of the AP and ML COP signal, separate 2 (age category) x 3 (counting difficulty condition) mixed-model ANOVAs with age (younger vs. older) as the randomized factor and counting difficulty condition (none vs. easy vs. hard) as the repeated factor were performed.

To assess whether age and cognitive task demands influenced compensatory arm and leg responses, EMG onset latencies were analyzed using separate 2 (age category) x 3 (counting difficulty condition) x 2 (perturbation direction), mixed-model ANOVAs for each of the muscles recorded (i.e., right and left AD, MD, PD as well as right MG and TA). Each ANOVA consisted of age (young vs. older adults) as the randomized factor and counting difficulty condition (none vs. easy vs. hard) and perturbation direction (forward vs. backward) as the repeated factors.

To assess whether age and the cognitive task demands influenced the magnitude of compensatory arm and leg responses, EMG amplitudes were analyzed using separate 2 (age category) x 3 (counting difficulty condition) x 5 (time interval) x 2 (perturbation direction) mixed-model ANOVAs. Each ANOVA consisted of age (young vs. older adults) as the randomized factor and counting difficulty condition (none vs. easy vs. hard), time interval (-100 ms- platform movement onset, muscle onset-100 ms, 100 ms-200 ms, 200 ms-300 ms, and 300 ms -400ms), and perturbation direction (forward vs. backward) as the repeated factors.

Changes in the kinematics of the compensatory arm response were assessed by separate 2 (age category) x 3 (counting difficulty condition) x 2 (perturbation direction) mixed model ANOVAs for movement onset time, movement termination, and movement displacement. Age (young vs. older adults) was the randomized factor with counting difficulty condition (none vs. easy vs. hard) and perturbation direction (forward vs. backward) as the repeated factors.

All statistical tests were performed using commercially available software (SPSS, Chicago, Il, USA). For all statistical analyses, significance was set at $p \leq 0.05$. Where appropriate, significant main and interaction effects were analyzed using Bonferroni-correction post-hoc t-tests. In analyses where the assumption of sphericity was violated (sphericity test $p \leq 0.05$), significance values were adjusted according to the Greenhouse-Geisser correction. For the purposes of brevity, direction main effects and interactions that involved direction but not counting difficulty are not presented for EMG measures. These effects are not directly relevant to the purposes of this thesis.

4.0 Results:

4.1 TUG Tests:

The time to complete the TUG test was influenced by an age x TUG type interaction effect ($F_{1.629,55.380}=3.69$; $p=0.040$). Post-hoc t-tests revealed that older adults required more time to complete the $TUG_{Original}$ ($t_{34}=-2.87$; $p=0.007$), the TUG_{Easy} ($t_{24.61}=-2.79$; $p=0.01$) and the TUG_{Hard} ($t_{34}=-3.04$; $p=0.005$) than young adults. However, differences between young and older adults were greater during the TUG_{Easy} and TUG_{Hard} than the $TUG_{Original}$ (Figure 4).

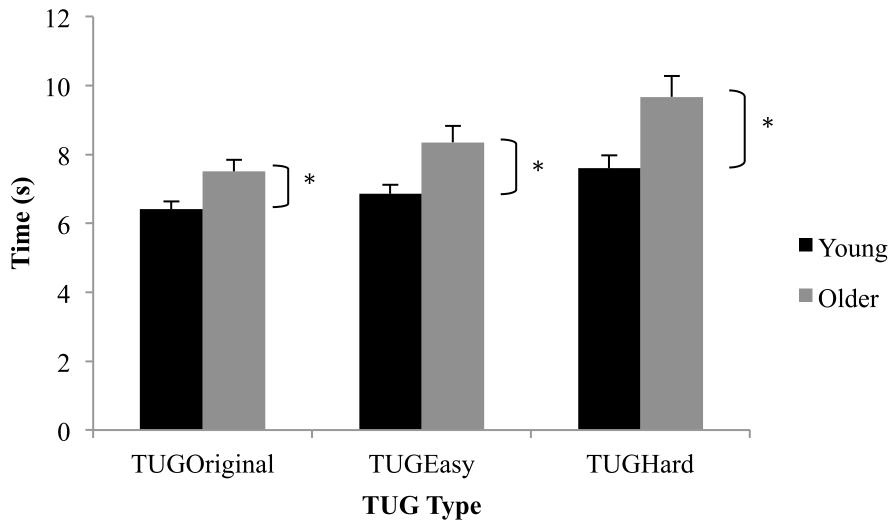

Figure 6: Mean ± 1 SE time required to complete the $TUG_{Original}$, the TUG_{Easy} and the TUG_{Hard}. The difference between younger and older adults was significantly greater with increasing dual-task difficulty compared to the $TUG_{Original.}$ * indicates a difference (p<0.05).

4.2 Counting Task Measures:

4.2.1 Number of Total Responses:

When performance on the counting task was quantified by the total number of responses, an age x counting difficulty interaction effect was observed ($F_{1,34}$= 7.790; p=0.008). Post-hoc analysis revealed that both young (t_{19}=12.227; p<0.001) and older adults (t_{15}=10.153; p<0.001) made fewer responses during the hard compared to the easy counting difficulty condition. However, the number of responses decreased more for younger adults (10.8±0.9 fewer responses) compared to the older adults (7.6±0.7 fewer responses).

The total number of responses on the counting task was also influenced by a task x counting difficulty interaction effect ($F_{1,34}$=14.697; p=0.001). Post-hoc analysis revealed that during the easy counting difficulty condition there was no difference in the number of responses between the single- and dual-task trials. However, for the hard counting difficulty condition, there were 0.6±0.1 more total responses during the dual-task than the single-task condition (t_{35}=-5.72; p<0.001) (Figure 5).

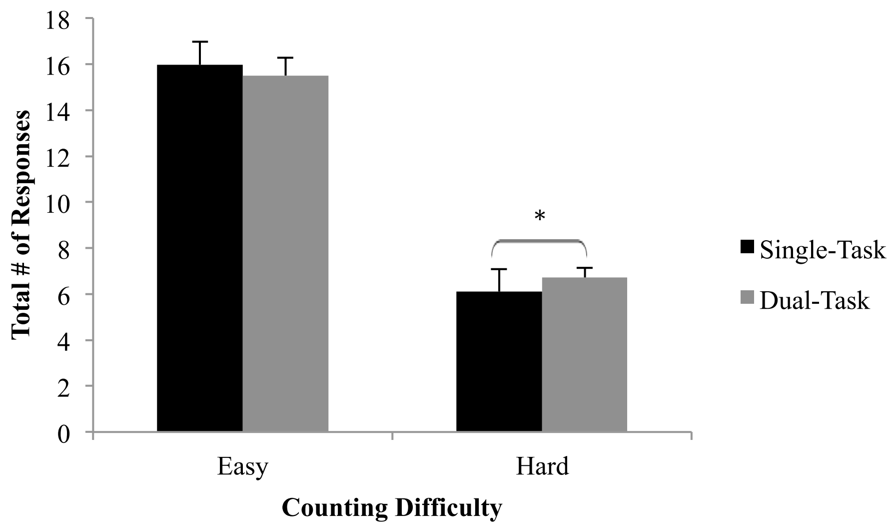

Figure 7: Mean±1 SE total responses during single and dual-task trials for the easy and hard counting difficulty conditions. There was an increase in the number of responses during the dual-task compared to the single-task of the hard counting difficulty condition, but no differences in the easy counting difficulty condition were observed.* indicates a difference (p<0.05).

