The Impact of Balance Disturbance on Cognition

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THE IMPACT OF BALANCE CHALLENGE ON COGNITION

by

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ABSTRACT

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Erin Elizabeth Quasney, M.S.

Marquette University, 2016

There have been remarkable gains within the scientific literature over the last few decades contributing to our understanding of the sequelae, recovery, and treatment of mild traumatic brain injury (mTBI), yet our knowledge of relationships among symptoms remains elementary in comparison. Cognitive and balance deficits are two of the most prevalent consequence of mTBI. There is some indication that a challenge to one or both of these functions can result in cognitive detriments due to constraints on attentional capacity. However, the evidence remains both conflicting and sparse. This study examined the impact of increasing balance challenge on attention and working memory. Forty-three healthy young adults completed three balance tasks of varying difficulty levels while also engaging first in an auditory sustained attention test followed by a verbal working memory task. These tasks were completed while participants stood on a force platform to measure postural sway during the three respective stances. While no differences in cognitive performance were evident based on level of balance challenge, sustained attention was predicted by both postural sway as measured by the force platform and by errors on a modified Balance Error Scoring System. In conclusion, these findings reveal a significant relationship between balance performance and sustained attention but not between balance performance and working memory, suggesting that impairments in balance may contribute to attentional impairments, even among healthy individuals. This highlights the importance of considering balance impairment as a contributing factor in cognitive symptoms among individuals with mTBI and, more broadly, among patients with various other neurologic and complex medical conditions.

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Literature Review

Traumatic brain injury (TBI), particularly mild traumatic brain injury (mTBI), continues to be a front-page favorite among popular media outfits. This is partially due to its high base rate among children and other beloved members of our society, like athletes and military service members, but also in part because there is much that remains unclear about how to best minimize acute symptoms and protect against adverse consequences without reacting with undue alarm. While the scope of research investigations addressing questions involving mTBI has grown exponentially over the last decade, gaps certainly remain. One such gap involves the interaction of cognitive and physical symptoms. More specifically, we know little about the impact that one common sequelae of mTBI, balance disturbance, might have on another common sequelae, deficits in memory and attention. Before launching into further discussion on this topic, this thesis will briefly review the prevalence, mechanisms, and personal and societal impact of mTBI.

Introduction to Traumatic Brain Injury and mTBI

TBI refers to a structural lesion or physiological disruption of brain function due to an external force acting upon central nervous system in a manner that immediately results in at least one of the following clinical features: (1) decrease or complete loss of consciousness (LOC) for any period, (2) retrograde or posttraumatic amnesia, (3) any degree and length of neurological deficits, and/or (4) any intracranial lesion (DoD/DVA, 2009). mTBI is commonly understood as being on the mild end of a TBI severity continuum (Bigler, 2008). The components listed above that serve to define TBI are also the components commonly used to differentiate between varying levels of TBI severity and between varying levels of mTBI severity. The DoD/DVA TBI grading system is presented in Table 1. It should be noted that for the purposes of this thesis, the terms “mTBI” and “concussion” are used interchangeably.

Table 1

Traumatic Brain Injury Grading Criteria

	Grade		
Criteria	Mild	Moderate	Severe
Structural imaging	Normal	Normal or abnormal	Normal or abnormal
Loss of consciousness	0–30 minutes	30 min – 24 hours	> 24 hours
Alteration of consciousness	< 24 hours	> 24 hours	
Post-traumatic amnesia	0–1 days	1 day – 7 days	> 7 days
Glasgow Coma Scale	13-15	9-12	< 9

Note. Adapted from DoD/DVA, 2009

Prevalence of TBI and mTBI. The existence of mTBI as a public health concern is a valid one, both in the scope of the population affected and in the associated financial implications. In 2010, the Centers for Disease Control and Prevention (CDC) released a report indicating that approximately 1.7 million people present at the emergency room annually due to traumatic brain injury (Faul, Xu, Wald, & Coronado, 2010), accounting for 30.5% of all injury-related deaths. Falls are the most common cause of TBI, accounting for 35.2% of these types of injuries, followed by motor vehicle accidents (17.3%). Those in the 0-4 age range are the most likely to acquire TBI, and men have a greater incidence of mTBI than do women (Bazarian et al., 2005; Faul et al., 2010). Because many individuals with concussion report to outpatient settings and even more don't seek medical care at all, estimates of TBI likely underestimate the true incidence (Faul et al., 2010; Orman et al., 2011; Sosin, Sniezek, & Thurman, 1996). Taking all of this into account, estimates of mTBI among the general public likely range from 1.2 to 3.8 million per year (Bazarian et al., 2005; Faul et al., 2010), which is equivalent to an estimated approximate population-based rate of above 600/100,000 per year (Cassidy et al., 2004). Prospective designs not reliant on retrospective self-report suggest a lifetime prevalence of TBI (up to the age of 25 year old) of 24% for females and 38% for males (McKinlay et al., 2008).

Mechanisms of injury, biomechanics, and neuropathology of mTBI. To understand the consequences of mTBI, one must be familiar with the mechanisms contributing to their cause. In addition to coup and contrecoup injuries (i.e., those that occur at the location of impact and those that occur on the part of the brain opposite the site of impact, respectively), shearing or tearing of axons may occur as a result of the rotation of the cerebrum around the fulcrum of the immobile brainstem (Ommaya, Grubb, & Naumann, 1971; Shaw, 2002; Viano et al., 2005). Areas susceptible to this type diffuse axonal injury include long white matter tracts such as those found in the corpus callosum, fornix, and medial temporal lobe regions (Bigler, 2012). Indeed, diffusion tensor imaging (DTI), a neuroimaging technique involving measurement of restricted diffusion of water molecules along nerve fibers (Mori & Tournier, 2014), reveals reduced white matter integrity in the corpus callosum, centrum semiovale, and internal capsule of patients with mTBI relative to controls (Inglese et al., 2005).

While lesions (Smith, 2011) can occur in a sizeable portion of people with mTBI, the great majority of those with mTBI have no structural damage visible on imaging traditionally used in clinical settings. Damage from mTBI not associated with specific lesions may come from diffuse axonal injury (Farkas & Povlishok, 2007). Accompanying these structural changes are metabolic changes related to abnormalities in the balance of potassium, sodium, calcium, and magnesium ions in the intra and extracellular space (Giza & Hovda, 2014).

Functional imaging research indicates increased activation during working memory tasks (e.g., Lovell et al., 2007), even when no impairment is detected on the cognitive tasks (McAllister et al., 2006; McAllister et al., 1999), suggesting that those with mTBI have deficits in their ability to optimally allocate or sustain attentional resources compared to controls (Belanger et al., 2007; McAllister et al., 1999; Pardini et al., 2010). In considering fMRI data from various studies, McCrea and colleagues (2009) propose a theory to explain the pattern of physiological recovery of mTBI. This theory suggests that within 24 hours of injury, decreased activation is evident in attention-related neural circuits. This appears to be followed by increased, perhaps compensatory, activation within one month after the injury and eventual subsequent return to normal activation patterns.

In order to understand the assumptions being tested in this investigation regarding the relationship between attention and balance disturbances following mTBI, one must have a basic understanding of (1) attention as a broad cognitive process and (2) theories regarding divided attention.

Attention

Attention in healthy individuals. Attention is understood as a system of components working together as a portal that monitors and allows information to enter the brain to be further processed (Cohen, 1993). It plays a role in the selection of pertinent information from the internal and/or external environment. Selective attention is the process by which an individual chooses one stimuli to attend to among competing stimuli available in both environments. Its function is to triage – to make decisions about what stimuli should be processed at a given time (Carr, 2004). As there is a limited amount of attentional resources for use at any one time, selective processes must determine what aspect(s) of the environment is/are most relevant to consider (Broadbent, 1958; Desimone & Duncan, 1995; Kastner & Ungerleider, 2000). Stimuli compete for attention based on various characteristics, such as uniqueness (Lavie & Cox, 1997), novelty (Jonides & Yantis, 1988), and pertinence or salience to the task at hand (Desimone & Duncan, 1995; Moray, 1959).

***Attentional capacity*.** Selective attention is a necessary mental process due to limits on attentional capacity. Filter theories of selective attention suggest that the amount of information that can be processed at one time is limited, necessitating use of a filter (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1960), while capacity theories focus on the quantity of information that can be processed simultaneously. Investigated first by Moray (1967) and later developed by Kahneman (1973), limited capacity theory suggests the existence of a general upper limit to the amount of information that can be attended to. An individual is able to allocate this limited attention among various stimuli based on a number of different factors, including level of arousal, transitory intention, and interest level (Baldwin, 2012; Galotti, 2008; Kahneman, 1973).