4.2.2 Number of Correct Responses:

When performance on the cognitive task was examined for the number of correct responses, an age x counting difficulty interaction effect was observed ($F_{1,34}$= 6.60; p=0.015). Post-hoc analysis revealed that both young (t_{19}=12.80; p<0.001) and older adults (t_{15}=11.35; p<0.001) had fewer correct responses during the hard compared to the easy counting difficulty condition. However, there was a larger decrease in the number of correct responses for the young (decrease of 11.2±0.9 correct responses) compared to the older adults (decrease of 8.2±0.7 correct responses).

The number of correct responses on the counting task was also influenced by a task x counting difficulty interaction effect ($F_{1,34}$=11.85; p=0.002). Post-hoc analysis revealed that there was no difference in the number of correct responses between the single- and dual-tasks for the easy counting difficulty condition (p>0.05). For the hard counting difficulty condition there were 0.6±0.1 more correct responses during the dual-task than the single-task, (t_{34}= -5.00; p<0.001) (Figure 6).

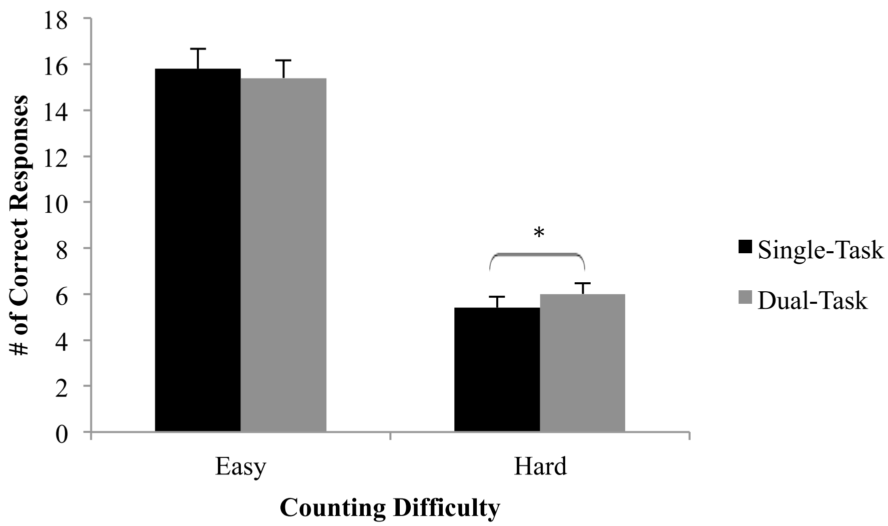

Figure 8: Mean±1 SE number of correct responses during the single- and dual-task trials for the easy and hard counting difficulty conditions. There was an increase in the number of correct responses during the dual-task hard counting compared to the single-task hard counting condition. However, there were no differences between the two easy counting difficulty conditions. * indicates a difference (p<0.05).

4.2.3 Attention Focus During the Counting Task:

The self-reported attention focus on the counting task was influenced by a counting difficulty main effect ($F_{1,33}$=6.55; p=0.015). During the dual-task trials, participants were more focused on the counting task during the hard (80.7±2.5 %) than the easy counting task (74.7±3.1 %).

4.3 Centre of Pressure:

The RMS of the AP and ML COP signals were examined to determine whether COP movements differed as a result of dual-task interference. When the RMS of the AP COP was examined, a counting difficulty main effect was observed ($F_{1.42,35.55}$=6.94; p=0.006). In comparison to the no counting condition, there were larger movements of the COP in the easy (p=0.019) and hard (p=0.050) counting difficulty conditions. When the RMS of the ML COP was examined, a counting difficulty main effect was observed ($F_{1.41,35.19}$=18.96; p<0.001). In comparison to the no counting condition, there were larger movements of the COP in the easy (p<0.001) and hard (p=0.001) counting conditions. For both of the AP and ML directions, there was no change in the RMS of the COP between the easy and hard counting difficulty conditions.

4.4 EMG Onset Latency:

EMG onset latencies were determined to examine how rapidly participants were able to generate a muscle response following a loss of balance. The mean±1 SE EMG onset latencies for each muscle, direction and counting difficulty condition are presented in Appendix E.

4.4.1 Left Anterior Deltoid:

The left AD EMG onset latency was influenced by an age x counting difficulty interaction effect ($F_{2,64}$= 5.64; p< 0.01). Post-hoc analysis revealed that only older adults were influenced by the dual-task, initiating left AD muscle activity earlier when counting than when not counting. Muscle activity was initiated 7±2 ms (t_{15}= 4.08; p=0.001) and 6±2 ms earlier (t_{15}= 3.63 p=0.002) during the easy and hard counting tasks, respectively compared to the no counting condition.

4.4.2 Left Medial Deltoid:

The left MD EMG onset latency was influenced by a counting difficulty x perturbation direction interaction effect ($F_{1.72, 58.30}$ = 4.31; p=0.023). Post-hoc analysis revealed that in response to a forward perturbation, muscle activity was initiated 5±2 ms earlier during the hard counting condition than when not counting (t_{35}= 2.48; p= 0.018). However, EMG onset latencies were not different between the easy and hard counting difficulty conditions in response to a forward perturbation or between any of the counting difficulty conditions in response to a backward perturbation.

4.4.3 Left Posterior Deltoid:

The left PD EMG onset latency was not affected by age, perturbation direction or counting difficulty.

4.4.4 Right Anterior Deltoid:

The right AD was influenced by a counting difficulty main effect ($F_{2,66}$=4.61; p=0.013) with muscle activity being initiated 3±1 ms earlier when performing the easy counting difficulty condition compared to the no counting condition (t_{34}=2.75; p=0.009).

4.4.5 Right Medial Deltoid:

The right MD EMG onset latency was not affected by age, perturbation direction or counting difficulty.

4.4.6 Right Posterior Deltoid:

The right PD EMG onset latency was influenced by an age x counting difficulty x perturbation direction interaction effect ($F_{1.60,\ 54.64}$= 3.57; p=0.044). This three-way interaction effect was examined using separate 2 (perturbation direction) x 2 (counting difficulty) repeated measures ANOVAs for each age group. For the young adults, a perturbation direction main effect was observed ($F_{1,19}$= 6.67; p=0.018), where the PD EMG onset latency was 9±3 ms earlier in response to a forward compared to a backward directed perturbation. For the older adults, a perturbation direction main effect was also observed ($F_{1,15}$= 5.10; p=0.039), where the EMG onset latency was 10±5 ms earlier in response to a forward compared to a backward directed perturbation. There were no differences in the initiation of the right PD muscle activity between age groups with changes in counting difficulty or perturbation direction.

4.4.7 Right Medial Gastrocnemius:

The right MG EMG onset latency was influenced by an age main effect ($F_{1,26}$=7.69; p=0.01). Older adults required 33±12 ms more time to initiate the right MG than the younger adults.

4.4.8 Right Tibialis Anterior:

The right TA EMG onset latency was influenced by an age main effect ($F_{1,32}$=13.51; p=0.001). Older adults required 21±6 ms more time to initiate the right TA than the younger adults.

4.5 EMG Amplitudes:

EMG amplitudes were calculated to characterize the size of the arm or leg postural response following a loss of balance. Five intervals were chosen for analyses: the 100 ms immediately prior to platform movement (i.e., background activity) and then four consecutive 100 ms intervals following muscle onset (when time=0 ms). The mean±1 SE EMG amplitudes for each muscle, direction and counting difficulty condition are presented in Appendix F through Appendix J.

4.5.1 Left Anterior Deltoid:

The left AD EMG amplitude was influenced by an age x counting difficulty x time interval interaction effect ($F_{5.46,174.82}$= 2.17; p= 0.043). To examine this three-way interaction, separate 3 (counting difficulty) x 5 (time interval) repeated measures ANOVAs were run for each age group. For the young adults a time interval main effect was observed ($F_{2.06,35.07}$= 15.00; p< 0.001). Specifically, EMG amplitudes were 5.3±2.0 % larger during the 0-100 ms than the 100-200 ms interval (t_{17}=2.63; p=0.017). EMG amplitude then decreased by 3.4±5.8 % during the 200-300 ms compared to the 100-200 ms interval (t_{17}=2.50; p=0.023). EMG amplitude also increased by 1.7±2.5 % in the 300-400 ms interval compared to the 200-300 ms interval (t_{17}=-3.00; p=0.008).

In contrast, the left AD EMG amplitude for the older adults was influenced by a counting difficulty x time interval interaction effect ($F_{8,120}$=2.83; p=0.007). Prior to the perturbation onset, there was an increase in the background EMG amplitude during the two dual-task conditions compared to the single-task balance condition. EMG activity during the easy and hard dual-task conditions increased by 0.3±0.1 % (t_{15}=-2.45; p=0.027) and 0.4±0.2 % (t_{15}=-2.23; p=0.041), respectively, compared to the single-task balance condition. There were no differences between the easy and hard dual-task conditions. Following a perturbation, there was a 2.2±0.9 % increase in EMG amplitude during the 0-100 ms interval of the hard dual-task condition compared to the single-task balance condition (t_{15}=-2.35; p=0.033). During the 100-200 ms interval, increases in EMG amplitude were also observed for the easy (3.5±1 % increase: t_{15}=-3.67; p=0.002) and hard (3.2±1 % increase: t_{15}=-3.22; p=0.006) dual-task conditions compared to the single-task balance condition. However, no differences were observed at the 200-300 ms and the 300-400 ms time intervals between three counting difficulty conditions.

4.5.2 Left Medial Deltoid:

The left MD EMG amplitude was influenced by an age x counting difficulty interaction effect ($F_{2,68}$=3.69; p=0.036). Post-hoc analysis revealed that the older but not the young adults' EMG amplitudes were affected by the dual-task. Older adults' EMG amplitudes during the easy and hard dual-task conditions were larger by 1.5±0.6 % (t_{15}=-2.48; p=0.025) and 2.3±1 % (t_{15}=-2.36; p=0.032), respectively, than the single-task balance condition. No differences were observed in the young adults' EMG amplitude between counting difficulty conditions.

4.5.3 Left Posterior Deltoid:

The left PD EMG amplitude was influenced by an age x time interval interaction effect ($F_{1.92,63.34}$=4.58; p=0.015). Post-hoc analysis revealed that older adults' EMG amplitude was larger for the background (1.3±0.3 %; $t_{18.57}$=-4.75; p <0.001), the 0-100 ms (10.3±3.9 %; t_{33}=-2.610; p=0.013), the 100-200 (10.1±3.8 %; t_{33}=-2.63; p=0.013), the 200-300 (10.3±2.8 %; $t_{19.03}$=-3.46; p=0.003), and the 300-400 (8.8±2.7%; $t_{20.40}$=-3.23;

p=0.004) intervals compared to young adults. However, the difference between older and young adults was largest in the post-perturbation time intervals.

4.5.4 Right Anterior Deltoid:

There were no differences in the EMG amplitude of the right AD between young and older adults, or between counting conditions.

4.5.5 Right Medial Deltoid:

The right MD EMG amplitude was influenced by a counting difficulty x time interval interaction effect ($F_{5.23,172.68}$=2.64; p=0.023). Prior to perturbation onset there was an increase in background EMG amplitude during the two dual-task conditions compared to the single-task (no counting) balance condition. EMG activity during the easy and hard dual-task conditions increased by 0.2±0.1 % (t_{34}=-3.03; p=0.005) and 0.2±0.1 % (t_{34}=-3.19; p=0.003), respectively, compared to the single-task balance condition. There were no differences in EMG amplitude between the easy and hard dual-task conditions. Following a perturbation, EMG amplitudes during the 0-100 ms interval were smaller for the two dual-task conditions compared to the single-task condition during the 0-100 ms interval. EMG activity for the easy and hard dual-task conditions were smaller by 2±0.9 % (t_{34}=2.13; p=0.041) and 2±0.8 % (t_{34}=2.40; p=0.022), respectively. During the 300-400 ms interval a 1.3±0.5 % decrease in EMG amplitude was observed for the easy dual-task condition compared to the single-task balance condition (t_{34}=2.67; p=0.012).

4.5.6 Right Posterior Deltoid:

The right PD EMG amplitude was influenced by a counting difficulty x time interval interaction effect ($F_{5.28,179.61}$=2.30; *p*=0.044). Prior to perturbation onset, there was an increase in background EMG amplitude during the two dual-task conditions compared to the single-task balance condition. EMG activity during the easy and hard dual-task conditions increased by 0.2±0.1 % (t_{35}=-3.15; *p*=0.003) and 0.2±0.1 % (t_{35}=-3.429; *p*=0.002), respectively, compared to the single-task balance condition. There were no differences between the easy and hard dual-task conditions. Following perturbation, there was a 1.9±0.8 % decrease in EMG amplitude for the hard dual-task condition compared to the single-task balance condition during the 0-100 ms interval (t_{35}=2.52; *p*=0.016). During the 300-400 ms interval, there was a 1.6±0.6 % increase in EMG amplitude for the hard dual-task condition compared to the easy dual-task condition (t_{35}=-2.72; *p*=0.010).