Capacity theory sets the stage for understanding divided attention. Divided attention refers to the ability (or inability) to perform two tasks at one time efficiently (or inefficiently). Specific to divided attention, capacity sharing theory (Kahneman, 1973;Wickens, 1980) holds that if two tasks are being performed concurrently, limited attentional reserves must be shared and allocated among them and are, therefore, diminished for each individual task, resulting in impaired performance on one or both tasks. Task-switching models suggest that, at least for some types of tasks, two tasks simply cannot be performed concurrently due to shared mechanisms of action and that in such an event, a bottleneck occurs that delays the processing of one of the two tasks (Bonnel & Hafster, 1998; Pashler, 1994; Sperling & Melchner, 1978). Thus, attention must switch between the two tasks. Over the years, support has accumulated for this theory (Al-Hashimi, Zanto, & Gazzaley, 2015; Marois & Ivanoff, 2005; Pashler, 1994; Tombu et al., 2011), including neuroimaging research suggesting that the bottleneck takes place in networks implicated in executive control (Al-Hashimi et al., 2015). Specific regions involved include frontal and parietal regions, including the superior parietal lobule (SPL), inferior parietal sulcus, inferior frontal junction, inferior frontal sulcus, as well as subregions within the superior, middle and inferior frontal gyri (Deprez et al., 2013; Herath, Klingberg, Young, Amunts, & Roland, 2001; Jiang, 2004; Takeuchi et al., 2013; Tombu et al., 2011).

In practice, response delays and errors are the hallmark costs of multitasking and are therefore often used in measuring dual-task performance (Al-Hashimi, Zanto, & Gazzaley, 2015). Several variables can influence the degree of impact of dual-tasking and result in costs in functioning. First, the ability to efficiently complete simultaneous tasks relies on task difficulty (Baldwin, 2012; Wickens, 1980; Wickens, 1984). The greater the difficulty of a task when performed alone, the greater likelihood that it will create larger dual-task costs when performed concurrently with other tasks (Baldwin, 2012; Wickens, 2008). Second, competition for use of certain networks or structures also impacts the degree of dual-task effects (Baldwin, 2012; Wickens, 1980; Wickens, 1984). It necessarily follows that sensory modality matters as well. If two tasks are of the same modality (e.g., two visual tasks) there may be more interference and, thus, poorer performance on one or both tasks than if the tasks are of different modalities and dependent on unique networks or structures. A series of studies by Wickens (1980, 1984, 2008) demonstrates that tasks presented in the same modality result in greater performance detriment than that which occurs when tasks are presented in different modalities. However, just because dual-task costs are generally more severe when tasks are of the same modality, this does not mean that dual-task costs do not exist when tasks are of different modalities (e.g., see Jolicoeur, 1999). Third, stage of processing (e.g., processing of cognitive and perceptual tasks versus selecting and carrying out action) also influences the efficiency of "time-shared tasks." Essentially, Wickens (1984, 2008) postulates that the more differences between two time-shared tasks that exist, the more efficient the performance. Finally, age has a well-documented influence on dual-task performance (Lindenberger, Marsiske, & Baltes, 2000; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003), with dual-task costs being greater in older adults, above and beyond the effect of aging-related general cognitive slowing.

Working memory. Working memory is closely affiliated with (and reliant on) attention systems, as this brief storage space provides the first holding place for information attended to in the internal or external environment (Kastner & Ungerleider, 2000; Knudsen, 2007). Working memory refers to a system that takes in information from perceptual sources and briefly retains and reserves this information in a setting where it can be manipulated (Baddeley, 2003), acting as a bridge to connect incoming perceptual information to long-term memory stores. It is also a limited capacity system and, thus, can store and maintain only a restricted amount of information at any one time. The amount of information that can be stored is based, in part, on unique individual differences (Daneman & Merikle, 1996).

The prefrontal cortex is activated in many diverse tasks that require working memory and is thought to function in the role of issuing executive control over regions that vary according to what type of information is being manipulated (Braver et al., 1997; Cohen et al., 1997; Knudsen, 2007; Miller, Erickson, & Desimone, 1996). The prefrontal cortex has connections both with brain regions involved in processing sensory and motor information from the external environment and with regions involved in long-term memory storage (Baddeley, 2003; Knudsen, 2007). The language areas in the temporal and inferior parietal cortex as well as the ventrolateral prefrontal cortex are involved in working memory when the information attended to is verbal in nature, whereas the dorsolateral prefrontal cortex, the right inferior parietal cortex, and the occipital cortex are involved when the information is visual in nature (Knudsen, 2007).

Effects of mTBI on Cognition

Having outlined attention and working memory functioning in healthy individuals, it is possible to focus on deficits observed in individuals with brain injury. Deficits related to mTBI are frequently observed on standardized neuropsychological measures. The most common include slowed processing speed (Cicerone, 1997; Cicerone & Azulay, 2002; McCrea et al., 2003; Petersen, Ferrara, Mrazik, Piland, & Elliott, 2003) and variable attention and working memory (Chan, Hoosain, Lee, Fan, & Fong, 2003; Chan, 2005; Cicerone, 1997; van Donkelaar et al., 2005; Echemendia, Putukian, Mackin, Julian, & Shoss, 2001; Halterman et al., 2006; Malojcic et al., 2008; Mayer et al., 2012; McAllister et al., 2001; McIntire et al., 2006; Stuss et al., 1989). Also common are deficits in speeded naming (Barrow, Collins, & Britt, 2006a; Barrow et al., 2006b), verbal fluency (Belanger et al., 2005; Binder et al., 1997; Echemendia et al., 2001; McCrea et al., 2003), and delayed memory (Echemendia et al., 2001; Malojcic et al., 2008; McCrea et al., 2003; Nolan, 2006), which are perhaps secondary to primary deficits in speed and attention. It is widely accepted that cognitive deficits are most salient within the first couple of days after sustaining an mTBI and that they then tend to dissipate within a few days to one week post-injury (Barth et al., 1989; Echemendia et al., 2001; Macchiocchi et al., 1996; McCrea et al., 2003).

Attention following mTBI deserves closer attention. Meta-analytic studies suggest that attention measures may be one of the most sensitive indices of mTBI (e.g., see Binder et al., 1997), and because attention is an essential cognitive ability for the proper participation in many other cognitive domains (e.g., memory), this topic is especially important in understanding a range of neurocognitive deficits following mTBI. Specific patterns of attentional deficits may exist among sufferers of mTBI. Sustained attention (Chan, 2005; Cicerone, 1996; Malojcic et al., 2008; Stuss et al., 1989), divided attention (Cicerone, 1996), and selective attention (van Donkelaar et al., 2005; Halterman et al., 2006; Mayer et al., 2012; McIntire et al., 2006) difficulties are commonly reported. In addition, working memory impairments are also commonly detected (Cicerone & Azulay, 2002; McAllister et al., 2001).

Functional imaging studies offer further support for the existence of attention deficits following mTBI. Even when performance deficits are not identified on traditional neuropsychological tests, there may be inefficiencies in brain activation while these tasks are completed. In one study, symptom severity was associated with bilateral prefrontal and parietal cortical hyperactivation on fMRI during a working memory task but was not associated with task accuracy, suggesting that as symptoms increase, more cognitive resources may be necessary in order to accurately complete the task (Pardini et al., 2010). Some researchers hypothesize that neurocognitive tests that assess different domains of attentional functioning (e.g., Attentional Network Test; Fan, McCandliss, Sommer, Raz, & Posner, 2002) may provide insight into the relationship between different types of attention deficits and functional brain areas most vulnerable to mTBI (van Donkelaar et al., 2005). An alternative hypothesis (but one that does not exclude the possibility of the first) may be that some cognitive dysfunction following mTBI is the result of decreased cognitive reserve due to additional resource allocation to complete a single cognitive task, leaving less attentional resources for completion of other tasks.

Postural Control

In addition to cognitive symptoms, individuals with mTBI frequently report difficulties with balance, including dizziness, vertigo, and/or lightheadedness. Dizziness is reported by over 75% of individuals in the acute phase following mTBI (McCrea, 2008), and athletes with mTBI demonstrate balance deficits relative to matched controls (Guskiewicz, Perrin, & Gansneder, 1996). These are understood to be the result of actual postural control deficits stemming from problems with sensory integration (Guskiewicz, 2001). In addition, there is evidence of sensory neural hearing loss following concussion resulting from disruption of the fluid of the inner ear, which also is implicated in balance symptoms (Nölle, Todt, Seidl, & Ernst, 2004). To appreciate this in form of deficit, one must be familiar with the mechanisms of postural control in the absence of brain injury.

Postural control in healthy individuals.