4.5.7 Right Medial Gastrocnemius:

The right MG was influenced by a counting difficulty x perturbation direction interaction effect ($F_{2,52}$=9.50; *p*=0.035). Post-hoc analysis revealed that for backward perturbations, the hard dual-task resulted in EMG amplitudes that were 1.1±0.5 % larger than the single-task condition (t_{27}=-2.12; *p*=0.043). For forward perturbations, the hard dual-task condition resulted in EMG amplitudes that were 1.1±0.5 % smaller than the single-task balance condition (t_{27}=2.12; *p*=0.044).

4.5.8 Right Tibialis Anterior:

There were no differences in the right TA EMG amplitude between young and older adults, or between counting difficulty conditions.

4.6 Right Arm Kinematics:

Across all experimental conditions movement of the right arm was initiated 115.5±0.3 ms following perturbation onset. However, the right arm movement initiation time was influenced by a counting difficulty main effect ($F_{2,52}$=7.62; p=0.001). Compared to the single-task (no counting) balance condition, the arm initiated movement 1.2±0.4 ms (t_{27}=3.53; p=0.001) and 1.4±0.4 ms (t_{27}=3.19; p=0.004) earlier for the easy and hard dual-task conditions, respectively. There was no difference between easy and hard dual-task conditions for movement initiation time.

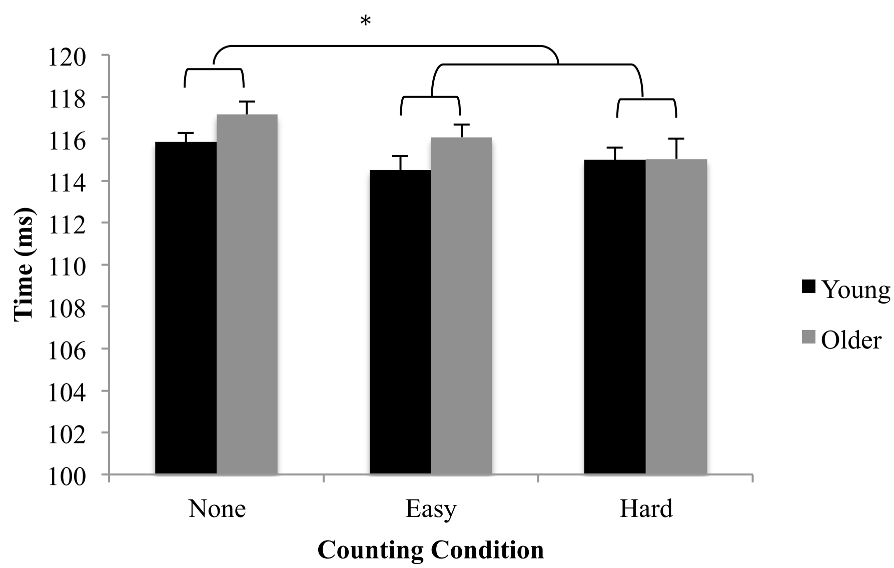

Figure 9: Mean + 1 SE time required to initiate the right arm in the three counting difficulty conditions. The initiation time was shorter for the two dual-task conditions compared to the no counting (single task balance) condition. * indicates a difference (p<0.05).

Arm movement termination occurred 169.2±1.5 ms after perturbation onset across all experimental conditions. However, time to terminate arm movement was influenced by a direction main effect ($F_{1,9}$=9.26; p=0.014). Participants required 4±1.3 ms more time to terminate movement following a forward directed perturbation, compared to a backward directed perturbation.

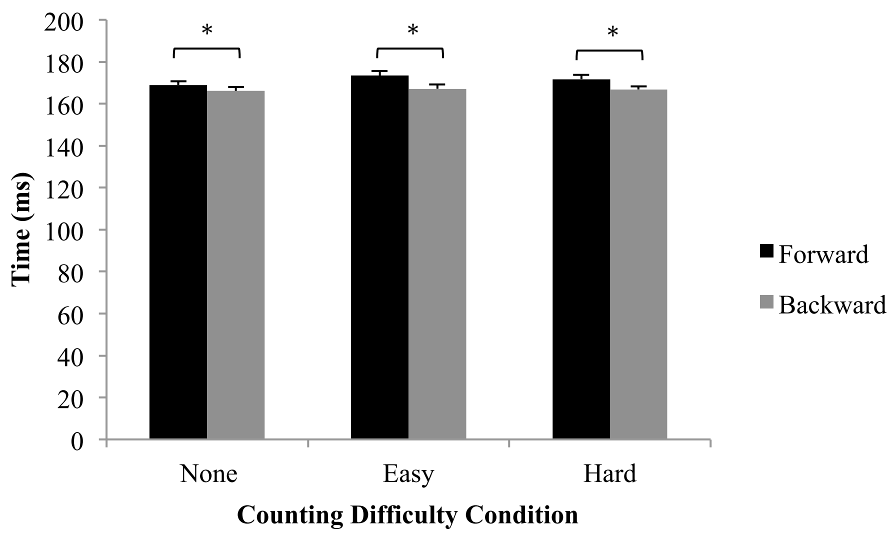

Figure 10: Mean + 1 SE time to terminate arm movement in the three counting difficulty conditions. In response to forward directed perturbations participants require more time to terminate movement than to a backward directed perturbation. * indicates a difference (p<0.05).

Total arm displacement was influenced by a counting difficulty main effect ($F_{2,52}$=4.68; p=0.014). Displacement of the right arm was 0.07±0.03 m greater during the hard dual-task than the single-task (no counting) balance task condition (p=0.041). Arm displacement was not different between the single-task balance and the easy dual-task conditions, or between the easy and hard dual-task conditions.

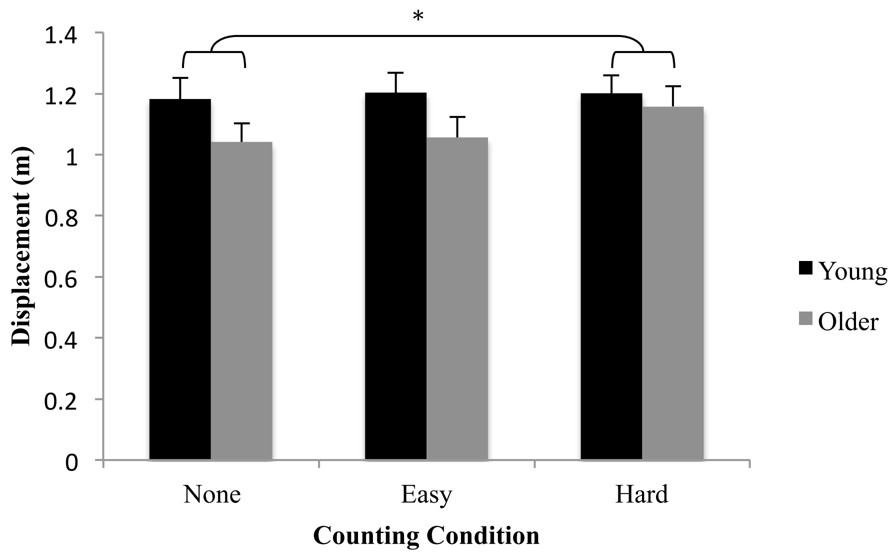

Figure 11: Mean + 1 SE displacement of the right arm in the three counting difficulty conditions. * indicates a difference (p<0.05).

4.7 Balance Recovery Strategies:

Both young and older adults relied on a stepping response even though they were instructed not to step. The number of stepping responses observed during each counting difficulty condition are presented in Table 3. Although there were no differences in the number of stepping responses that occurred between the three counting difficulty conditions, older adults appear to rely on a stepping response more frequently than the young adults.

Grasping responses did not occur as often as stepping responses (Table 3). The number of grasping responses did not differ between the three counting difficulty conditions or between the young and older adults.

		Counting Difficulty Condition		
Strategy	**Age Category**	**No Counting**	**Easy**	**Hard**
Stepping	Young adults	8.1 ± 3.4	8.0 ± 3.7	8.5 ± 3.4
	Older adults	9.4 ± 3.0	9.8 ± 2.7	10 ± 2.8
	Overall	8.7 ± 3.3	8.8 ± 3.4	9.1 ± 3.2
Grasping	Young adults	4.6 ± 4.3	3.9 ± 4.1	3.7 ± 4.2
	Older adults	4.5 ± 4.0	4.4 ± 4.1	3.9 ± 3.6
	Overall	4.6 ± 4.1	4.1 ± 4.1	3.8 ± 3.9

Table 3: Average + 1 SD number of trials (out of 12) with observed stepping and grasping responses for young and older adults during each of the counting difficulty conditions.

5.0 Discussion:

The purposes of this thesis were to determine (i) whether dual-tasking influences an individual's ability to generate a compensatory arm response following a loss of balance, (ii) whether the amount of dual-task influence is scaled to the difficulty of the cognitive task, and (iii) whether older adults are more influenced by dual-tasking than younger adults. Contrary to the hypotheses, compensatory arm responses that occurred in response to a loss of balance were minimally influenced by or scaled to the level of dual-task difficulty. Further, there were few disproportionate effects between older and young adults.

5.1 Cognitive Task Influence on Static and Anticipatory Measures:

Many studies have examined the effects of dual-tasking in young and older adults. Relying primarily on static (e.g., quiet standing) and anticipatory balance tasks (e.g., TUG), previous research has reported declines in dual-task performance, with larger effects occurring when the tasks are made more difficult or are performed by older compared to young adults (Medley & Thompson, 2005; Pellecchia, 2003; Shumway-Cook et al., 2000; Sturnieks et al., 2008). Based on this study's functional assessment measures as well as those obtained during the static postural component of the dual-task protocol, the results of this thesis largely corroborate with these previous findings. For example, it was found that participants required more time to complete the TUG_{Hard} (i.e., TUG while counting backwards by 7's) than the TUG_{Easy} (i.e., TUG while counting backwards by 2's) or the TUG test, with larger declines in performance in older compared to young adults. Similarly, when counting performance prior to a perturbation was considered, both young and older adults responded with fewer correct responses (decreases of 11.2 and 8.2 responses, respectively) during the hard compared to the easy counting difficulty condition. Finally, participant self-reported focus of attention was greater by 6 % for the hard compared to the easy counting difficulty condition.

In contrast to the aforementioned results, the RMS error of the COP signal did not scale to the difficulty of the cognitive task. Specifically, no differences in the RMS of AP and ML COP signal were observed between the easy and hard dual-task conditions. This lack of finding may have occurred because the cognitive requirements associated with standing on a solid surface were not large enough to cause a significant task interference effect. To see a change in the RMS of the COP it may be necessary to have participants stand on a compliant surface (e.g., foam). The greater postural instability, combined with a difficult cognitive task, would force individuals to use additional cognitive resources, leading to a greater task interference effect. Consequently, greater postural sway should be observed (Pellecchia, 2003). While standing on foam could have resulted in greater dual-task difficulty and larger declines in balance task performance, a compliant surface was not used for this study. It was thought that a more difficult balance task would make it less likely that individuals would exhibit a foot in place strategy and would reduce their reliance on a compensatory arm response for balance recovery.

In spite of some observed inconsistencies, the results of this study generally suggest that the three levels of counting difficulty (i.e., no counting, counting backwards by 2's, counting backwards by 7's) provided the intended step-wise increase in the amount of cognitive resources required for cognitive task performance. Consequently, fewer resources can be assumed to have been available for the balance task and thus, declines in balance task performance were often observed. Further, differences in performance between the young and older adults on the TUG tests suggest that dual-tasking had a greater effect on the older adults at each of the three counting difficulty levels.

5.2 Cognitive Task Influence on Reactive Postural Control:

Although dual-tasking and the difficulty level of the cognitive task influenced many of the static and anticipatory postural control measures, they had limited influence on an individual's ability to generate a compensatory arm response to a loss of balance. EMG onset latencies from only two (i.e., left and right AD) of the eight muscles were affected by dual-tasking or dual-task difficulty. Similarly, only five (i.e., Left AD and MG; right MD, PD and MG) of the eight recorded muscles demonstrated changes in EMG amplitude with the addition of a cognitive task or with an increase in dual-task difficulty. As a result, it is not surprising that there were little differences in the kinematics of the right arm between the various experimental conditions. In addition to the small and inconsistent number of dependent measures being affected with the cognitive task or increasing dual-task difficulty, the amount of change for each of these measures was quite small. Across all experimental conditions, EMG onset latencies differed by 3.2-7.2 ms while changes in EMG amplitudes ranged from a decrease of 2%

to an increase of 3.5% MVC. Similarly, the presence of dual-tasking only resulted in the right arm being initiated less than 1.5 ms earlier and displacing 7 cm greater compared to the single balance task condition. Thus, even when a significant finding was observed, the functional consequences of dual-tasking and dual-task difficulty to the generation of compensatory arm responses appears to be minimal.

The minimal relationship between dual-tasking or dual-task difficulty and the ability to generate a compensatory arm response is surprising. This suggests that cognitive resources required by the secondary cognitive task were not required or relied upon for the generation of a compensatory arm response. This would imply that postural responses of the upper limbs are controlled differently than those of the lower limbs. These results contrast with the work of Rankin et al. (2000), who used a similar dual-task paradigm to establish that lower limb postural responses are smaller during dual- compared to single-tasking. Further, the current results do not agree with the work of Bolton et al. (2011) who used TMS to demonstrate that motor cortical areas are required for the generation of compensatory grasping responses to a loss of balance.