Physiological maintenance of postural control. Postural orientation involves positioning the torso and head in relation to gravity, supporting surfaces, and the visual environment (Horak, 2006). In order to maintain postural control in this way, corrective torque is required to work against destabilizing torque through a series of feedback mechanisms generated when the visual, somatosensory, and/or vestibular systems detect body sway, or an instance when the orientation of the body diverges from reference points (Peterka, 2002). The sensory information from the visual, somatosensory, and vestibular systems must then be integrated in order to be useful for the initiation and execution of an appropriate musculoskeletal response (Guskiewicz, 2001; Horak, 2006; Shumway-Cook & Horak, 1986; Widmaier, Raff, & Strang, 2008). Different weights can be given to the sensory information coming in from each of these systems based on the environment. Healthy individuals in the absence of environmental hazards or challenges base corrective motor responses on somatosensory input (70%), vestibular input (20%), and visual input (10%; Peterka, 2002). If one source of input is compromised (e.g., visual system is compromised in a dark room), the central nervous system is responsible for reintegrating or redistributing weight as optimally as possible (Horak, 2006).

Postural control deficits in mTBI. Balance related symptoms reported in the days and weeks after mTBI (e.g., dizziness, vertigo, and/or lightheadedness) are understood to be the result of actual postural control deficits associated with issues of sensory integration (Guskiewicz, 2001). Dizziness, one of the most common complaints following mTBI, is endorsed by more than 75% of injured individuals (McCrea, 2008). It is not surprising, then, that postural control deficits are often identified during assessment using either clinical (Riemann & Guskiewicz, 2000) or force plate measures (Guskiewicz et al., 1996; Sosnoff, Broglio, & Ferrara, 2008), and that it is standard to assess balance performance as part of the comprehensive sideline testing of athletes to guide return-to-play decisions (Broglio, Ferrara, Sopiarz, & Kelly, 2008; Guskiewicz et al., 1996).

Longitudinal testing to track the course of recovery of balance perturbation following brain injury reveals that it continues for several days following concussion (Broglio, Sosnoff, & Ferrara, 2009; Cavanaugh et al., 2005; Guskiewicz et al., 1996) and may remain in effect for greater than 10 days following injury (Broglio & Puetz, 2008; Petersen et al., 2003). Notably, these balance deficits may remain in the absence of self-reported balance-related symptoms, suggesting that there may be a balance deficit even when it is not noticeable to the patient (Broglio et al., 2009; Riemann et al., 2000).

Contributions to postural control deficits following mTBI. Subcortical central nervous system structures implicated in postural control include the cerebellum, basal ganglia, and brainstem nuclei. In addition, cortical areas, including the association cortex and somatosensory cortex, as well as areas involved in attention, memory, and emotion contribute to balance control, as well (Guskiewicz, 2001). The breadth of brain regions and cognitive processes involved in postural control allows for numerous and varied potential mechanisms for the balance disturbances observed after mTBI.

The two most likely mechanisms for balance deficits include damage to peripheral vestibular receptors, resulting in the relay of inaccurate information about the individual's position in space, or dysfunction of the actual central integration processes necessary for integrating incoming information and determining motor response (Guskiewicz, 2001; Guskiewicz et al., 2001). Regarding the latter contribution, Guskiewicz and colleagues (1996) used an experimental protocol that allowed for the assessment of balance performance following disturbance of each of the three sensory systems (i.e., visual, somatosensory, and vestibular) implicated in its successful maintenance. The researchers found that, relative to controls and to their own baseline test results, individuals with mTBI experience vestibular deficits that contribute to their increased sway on force plate measures. The contributions of these two mechanisms are not mutually exclusive; they may, at times, both have a hand in balance deficits.

In addition, it also has been proposed that balance deficits after concussion could be partially explained by primary attentional or processing speed deficits resulting from the head injury, as it is known that these cognitive deficits are prominent sequelae of mTBI (Guskiewicz, 2001; Guskiewicz et al., 2001). This hypothesis remains speculative. Additional research is necessary to parse out the etiological contributions and potential cognitive consequences of balance deficits after concussion.

The Interaction of Attention and Postural Control

As stated above, postural control does not occur only at an automatic level through the interaction of the spinal cord and brainstem. It involves higher order cognitive processes as well (Horak, 2006; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Teasdale & Simoneau, 2001). Thus, it is not inconceivable to imagine the existence of a relationship between balance and cognition. Indeed, the interaction between postural instability and neurocognitive deficits has been presented and debated in the literature (Ellemberg, Henry, Macciocchi, Guskiewicz, & Brogio, 2009; Guskiewicz, 2001; Hanes & McCollum, 2006).

To clarify how this relationship is plausible, its theoretical support will be reviewed. As discussed previously, if two tasks are performed concurrently, limited attentional reserves must be shared and allocated among them and are, therefore, diminished for each individual task, resulting in impaired performance on one or both tasks (Kahneman, 1973; Wickens, 1980). This impaired performance when tasks are performed concurrently in comparison to when they are performed alone is referred to as a dual-task effect. There is some evidence of a dual-task effect of a secondary cognitive task on postural stability in healthy adults (e.g., Rankin et al., 2000), suggesting that attentional demands are required during balance maintenance. The tax on the attentional system seems to increase with age, which can be partially explained by age-related changes that occur to the three sensory systems implicated in postural control (Rankin et al., 2000). It has been suggested that as age-related decline occurs within these sensory systems, a greater degree of attentional resources must be allocated to maintain postural control, leaving, in turn, fewer resources to complete a specific cognitive task. In support of this idea, Rankin and colleagues (2000) found a decrease in neuromotor response during platform perturbation while subjects were also performing a math task as opposed to when subjects were performing the balance perturbation task alone. They argue that this finding supports the idea that attention is necessary for balance maintenance, and it is also in line with limited capacity theories (Kahneman, 1973; Wickens, 1980; Wickens, 1984). When multiple tasks must share a limited amount of resource capacity and the resources must be distributed between them, fewer resources exist for any individual task and this leads to performance impairment (Catena et al., 2011; Teasdale et al., 1993; Yardley et al., 2001).

If attention is indeed necessary for balance maintenance, it is fair to postulate that the reverse is also true. When there is balance disturbance (as in mTBI), the attention necessary to correct this disturbance should theoretically take away from that which is available for other tasks. This proposition entails that when incoming sensory information is skewed during balance challenge tasks (such as the one indicated above) or when there is some sort of disturbance of balance (as exists with mTBI), cognitive resource recruitment occurs with the purpose of initiating a corrective response. This resource recruitment requires engagement of the dorsolateral prefrontal cortex, the presupplementary motor area, and the anterior cingulate cortex (Serrien, Ivry, & Swinnen, 2007). A greater proportion of the limited cognitive resources available now must be directed towards maintaining balance, leaving a smaller proportion available to devote to other simultaneously performed cognitive tasks. Maki & McIlroy (2007) suggest that the execution of corrective, stabilizing reactions in response to balance perturbation demands attentional resources and, thus, interferes with other cognitive processes. The following section will explore additional lines of evidence in support of the interaction between balance and cognition, including correlational research that explores the relationship between these domains as well as dual-task investigations that highlight the existence of balance-cognitive effects.

Associations between balance and attention. Correlational research, despite the inherent problem of being unable to draw any assumptions about the direction of influence, provides a starting point for examining the relationship between motor and cognitive functions following mTBI. Sosnoff and colleagues (2008) examined the association between balance as measured objectively through center of pressure recordings and neuropsychological test performance on measures administered to a group of varsity level college athletes both at baseline and following physician diagnosed mTBI. After mTBI, there were large correlations between three neurocognitive tasks - visual memory, verbal memory, and reaction time - and balance scores whereas these correlations did not exist prior to the injury leading the investigators to suggest that an association exists between cognitive and motor function following mTBI. The possibility of a meaningful relationship can also be found in patients' symptom reports. For example, in one study, there were strong positive relationships between self-reported balance problems and the cognitive complaints of feeling "mentally foggy" and having "difficulty concentrating" (Broglio et al., 2009).

Investigations examining recovery curves after concussion have also been conducted with the purpose of determining the existence of a relationship between balance disturbance and cognitive deficits following mTBI. While some findings support similar recovery curves for postural instability and neuropsychological performance (Guskiewicz et al., 2001; Petersen et al., 2003), others do not (Broglio & Puetz, 2008; Parker, Osternig, van Donkelaar, & Chou, 2007). Differences in measurement techniques (e.g., balance assessment or cognitive assessment) conceivably contribute to the contrasting findings. However, even if cognitive and balance deficits resolve differently and are not directly related in a dose-response fashion, this does not necessarily mean that partial contributions do not exist. It is not entirely clear why these different recovery trajectories have been observed; however, sample demographics, measurement method, and task difficulty may be contributory.

In addition to the association between balance and cognition in individuals with head injury, similar relationships are found between balance and cognition in studies involving individuals with other neurological disorders. For example, children with cerebellar lesions show mild working memory deficits (Konczak & Timmann, 2007), and children with attention-deficit/hyperactivity disorder (ADHD) perform more poorly than controls on balance tasks (Shum & Pang, 2009; Zang et al., 2002).