Several reasons may account for why this study's results do not support previous work. First, it is possible that the chosen dual-task paradigm was not appropriate or sensitive enough for eliciting changes in compensatory arm responses. For example, despite instructions to continue with the cognitive task, many participants stopped counting immediately after perturbation onset. This may have occurred because participants adopted a posture first strategy (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997), where they rapidly switched their attention from the cognitive to the balance task in order to prevent a fall. If this were the case, dual-tasking would not actually have taken place during the balance recovery phase. However, since attention switching is believed to take place around ~180-390 ms after perturbation (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001), which is much later than the initial arm response measured in this study, the participants should have still been affected by some amount of task interference. Thus, the likelihood that attention switching was responsible for the minimal effect of dual-tasking at varying cognitive task difficulty levels is small. Nevertheless the use of a continuous tracking instead of a counting task could help to determine and confirm when attention switching and dual-task interference effects occur

Alternatively, there is the possibility that the specific cortical areas utilized by the cognitive task, may not be required during compensatory arm response generation. It is an assumption of dual-task research that individuals require activation of common cortical areas for processing and completing the balance and cognitive tasks. Mihara, Miyai, Hatakenaka, Kubota, and Sakoda (2008) observed increased activation of the prefrontal cortex, and posterior parietal cortex, presumably to allocate attention to postural control when individuals lost their balance. Similarly, the prefrontal cortex, the superior and inferior parietal areas as well as the lingual and fusiform gyri are known to activate during the performance of a mental arithmetic task (Rickard et al., 2000). Therefore, based on capacity models of attention, task interference effects should be observed when both tasks are performed at the same time. However, it is important to acknowledge that there may be other neural structures that are not shared between a balance and cognitive task. For example, cortical areas such as the supplementary motor area (SMA), and sub-cortical structures such as the cerebellum have also been deemed important for maintaining posture and scaling responses to a loss of balance (Morton &

Bastian, 2004; Mushiake, Inase, & Tanji, 1991). Furthermore, if compensatory arm responses can be pre-planned, due to warning of an upcoming perturbation, or through prior experience, there will be increased activation of the posterior parietal cortex as well as the SMA (Mihara et al., 2008). Both are believed to be preparatory mechanisms to integrate vestibular stimuli and prepare to initiate a balance correcting response (Mihara et al., 2008). Since the participants of the study received familiarization trials at the beginning of the experiment and were aware of the unchanging nature of the perturbation characteristics, it is likely that they were able to develop a compensatory motor plan prior to perturbation onset (Sparrow & Tirosh, 2005), and thus, could rely on neural structures that were not involved in the cognitive task. This could explain the small interference effects that were observed with cognitive task and increasing dual-task difficulty.

It is also possible that the choice of balance task was not ideal to elicit differences in compensatory arm responses. The support surface translations in the current study employed larger displacements and peak velocities than what has previously been used (Brown et al., 1999; Rankin et al., 2000). If participants deemed the platform perturbations to be too difficult to recover balance using a foot in place strategy, this would explain why both young and older adults relied on a stepping strategy for balance recovery. A stepping response was observed in 68±6% and 81±5% of trials for the young and older adults, respectively, even though participants were instructed to refrain from using a step and had their feet constrained by a foam surround. Consequently, any observed compensatory arm response would likely have been smaller than if a grasping response was prioritized as the only means of balance recovery. In order to decrease the predictability and reliance on a stepping strategy for balance recovery, incorporating continuous or multidirectional surface translations or physically constraining foot movement may increase the likelihood of observing a compensatory arm response for balance recovery.

Differences in the ability to generate compensatory arm reactions between young and older adults during single- and dual-tasking were quite small or opposite to what has previously been reported. For example, previous work have found that compared to young adults, older adults elicit arm muscle responses that are 15-74 ms slower and 16% smaller to a loss of balance (Weaver et al., 2012). Older adults have been shown to be more negatively influenced by dual-tasking than young adults (Rankin et al., 2000). This contrasts with the current results, where compared to young adults, older adults demonstrated earlier EMG onset latencies in the left AD and MD, as well as larger EMG amplitudes in the left AD, MD and PD during the dual-task conditions. The results indicate that the older adults of this study were not more negatively affected by the presence of a dual-task or with increasing cognitive task difficulty. The contrasting results cannot be attributed to the study's older adults having a higher balance and/or cognitive function than "normal" because the same participants exhibited the typical age-related declines during dual-task performance when static and dynamic postural tasks were involved (see section 5.1). It is also unlikely that the study tested too young of an older adult cohort, as age-related deficits in muscle onset latencies and amplitudes have previously been found in older adults with a mean age of 69 years (Weaver et al., 2012) (compared to the older adults of the present study with a mean age of 71 years). Exclusion criteria such as requiring participants to be free of any neurological and sensory disorders, joint pain and musculoskeletal injury are also consistent between studies. Therefore, the lack of dual-task related deficits may be an indicator that the use of a dual-task paradigm, as incorporated in this study, may be better suited for assessing static or anticipatory instead of reactive balance control.

5.3 Practical Implications:

Multi-faceted exercise programs have recently included balance training combined with dual-task performance to mimic real-life situations. However, based on the findings of the current study, using training exercises that specifically target compensatory arm responses while dual-tasking need not be of high priority for all older adults. This does not indicate that training dual-tasking abilities should be avoided completely. There are still many potential benefits of dual-task exercises such as enabling older adults to gain more confidence when performing two tasks simultaneously, as well as helping to maintain their cognitive function, and improve their overall reactive balance abilities. Further, the importance of training compensatory arm responses while dual-tasking may have the greatest benefits for balance impaired older adults who are at an increased risk of experiencing a fall and fall-related injuries.

5.4 Conclusion:

In conclusion, this study found that dual-tasking, regardless of difficulty level, had minimal effects on an individual's ability to generate compensatory arm responses to an unexpected loss of balance. This suggests that compensatory arm responses are activated via different mechanisms than postural responses of the lower limbs. However, given the discrepancy in findings between the results of this study and those incorporating TMS (which can directly assess the cortical contribution to movement control), it is more probable that a dual-task paradigm, particularly as employed in this study, is not a sensitive enough method to examine the neural control of reactive balance control strategies of the upper limbs. Therefore, due to the contrasting nature of the findings in the current study, more research is required to determine the mechanisms responsible for compensatory arm response generation and control.