Some researchers speculate that correlations between postural instability and cognitive deficits following mTBI are the result of a shared mechanism impacting both constructs (Broglio et al., 2009), which supports both bottleneck (Sperling & Melchner, 1978) and cross-talk (Navon & Miller, 1987) theories of dual-task interference. Specific to balance and cognition, bottleneck models suggest that one would not be able to engage in centrally mediated balance maintenance, for example, without "pausing" the processing of the cognitive task, presumably resulting in poorer performance (Maki & McIlroy, 2007; Pashler, 1994). Cross-talk theory (Navon & Miller, 1987) suggests that the necessity for similar "processing machinery" for both tasks results in static created by one task that interferes with processing of the other (Maki & McIlroy, 2007; Pashler, 1994; Pashler, 1999). Dual-task effects between balance and cognition may be due either to the contending sensory requirements required for each task or to contending motor control requirements necessary for maintenance of postural control and cognitive response engagement (Yardley et al., 2001).

It also seems possible that there is some degree of causal relationship between the two – perhaps that balance deficits contribute to cognitive deficits, or vice versa. Cognition is involved in motor control through attention to action. The prefrontal cortex guides selective attention. In the case of motor tasks, attentional resources are implicated in the selection and maintenance of motor control (Serrien et al., 2007). When balance is disturbed, as in mTBI (and various other neurological disorders, such as movement disorders and multiple sclerosis, among others), theory would indicate that one sequelae of this disturbance may be that it requires more attentional resources to maintain balance and, thus, fewer resources to efficiently carry out cognitive tasks. This theory can be tested using a dual-task design involving cognitive and postural control tasks.

Balance-cognition dual-task research. Dual-task design involves comparison of performance of a particular task in isolation with performance on that task when there is a concurrently performed second task and, due to the experimental manipulation involved, can offer a clearer picture than correlational research of the impact of the addition of a second task on the performance of the first. When there is a change in performance when the tasks are performed together, this is referred to as a dual-task effect. A dual-task effect suggests that attention is divided – that there is competition occurring for attentional resources (Andersson, Hagman, Talianzadeh, Svedberg, Larsen, 2002).

The two possible outcomes when employing dual-task design to the study of cognition and balance are the following: (1) the possible effect of a balance challenge on cognition and (2) the possible effect of a cognitive challenge on balance. Should performance impairment exist on the cognitive task in the presence of the balance task, it can be deduced that the balance task requires attention – attention that is limited in terms of load and now must be reallocated, perhaps leaving less attentional resources for the cognitive task (Maki & McIlroy, 2007).

A review of research examining the dual-task effects of simultaneously presented cognitive tasks and balance tasks results in inconsistent findings. Examples exist of simultaneous performance deficits on either the cognitive task (Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1993), the balance task (Dault, Geurts, Mulder, & Duysens, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997), both (Brauer, Woollacott, & Shumway-Cook, 2001), or neither (Akram & Frank, 2009). This research has been performed with healthy subjects and neurologically impaired subjects, using paradigms that allow assessment of both static and dynamic postural control.

Dual-task results with healthy participants. There is limited support for the notion that postural instability can result in reduced cognitive task performance, even in healthy young adults (Brauer et al., 2002; Kerr et al., 1985; Swan, Otani, & Loubert, 2007; Yardley et al., 2001). During a more challenging balance task (versus a less challenging balance task), Yardley and colleagues (2001) reported increased reaction time on low load cognitive tasks (i.e., low attentional resources required) and decreased accuracy on high load cognitive tasks (i.e., high attentional resources required). The same has been reported using a vocal reaction time task (Brauer et al., 2002) and a spatial memory task during blindfolded tandem stance (Kerr et al., 1985). Similarly, Swan and colleagues (2007) reported decreased cognitive performance when blindfolded participants were standing (either feet together stance, tandem stance, or feet together stance with lower leg vibration) versus when they were sitting, which supports the hypothesis that postural instability, be it from balance system impairment, aging, or balance-task difficulty, can diminish attentional capacity, which can then result in impairment on cognitive tasks (Yardley et al., 2001). However, other research is contradictory, touting no cognitive deficits for healthy adults in the dual-task condition when balance is perturbed (Akram & Frank, 2009; Olivier, Cuisinier, Vaugoyeau, Nougier, & Assaiante, 2010). Obviously, the degree of balance disturbance should be such that its compensation requires processing above and beyond that which occurs at the automatic level. It is possible that balance tasks that inadequately tax the postural control system may, at times, be the reason for a lack of interference effects (Akram & Frank, 2009).

Likely due to the extensive technological distractors present in our everyday lives and due to an understandable focus on physical safety, most investigators studying balance and attention have chosen to focus on the impact of a secondary cognitive task on motor performance. These studies suggest that postural control may be altered during simultaneous performance of a cognitive task (Dault et al., 2001). While there is limited support for the idea that the more difficult the cognitive task, the greater the postural sway (Pellecchia, 2003), this conflicts with a larger body of evidence suggesting no effect of accompanying cognitive task on balance (Akram & Frank, 2009 Dault et al., 2001; Yardley et al., 2001). Interestingly, the opposite has also been reported – decreased postural sway in the presence of a cognitive task (Riley, Baker, & Schmit, 2003; Swan, et al., 2007). Riley and colleagues (2003) administered a short-term memory task with three levels of difficulty and compared both balance and cognitive performance in these three conditions to a control condition. Participants showed reduced postural sway under more difficult memory conditions. The authors suggest that their findings support the posture-first principle, which indicates that maintenance of balance is given priority over other tasks due to its influence on avoidance of bodily harm (Andersson et al., 2003; Catena et al., 2011; Maki & McIlroy, 2007; Redfern, Muller, Jennings, & Furman, 2002). Thus, resources are allocated in such a way that posture and balance are favored over other tasks (Redfern et al., 2002). They also argue that general arousal may increase as cognitive demand increases, thus improving balance performance.

Dual-task results with balance-impaired participants. Comparisons of dual-task performance in balance impaired adults versus control subjects reveals that older adults (Maylor & Wing, 1996) and those with pre-existing balance impairment (Brauer et al., 2001; Brauer, Woollacott, & Shumway-Cook, 2002; Negahban et al., 2011; Shumway-Cook et al., 1997; Yardley et al., 2001) appear to be especially susceptible to dual-task inference. For example, cognitive task decrements occur during dual-task conditions in balance-impaired older adults, as evidenced by longer reaction times (Brauer et al., 2002). Negahban and colleagues (2011) administered a silent backward counting task to healthy subjects and patients with multiple sclerosis (MS) under four different postural conditions. There were no differences in cognitive task performance regardless of level of difficulty of the balance task for either group. However, the MS group showed increased postural disturbance during the dual-task backward counting condition versus the single task condition, whereas the healthy adults did not.

Limited research is available specific to individuals with a history of mTBI. Gait disturbance and static postural control deficits are evident among individuals with mTBI when they are engaging in a simultaneously presented cognitive task (Catena et al., 2011; Catena, van Donkelaar, & Chou, 2009; Catena, van Donkelaar, & Chou, 2007; Catena, van Donkelaar, Halterman, & Chou, 2009; van Donkelaar, Osternig, & Chou, 2006; Kleffelgaard, Roe, Soberg, & Bergland, 2012; Parker et al., 2005; Parker, Osternig, van Donkelaar, & Chou, 2006). This interference effect has been found even in the subacute phases after injury and can extend for up to four weeks (Parker et al., 2006; Parker et al., 2007). However, these studies focus on the impact of an added cognitive task on postural control during gait and fail to even report cognitive task performance (e.g., Catena et al., 2009a; Parker et al., 2006). Of the very few studies that do, results are inconsistent and sample sizes are small. Some findings suggest there are deficits on the cognitive task during dual-task conditions (Catena et al., 2007) whereas others do not (Catena et al., 2011). The investigators in the latter study suggest that the cognitive task chosen, which was an auditory Stroop task, may have been inappropriate due to evidence of a ceiling effect during trials with little balance challenge.

Methodological considerations. There are a number of methodological issues that likely contribute to the vast discrepancy among results presented here. Perhaps the most obvious of these include the type of cognitive task chosen, the level of difficulty of the cognitive task, and the level of difficulty of the balance task. Some studies make use of more difficult tasks than others, and this could certainly affect outcome (Andersson et al., 2001; Andersson et al., 2003; Baldwin, 2012; Pellechia, 2003; Wickens, 2008). If a cognitive task is relatively easy, for example, the attentional resources required for its successful completion are less than if the task is more complicated (Maki & McIlroy, 2007). As such, an added balance task may not tax attentional resources to the degree that would impact task performance on a relatively easy cognitive task. Likewise, if a balance task is too challenging and an individual feels as though he or she is likely to fall, attention may shift quickly to avoidance of that fall (Maki & McIlroy, 1996; Yardley et al., 2001). Thus, the degree of difficulty of the balance task should be such that it is sufficient to induce sway but not so difficult that the subject is regularly falling. On the other hand, too stable of a stance would allow participants to allocate attention primarily to the cognitive task, which could result in increased postural sway during the dual-task condition with no impact on cognitive task performance.