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APPENDIX A

ABC scale - F

0____10____20____30____40____50____60____70____80____90____100

I do not feel at all confident	I feel moderately confident	I feel completely confident

Please use the scale to rate the <u>amount of confidence</u> you have in <u>avoiding a fall</u> when you have to:

1. **Walk around house** __________
2. **Walk up/down stairs** __________
3. **Pick up object from floor** __________
4. **Reach forward** __________
5. **Reach forward on tiptoes** __________
6. **Stand on chair to reach object** __________
7. **Sweep the floor** __________
8. **Walk outside to nearby car** __________
9. **Get in/out of car** __________
10. **Walk across parking lot** __________
11. **Walk up/down ramp** __________
12. **Walk in crowded mall** __________
13. **Walk in crowd and bumped in to** __________
14. **Ride escalator holding rail** __________
15. **Ride escalator not holding rail** __________
16. **Walk on icy sidewalk** __________

APPENDIX B

Edinburgh Handedness Inventory

Participant ID: _________ __ Sex: ___________

Please indicate your preference in using your left or right hand in the following tasks by putting a + in the appropriate box.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put + +.
If you are indifferent, put one + in each column.

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsycholoolgia*, *9*, 97-113.

	Task/Object	**Left Hand**	**Right Hand**
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (Upper Hand)		
9	Striking a Match (match)		
10	Opening box (lid)		
11	Which foot do you prefer to kick with?		
12	Which eye do you use when using only one?		
	Total + Signs:	LH=	RH=
	Cumulative Total:	CT = LH + RH =	
	Difference:	D = RH – LH =	
	Result:	R = (D/CT) x 100 =	
	Interpretation: Left Handed: R<-40 Ambidextrous: -40≤R≤+40 Right Handed: R>+40		

APPENDIX C

Fall Risk Questionnaire

1. I have fallen in the last 6 months..YES / NO

   A fall is “an unexpected event in which you came to rest on the ground, floor, or lower level.”
2. I am worried about falling...YES / NO
3. Sometimes, I feel unsteady when I am walking....................................YES / NO
4. I steady myself by holding onto furniture when walking at home.........YES / NO
5. I use or have been advised to use a cane or walker to get around safely. ....

   ....YES / NO
6. I need to push with my hands to stand up from a chair..........................YES / NO
7. I have some trouble stepping up onto a curb...YES / NO
8. I often have to rush to the toilet...YES / NO
9. I have lost some feeling in my feet...YES / NO
10. I take medicine that sometimes makes me feel light-headed or more tired than usual. ....YES / NO
11. I take medicine to help me sleep or improve my mood. ....YES / NO
12. I often feel sad or depressed..YES / NO
13. Because I don’t see well, I have difficulty avoiding hazards in my path, such as tree roots or electrical cords. ....YES / NO

APPENDIX D

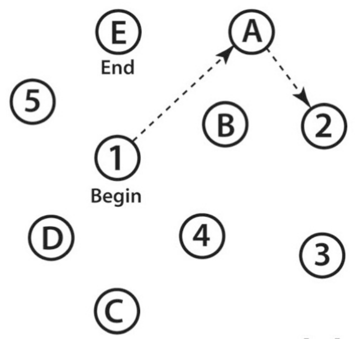
NAME :
Education : **Date of birth :**
Sex : **DATE :**

MONTREAL COGNITIVE ASSESSMENT (MOCA)

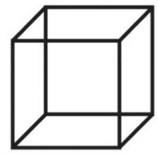
Version 7.1 Original Version

POINTS

VISUOSPATIAL / EXECUTIVE



[ ]



Copy cube

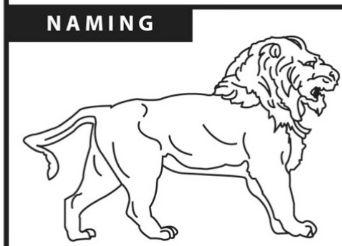
[ ]

Draw CLOCK (Ten past eleven)
(3 points)

[ ] Contour [ ] Numbers [ ] Hands

___/5

NAMING



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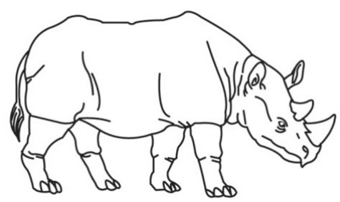

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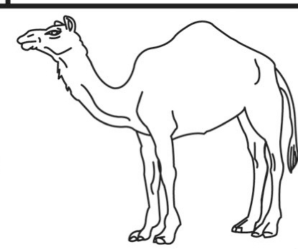

[ ]

___/3

MEMORY

Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful.
Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION

Read list of digits (1 digit/ sec.).
Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2

___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B

___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**

___/3

LANGUAGE

Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ]

___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words)

___/1

ABSTRACTION

Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler

___/2

DELAYED RECALL

Has to recall words	FACE	VELVET	CHURCH	DAISY	RED	
WITH NO CUE	[ ]	[ ]	[ ]	[ ]	[ ]	Points for UNCUED recall only
Optional Category cue						
Multiple choice cue						

___/5

ORIENTATION

[ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City

___/6

Normal ≥26 / 30

TOTAL ___/30
Add 1 point if ≤ 12 yr edu

Administered by: ______________________________

APPENDIX E

Mean (SE) EMG Onset latency for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed in ms from perturbation onset.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	143 (3)	144 (4)	143 (3)
	Left MD	144 (3)	143 (3)	147 (3)
	Left PD	156 (4)	157 (4)	161 (5)
	Right AD	136 (3)	136 (3)	135 (3)
	Right MD	140 (3)	139 (3)	141 (3)
	Right PD	149 (5)	147 (3)	151 (4)
	Right MG	133 (4)	135(3)	134 (4)
	Right TA	182 (6)	182 (6)	180 (6)
Forward	Left AD	152 (4)	149 (4)	147 (4)
	Left MD	148 (4)	144 (4)	143 (4)
	Left PD	153 (4)	151 (5)	151 (6)
	Right AD	141 (3)	140 (3)	137 (3)
	Right MD	140 (3)	135 (3)	135 (3)
	Right PD	141 (3)	138 (4)	139 (3)
	Right MG	214 (11)	215 (11)	213 (11)
	Right TA	122 (2)	122 (2)	124 (2)

APPENDIX F

Mean (SE) background EMG amplitude for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed as % MVC.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	0.73 (0.08)	0.94 (0.15)	0.86 (0.13)
	Left MD	1.18 (0.12)	1.46 (0.22)	1.40 (0.18)
	Left PD	1.18 (0.12)	1.57 (0.23)	1.50 (0.20)
	Right AD	0.70 (0.09)	0.79 (0.09)	0.78 (0.09)
	Right MD	1.18 (0.15)	1.41 (0.20)	1.35 (0.17)
	Right PD	1.31 (0.16)	1.50 (0.23)	1.46 (0.19)
	Right MG	8.13 (0.82)	8.50 (0.76)	8.31 (0.71)
	Right TA	4.59 (0.38)	4.92 (0.43)	4.63 (0.40)
Forward	Left AD	0.72 (0.07)	0.87 (0.13)	0.94 (0.15)
	Left MD	1.20 (0.13)	1.34 (0.17)	1.47 (0.19)
	Left PD	1.19 (0.12)	1.43 (0.18)	1.61 (0.22)
	Right AD	0.71 (0.09)	0.75 (0.09)	0.83 (0.12)
	Right MD	1.19 (0.15)	1.29 (0.17)	1.49 (0.23)
	Right PD	1.30 (0.17)	1.47 (0.19)	1.63 (0.24)
	Right MG	7.39 (0.70)	7.83 (0.74)	7.69 (0.76)
	Right TA	4.87 (0.39)	4.97 (0.42)	4.74 (0.44)