Cognitive outcome measures of choice and response style should also be considered. Tasks with a reaction time component appear to be more sensitive to dual-task effects when balance is perturbed than those with only an accuracy component (Anderrson et al., 2002; Teasdale et al., 1993). In addition, a verbally mediated response may result in sway due to postural perturbation brought on by articulation and accompanied respiration (Yardley, Gardner, Leadbetter, & Lavie, 1999). Some researchers also question the impact of a visual task on postural sway, as eye movement may have the potential to impact balance during more difficult balance tasks (Dault et al., 2001; Hanes & McCollum, 2006).

Current Study

Neuropsychologists play an important role in the evaluation of cognitive and emotional sequelae of mTBI. They provide guidance for return-to-play and return-to-duty decisions in both the acute and subacute phases of injury. After emergency room visits, they are often key members of multidisciplinary teams that conduct follow-up evaluations. They provide psychoeducation to patients and family members about when they should expect to return to normal cognitive functioning. They also either treat directly or make treatment recommendations to guide patients toward avenues to reduce distress and impairment should symptoms persist past the typical window of recovery. Given the depth of this involvement with the mTBI population, it seems imperative that neuropsychologists strive to fully understand the etiology of their patients' symptoms. This topic is equally relevant to other patient populations treated by neuropsychologists, including but not limited to movement disorders, multiple sclerosis, dementia, and primary brain tumor as well as non-neurologic medical conditions impacting balance (e.g., peripheral neuropathy, vision loss), medication side-effects, and even healthy aging. Given the broad reach of the question, the paucity of research examining the impact of balance disturbance on attention is surprising. This thesis attempts to contribute to more complete management of these conditions through better understanding of overlapping symptoms.

Both balance and cognition are frequently impaired in the hours and days following mTBI. Sparse dual-task research suggests that increased balance perturbation can lead to increased cognitive difficulties (e.g., Brauer et al., 2002; Swan et al., 2007;

Yardley et al., 2001); however, findings are predominantly mixed (e.g., Akram & Frank, 2009; Olivier et al., 2010), making conclusions difficult to draw. In addition, the great majority of these investigations are presented in biomechanics and physical therapy journals, meaning that clinical neuropsychologists have very little exposure to the limited literature that is available and that cognitive assessment often seems secondary in nature and glossed over in the reporting of results. Of the literature that *is* available, there is only scant focus on the impact of balance on cognition. Instead, researchers' focus is typically on understanding whether challenging cognitive tasks impact balance. Not only is the cognitive piece secondary, but the methods of assessing cognition in many of these dual-task studies tend to be inadequate due to ease or inability to measure what they are intended to measure. In addition, the mTBI literature only very minimally explores this relationship and what it may mean for patients in terms of functional outcomes and management of symptoms and cognitive deficits. The overarching purpose of this thesis is to explore the impact of increasing balance challenge on attention and working memory performance.

Should it be determined using a sound methodological approach and a greater focus on the cognitive portion of the experiment that balance deficits impact attention and working memory, even in healthy subjects, this will help to inform not just our understanding of the etiological contributions to these symptoms after mTBI, but also their management and treatment. mTBI patients may be more often encouraged to take part in physical rehabilitation to improve balance functioning early in recovery, for example. Or there might be a decrease in the weight and meaning given to cognitive deficits remaining after mTBI should balance deficits be present in tandem.

The current paradigm elucidates the causal impact of balance disturbance on attention and working memory by having participants engage in balance tasks of increasing difficulty while also performing cognitive tasks – one each of sustained attention and working memory. The sustained attention task has several outcome measures, including accuracy, reaction time, and reaction time variability. The outcomes of interest for the working memory task are the number of correct responses for each of two levels of task difficulty as well as total number of correct responses overall.

It is hypothesized that as balance tasks increase in difficulty from least difficult to most difficult, accuracy will decrease on the sustained attention task. Additionally, it is expected that reaction time and reaction time variability will increase. In regard to the working memory task, a similar decrease in performance is expected. Specifically, a decrease in total correct responses is expected as participants attempt increasingly challenging balance tasks.

Method

Participants

Forty-three college students from a mid-sized private Midwestern University completed this study for course credit. Sample demographics are presented in Table 2. Participants ranged from 18- to 26-years-old, with a median age of approximately 19 years. They have an average of 13.07 years of education among them and a mean Scaled Score on the WTAR (Wechsler Test of Adult Reading; Holdnack, 2001) of 109.95. Participants were excluded if they endorsed more than transient dizziness within the last month, history of neurological conditions (e.g., epilepsy, ADHD; Swan et al., 2007), history of balance/vestibular disorder, or injuries incurred within the last year that have the potential to affect balance (e.g., ankle injury; Riley, 2003); however, no subjects endorsed any of the above. Participants were asked to abstain from alcohol for at least 8 hours prior to participation.

Tasks and Procedure

After completing a paper-and-pencil demographic questionnaire, subjects completed three trials of each cognitive task, while standing barefoot on a force platform centrally located in the lab. Subjects were instructed on how to carry out the first stance (of three, pseudorandomly administered). This process was repeated for each balance trial for each of the two cognitive tasks. Finally, participants completed a measure of estimated intelligence.

Table 2

Sample Characteristics

	Frequency	*M (SD)*	Range
Sex			
Female	37		
Male	6		
Age (years)		19.47 (1.79)	18-26
Height (inches)		65.52 (3.95)	59-74
Education (years)		13.07 (1.47)	12-18
Race			
Asian	4		
Black/African Amer.	1		
White	34		
Multiracial	2		
No Answer	2		
Ethnicity			
Hispanic/Latino	6		
Not Hispanic/Latino	37		
Exercise (days/week)		1.72 (.91)	0-4
WTAR Raw Score		38.49 (7.05)	20-50
WTAR SS		109.95 (12.07)	78-128

Note. *N*'s range from 36 to 43 due to occasional missing data. WTAR = Wechsler Test of Adult Reading. SS = Scaled Score (*M* = 100, *SD* = 15).

Balance manipulation and postural control assessment. Postural control was assessed under three conditions of increasing difficulty. The first condition was a double leg stance, which served as a control stance. Cognitive task performance in this stance could then be compared to performance while subjects engaged in more difficult stances. The second position was a tandem stance, which involved standing with the toes of the nondominant foot touching the heel of the dominant foot while feet were positioned in a line. The third and final stance was a single leg stance, which involved standing on the nondominant foot only. All conditions were performed with the arms and hands at rest at the participants' sides and with their eyes open. Subjects were instructed to keep their eyes on a white display board placed directly in front of the forceplate to minimize visual cues and increase balance challenge.

These stances were adapted from the Balance Error Scoring System (BESS; Riemann et al., 1999). The particular stances were chosen for two primary reasons. First, normative scores on the BESS were reviewed to determine body positions with increasing level of balance difficulty without so much difficulty that the subject is falling excessively. Of note, in its original form, the BESS is typically administered with the eyes closed, whereas this experiment allowed subjects to keep their eyes open. As such, it is expected that there will be less significant balance disturbance on the tasks used here as they do not exclude vision as a sensory contribution to balance maintenance. Second, particular stances were selected after collecting pilot data from 9 adult volunteers. Specifically, pilot subjects completed each of the BESS stances and balance errors and level of observable sway within a 120 second period were recorded. Volunteers made no errors during pilot testing of double leg stance and observationally, there was no visible sway. During the tandem stance, a total of one balance error was summed across all subjects. Sway was visible but minimal. Single nondominant leg stance yielded the most observable sway and resulted in a total of 2 balance errors across all subjects. This information in combination with BESS normative data supports the selection of these stances. Given this, it was expected that these three stances would adequately increase balance perturbation in a stepwise manner. During the experiments, balance performance was objectively measured in two ways. First, a research assistant who was trained in detecting BESS errors recorded each time a subject moved out of the desired stance. Errors included: (a) lifting hands above the waist, (b) taking a step, (c) stumbling/stepping/falling, (d) remaining out of the testing position for more than 5 seconds, (e) moving hip into more than 30˚ of either flexion or abduction, and (f) lifting any part of the foot or feet off of the floor. Participants were instructed that, should they lose their balance, they should make requisite corrections and to immediately return to the starting stance.

In addition to recording BESS errors, a vestibular force platform quantified postural control. Computerized posturography (Nashner, 1997) was obtained using an Advanced Mechanical Technologies, Inc. force plate on which participants stood barefoot for the duration of all balance and cognitive tasks. A vestibular force platform measures postural sway using sensors that record changes in center of mass or center of pressure over time (Riemann, Guskiewicz, & Shields, 1999; Guskiewicz et al., 2001). In brief, the differences in pressure detected by four sensors in the corners of each platform are utilized to define an individual's center of pressure variability over time, which is then used to compute sway area. Movement was recorded continuously, with 100 data points acquired every second (100 Hz). For visual representation, graphs of all raw data points for one participant (Subject 4) are provided in Figures 1-3. To reduce potential error that might have occurred from participants beginning and ending the tasks, the first and last 10 seconds of each trial were not included in the calculations. Postural sway was measured as the displacement of center of pressure (COP) in a two-dimensional horizontal plane on the support surface. To approximate the postural sway area, a closed parameterization of the recorded COP points was created from the maximum amplitude of sway in both the anterior-posterior (A-P) and medial-lateral (M-L) axes over the duration of the trial (Kim, Ferdjallah, & Harris, 2009). Figure 4 illustrates the procedure used to determine the outermost grid points. The outermost grid points form the optimum contour. Figure 5 depicts the optimum contour for Leg 1 during the Double Leg stance trial of the RASA for Subject 4. The sway area (SA) of this enclosed contour, an indication of precision of postural control, was then estimated by applying a numerical approximation of the Gauss-Green formula, where *M* is the number of grid points in the optimum contour.

$$SA = \frac{1}{4}\sum_{i=1}^{M}[(x_{i+1} + x_i)(y_{i+1} - y_i) - (x_{i+1} - x_i)(y_{i+1} + y_i)]$$

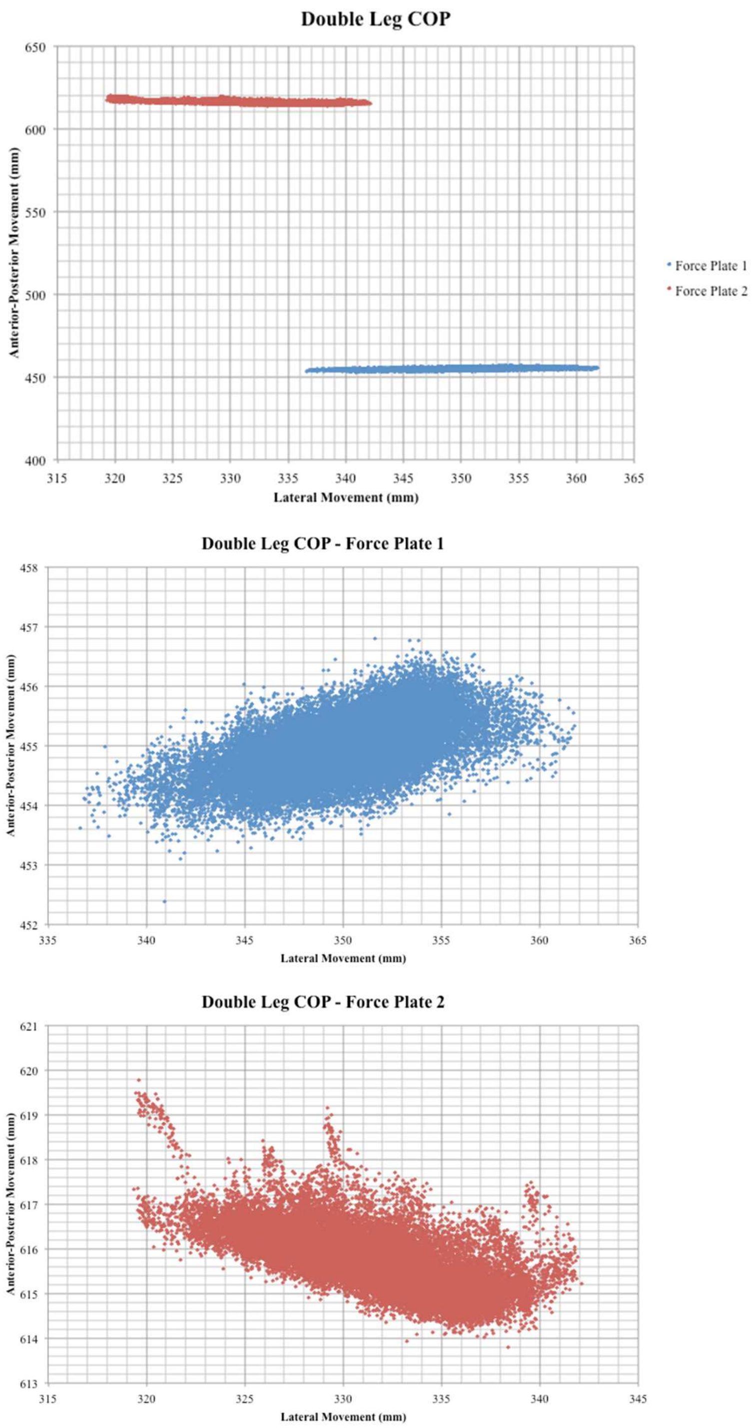

Figure 1. Raw COP data from Subject 4's Double Leg RASA trial displayed together (Graph A) and separately by each force plate (Graphs B and C).

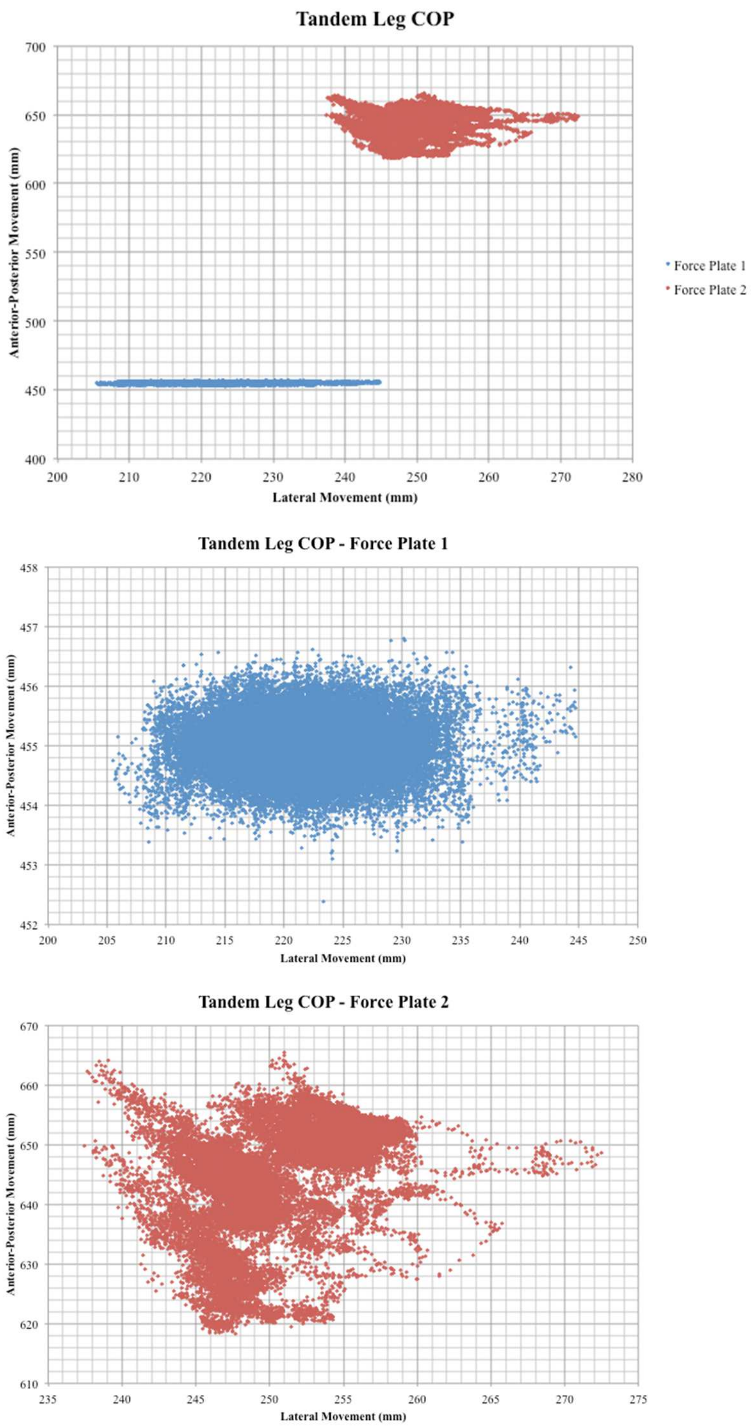

Figure 2. Raw COP data from Subject 4’s Tandem stance RASA trial displayed both together (Graph A) and separately by each force plate (Graphs B and C).

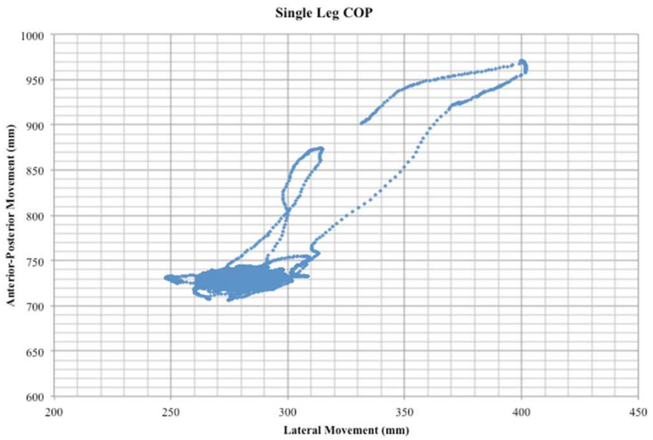

Figure 3. Raw COP data from Subject 4's Single Leg stance RASA trial.