APPENDIX G

Mean (SE) 0-100 ms EMG amplitude for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed as % MVC.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	15.00 (0.08)	16.50 (1.90)	15.94 (1.87)
	Left MD	16.10 (2.34)	16.81 (2.52)	16.75 (2.42)
	Left PD	15.13 (2.09)	15.52 (1.86)	14.82 (1.72)
	Right AD	19.63 (2.68)	19.84 (2.89)	19.54 (3.05)
	Right MD	24.35 (3.45)	23.63 (3.39)	23.50 (3.63)
	Right PD	22.85 (2.64)	22.89 (2.57)	22.37 (2.42)
	Right MG	37.08 (3.13)	37.80 (3.42)	37.89 (3.27)
	Right TA	39.59 (3.58)	42.03 (3.60)	41.72 (3.95)
Forward	Left AD	20.35 (2.26)	20.07 (0.13)	20.04 (2.50)
	Left MD	22.63 (3.51)	21.78 (3.70)	21.84 (4.00)
	Left PD	20.16 (2.53)	21.08 (2.87)	19.41 (2.69)
	Right AD	23.67 (2.34)	21.79 (2.51)	22.41 (2.20)
	Right MD	31.08 (3.81)	27.76 (3.51)	28.52 (3.57)
	Right PD	26.41 (2.59)	23.95 (2.41)	23.09 (2.49)
	Right MG	24.07 (2.21)	27.48 (2.48)	24.94 (2.43)
	Right TA	62.26 (2.75)	62.00 (2.78)	62.91 (2.66)

APPENDIX H

Mean (SE) 100-200 ms EMG amplitude for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed as % MVC.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	7.69 (1.26)	9.60 (1.43)	9.32 (1.56)
	Left MD	9.06 (1.34)	10.82 (1.52)	10.96 (1.59)
	Left PD	10.65 (1.62)	11.37 (1.63)	11.76 (1.81)
	Right AD	13.08 (2.14)	12.63 (1.97)	12.95 (1.88)
	Right MD	15.37 (2.40)	15.08 (2.22)	15.64 (2.42)
	Right PD	15.20 (1.84)	14.89 (1.67)	15.64 (1.89)
	Right MG	22.89 (2.60)	23.01 (2.46)	23.96 (3.02)
	Right TA	39.39 (4.04)	39.04 (4.05)	37.48 (3.90)
Forward	Left AD	13.60 (2.75)	15.17 (2.41)	14.84 (2.61)
	Left MD	15.25 (2.22)	17.78 (2.71)	17.54 (3.00)
	Left PD	17.11 (2.55)	19.31 (2.97)	18.62 (2.99)
	Right AD	17.95 (2.29)	19.99 (2.68)	18.87 (2.55)
	Right MD	24.76 (3.24)	26.38 (3.48)	26.49 (3.68)
	Right PD	23.80 (2.93)	23.69 (2.57)	24.17 (2.87)
	Right MG	19.41 (2.01)	20.15 (2.27)	18.11 (1.96)
	Right TA	63.35 (4.32)	59.17 (3.98)	61.75 (4.29)

APPENDIX I

Mean (SE) 200-300 ms EMG amplitude for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed as % MVC.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	7.30 (1.29)	6.36 (1.12)	7.05 (1.25)
	Left MD	7.68 (1.12)	7.69 (1.40)	7.62 (1.25)
	Left PD	9.69 (1.42)	9.40 (1.40)	9.27 (1.38)
	Right AD	11.96 (2.03)	12.50 (2.06)	11.10 (1.99)
	Right MD	11.72 (1.79)	11.79 (1.91)	11.01 (1.79)
	Right PD	11.63 (1.58)	11.79 (1.63)	10.99 (1.46)
	Right MG	31.96 (2.95)	31.77 (3.27)	32.81 (3.04)
	Right TA	22.99 (2.62)	22.69 (2.59)	21.26 (2.55)
Forward	Left AD	10.86 (1.71)	10.95 (1.81)	11.52 (1.88)
	Left MD	11.51 (1.90)	11.51 (1.91)	13.63 (2.63)
	Left PD	11.39 (1.83)	11.74 (2.18)	12.58 (2.25)
	Right AD	14.25 (1.95)	12.47 (1.81)	13.96 (1.96)
	Right MD	18.35 (2.68)	16.55 (2.41)	19.24 (3.07)
	Right PD	17.23 (2.50)	17.21 (2.50)	17.88 (2.98)
	Right MG	17.87 (2.56)	16.33 (1.66)	16.31 (2.14)
	Right TA	54.55 (4.27)	54.17 (4.60)	52.28 (4.07)

APPENDIX J

Mean (SE) 300-400 ms EMG amplitude for each muscle in the forward and backward perturbation directions for all counting difficulty conditions. All values are expressed as % MVC.

Direction	Muscle	Quiet	Easy	Hard
Backward	Left AD	7.67 (1.26)	8.09 (1.25)	7.69 (1.14)
	Left MD	8.85 (1.24)	9.27 (1.32)	9.58 (1.42)
	Left PD	9.79 (1.37)	9.35 (1.18)	10.03 (1.53)
	Right AD	12.27 (1.79)	12.81 (1.94)	12.57 (1.80)
	Right MD	13.10 (1.69)	12.17 (1.54)	12.77 (1.58)
	Right PD	12.94 (1.65)	12.56 (1.61)	13.70 (1.73)
	Right MG	33.04 (2.80)	34.97 (2.89)	33.64 (2.57)
	Right TA	22.33 (2.44)	23.83 (2.83)	21.45 (2.35)
Forward	Left AD	13.35 (1.59)	13.26 (1.64)	14.10 (1.75)
	Left MD	13.12 (1.70)	13.14 (1.84)	15.85 (3.28)
	Left PD	12.44 (1.87)	12.19 (1.96)	12.34 (1.78)
	Right AD	15.16 (1.84)	14.76 (1.93)	15.73 (1.99)
	Right MD	20.31 (2.86)	18.69 (3.00)	21.16 (3.73)
	Right PD	19.44 (2.85)	19.12 (3.48)	21.20 (3.98)
	Right MG	16.66 (2.30)	17.39 (2.16)	15.93 (1.84)
	Right TA	57.49 (3.65)	57.12 (3.49)	57.60 (3.55)