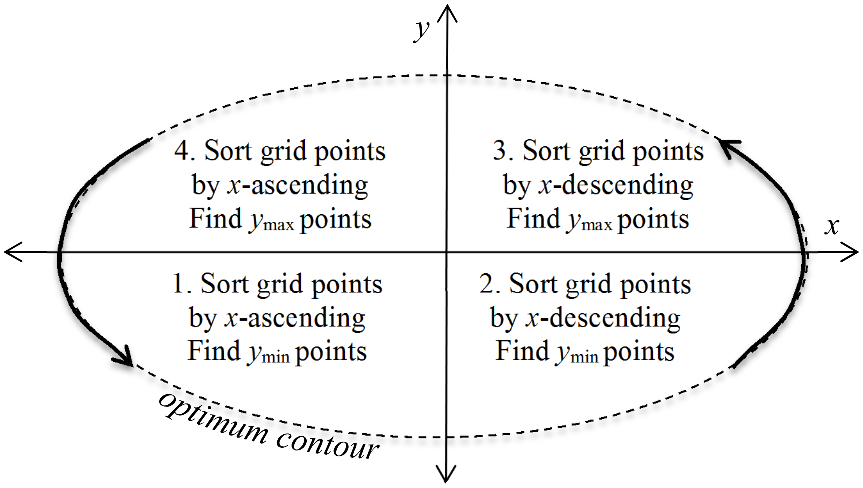

Figure 4. The procedure used to determine the outermost grid points in the anterior-posterior and lateral axes. Sway area of the outermost contour was then derived using the Gauss-Green formula.

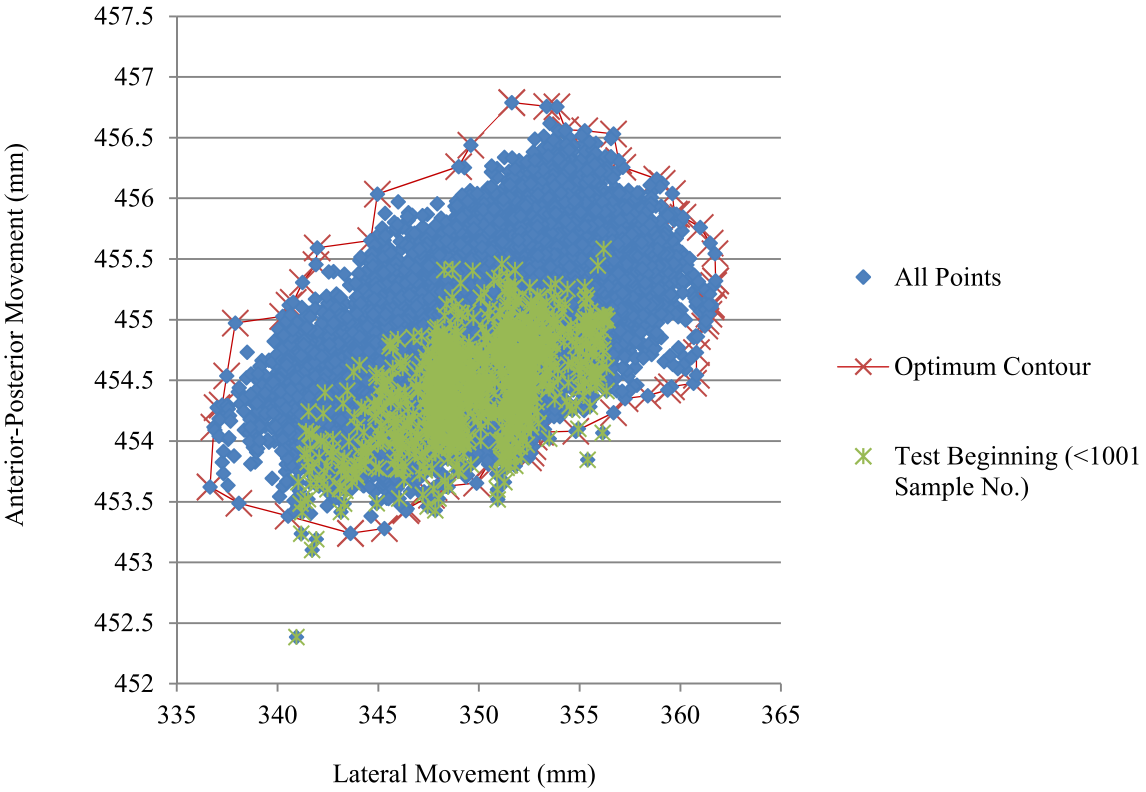

Figure 5. Raw COP data from Subject 4's Double Leg RASA trial for Leg 1. The optimum counter is displayed in red. Points displayed in green represent data points acquired during the first 10 seconds of the trial that were removed prior to subsequent analyses.

The Gauss-Green formula estimates the area within the optimum contour by generating and subsequently summing the area of smaller, two-dimensional rectangles whose area is defined as the differences between the maximum and minimum in sway in the A-P plane and sway in the the M-L plane (Kim et al., 2009). When summed, the area of the two-dimensional rectangular components define the area of the optimum contour. Finally, the sum is divided by 4. COP data is acquired by the force platform, whereby 4 sensors in the outer corners of each plate measure force applied to that corner alone, providing a measure of force distribution upon the platform and requiring computation of the area of a quarter of each contour at a time.

Practice effects occur when there are multiple exposures to the BESS over a short period of time (Broglio, Zhu, Sopiarz, & Park, 2009). In order to control for this, the order of balance task administration varied such that there was an equal number of participants engaging in each permutation of administration order. The sustained attention task was always completed prior to the working memory task. Subjects were given a short break in between each trial within a task and a longer break was offered between each cognitive task.

Cognitive tasks.

Sustained attention task. First, sustained attention was assessed using an experimental rapid information processing task. This task was modeled after the rapid visual information processing task (RVIP; Wesnes & Warburton, 1983), which was initially developed to evaluate the impact of nicotine on attention. It requires the subject to monitor rapidly presented digits over time and indicate a response to target stimuli. In addition to accuracy, the task allows for measurement of reaction time and reaction time variability. With the RVIP, Wesnes and Warburton (1983) demonstrated an increase in both accuracy and reaction time ten minutes after smoking a cigarette relative to performance before smoking. Both reaction time and reaction time variability are known to be sensitive markers of sustained attention (Segalowitz, Dywan, & Unsal, 1997; Tamm et al., 2012). Reaction time is affected by problems with sustained attention due to the impact of information processing deficits caused by attentional slips or lapses (Segalowitz et al., 1997). Reaction time variability (i.e., the within subject variation in reaction time) provides an indication of intermittent lapses in attention, which may reflect an interruption of task relevant brain activity by task irrelevant activity (Tamm et al., 2012). Developing the task allowed for the inclusion of each of these variables and provided the flexibility to adjust task length and speed of stimuli presentation during development. Additionally, the task was adapted as an auditory task to avoid the potential unwanted influence of visual stimuli on postural control. The adaptation developed for the present study will be referred to as the rapid auditory sustained attention (RASA) task.

During the RASA, the subject was required to monitor rapidly presented single digits (2-9) over time and indicate a response to target stimuli by button press. Digits were presented in the auditory modality through wireless headphones, and a wireless mouse was used to record button presses. A target stimulus was defined as any switch from odd numbers to even numbers, or from even numbers to odd numbers. See Figure 6 for an example. Digits were presented at a rate of 1 stimulus per 750 milliseconds or 80 stimuli per minute. Intersperse trials between target switches ranged from 2 to 5 digits long, and stimuli were presented pseudorandomly from previously derived digit strings. Total trial time was approximately 6 minutes to allow for ample targets to generate a reliable measure of intrasubject reaction time variability (Saville et al., 2012).

Outcome variables associated with the RASA included response accuracy; percent correct, or the percentage of total responses that were indeed correct; reaction time to targets; intrasubject reaction time variability, or the standard deviation of the reaction time across correct responses within the same trial (Saville et al., 2012); commissions; and omissions. Correct responses to target stimuli were defined as

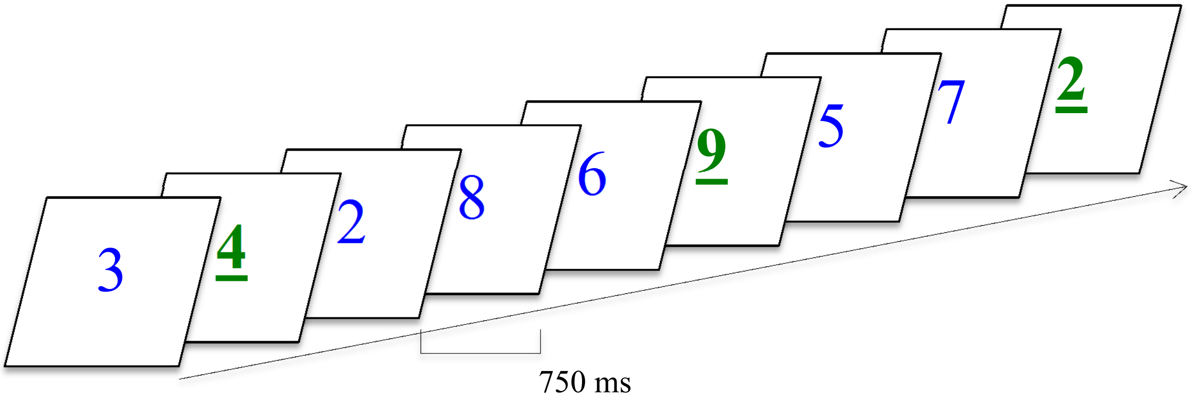

Figure 6. Example of the stimulus sequence for the RASA task. Participants respond to switches between odd and even digits or even and odd digits. Correct responses are denoted in green in addition to being underlined. There is a 750 ms interstimuli interval and between 2 and 5 intersperse stimuli between targets.

responses occurring (a) before the presentation of the subsequent target, (b) 350 ms after presentation of the target of interest, and (c) prior to an upper limit of 2500 ms after presentation of the target of interest. These cutoffs were chosen for several reasons. Healthy young adults have an average response time on simple auditory reaction time tasks of 230 ms (Jain, Bansal, Kumar, & Singh, 2015). Reaction time on choice reaction time tasks, such as this one used here, are longer (Der & Deary, 2006), with various factors contributing to just how much longer, including stimulus task difficulty and presence or absence of distraction (Lowe & Rabbit, 1998). Observation of performance and limits set by the subsequent target determined the acceptable upper limit. Commission errors were responses occurring within 350 ms of the target of interest as well as responses that followed a correct response but occurred before the presentation of a subsequent stimulus. Omission errors were defined as a lack of response following a target stimulus. To summarize, a correct response could be scored as such if it occurred between 350 ms and 2500 ms following the presentation of the target and did not follow a previous correct response.

Working memory task. Working memory was assessed using a modified version of the Auditory Consonant Trigrams test (ACT; Brown, 1958; Peterson & Peterson, 1959). During this modified ACT, participants must hold in working memory a series of three consonants (e.g., RXT) presented orally by a research assistant and recall them after a delay of either 9 or 36 seconds. During the delay period, the participant counts backward out loud, beginning from a 2 or 3 digit starting number offered by the experimenter immediately after the presentation of the consonant trigram. Five trials were presented for each delay period. Variables of interest include ACT Total Score, ACT Short Delay Score, and ACT Long Delay Score.

Normative data is provided by Stuss and colleagues (1987, 1988) for individuals between the ages of 16 and 69, and is stratified for trials with specific delay periods (9, 18, or 36 seconds). Internal consistency was determined to be high in a Turkish language version of the task (Anil et al., 2003), and small test retest effects are reported (Stuss et al., 1987, Stuss et al., 1989) in both neurologically intact and brain injured adults. Scores on the ACT correlate with measures of attention and working memory in healthy adults (Anil et al., 2003) and in a clinical sample (Boone et al., 1998). The ACT is able to differentiate between healthy controls and individuals with concussion (Stuss et al., 1989). It is, in fact, conceptually similar to the letter memory task that contributes to the Verbal Memory composite score on the ImPACT and provides a measure of working memory following concussion.

Finally, to estimate general intelligence the Wechsler Test of Adult Reading (WTAR; Psychological Corporation, 2001) was administered. This task involved reading 50 irregularly spelled words. The WTAR has good internal consistency (.90-.97) and correlates highly with the full scale intelligence quotient (FSIQ) and the verbal composite on the WAIS-III and moderately with other WAIS-III derived indices (Psychological Corporation, 2001). A raw score and a scaled score was calculated for each subject.

Results

Excluded and Missing Data

Forty-three subjects participated. One participant was excluded from all RASA analyses due to implausible performance that clearly indicated a lack of understanding of the task instructions. There was also missing RASA data as the result of hardware errors. Eight participants were missing data in all RASA administrations, while one additional participant was missing RASA data in the Double Leg condition and another participant was missing RASA data in the Single Leg condition. Four participants have no ACT data due to time constraints during the final stages of data collection. Each analysis included the maximum number of participants possible in order to strengthen statistical power, which at times results in slight inconsistencies in sample sizes.

Postural Stability

First, the success of the balance manipulation will be addressed. Raw sway area COP values for each subject in each condition are presented in Tables 3 and 4. Means and standard deviations of COP and BESS errors across conditions are represented in Table 5 as well as in Figures 7 and 8, respectively.

Table 3

Sway Area and BESS Errors During ACT Trials

Subject Number	Double Leg COP (mm^2)	Tandem COP (mm^2)	Tandem BESS Errors	Single Leg COP (mm^2)	Single Leg BESS Errors
1	3,024.95	2,263.85	0	1,271.83	0
2	134.35	5,979.92	2	8,578.30	32
3	577.91	2,005.96	0	2,724.93	3
4	189.86	4,730.73	2	2,173.44	3
5	194.88	1,091.52	0	6,795.36	12
6	3,266.10	2,371.40	0	2,038.04	9
7	351.96	2,592.77	1	4,265.42	3
8	140.66	965.42	0	648.48	0
9	5,649.07	1,456.87	0	20,806.56	43
10	6,418.62	4,955.96	0	4,082.63	7
11	3,347.69	3,358.40	5	3,431.77	9
12	190.38	7,357.88	1	1,640.37	4
13	13,613.64	7,547.79	0	8,981.19	4
14	756.20	2,059.94	0	1,673.13	0
15	2,054.14	2,284.47	0	1,345.44	0
16	1,450.45	1,690.14	0	28,387.95	1
17	1,363.98	2,736.78	0	2,055.45	5
18	81.69	1,073.31	0	1,224.18	4
19	753.01	26,192.08	6	8,983.74	39
20	576.02	3,460.27	0	2,143.34	6
21	5,148.48	8,344.48	1	2,480.48	6
22	1,673.83	2,599.90	1	8,116.83	9
23	248.37	8,482.97	2	1,295.19	5
24	2,312.79	4,553.09	0	2,496.42	0
25	207.43	739.35	0	795.05	0
26	2,447.62	2,641.30	2	3,114.80	6
27	355.85	5,246.30	1	7,738.72	3
28	703.09	2,895.00	0	1,648.56	6
29	4,786.26	8,725.73	5	6,720.17	21
30	19,157.58	50,500.17	6	37,400.19	12
31	928.61	2,880.67	0	3,971.63	8
32	517.97	9,237.77	1	4,399.08	15
33	11,911.33	6,905.79	0	30,399.14	8
34	6,323.71	4,112.31	1	1,840.86	6
35	3,101.29	9,613.63	1	23,467.86	3
36	2,007.10	18,727.31	1	14,396.78	6
37	1,528.60	4,732.39	1	7,871.32	5
38	4,019.21	8,998.73	1	1,809.86	4
39	2,134.91	7,099.05	0	2,065.32	0

Note. There were no BESS Errors for any subject in the Double Leg stance condition. COP = Center of Pressure. BESS = Balance Error Scoring System. ACT = Auditory Consonant Trigrams. RASA = Rapid Auditory Sustained Attention

Table 4

Sway Area and BESS Errors During RASA Trials

Subject Number	Double Leg COP (mm^2)	Tandem COP (mm^2)	Tandem BESS Errors	Single Leg COP (mm^2)	Single Leg BESS Errors
1	393.70	1,242.76	0	927.74	3
2	223.69	3,467.75	3	10,064.74	34
3	481.69	1,797.61	0	2,320.82	10
4	131.39	1,483.38	0	8,969.36	2
5	202.82	2,571.97	0	1,393.20	0
6	4,283.10	4,708.67	0	2,166.75	13
7	221.17	5,728.62	1	2,865.61	4
8	87.05	1,176.05	0	709.00	0
9	1,185.14	1,646.90	0	41,182.32	43
10	929.29	1,819.19	0	948.40	1
11	465.16	3,309.57	8	1,655.44	6
12	139.12	1,930.56	2	911.84	4
13	3,015.10	5,424.59	0	5,110.56	3
14	337.27	1,234.63	0	1,149.17	1
15	328.13	3,132.45	0	1,097.63	0
16	11,541.89	2,293.14	0	939.01	2
17	228.95	3,738.02	0	1,337.91	2
18	137.20	2,200.31	0	1,429.69	1
19	442.51	33,493.69	9	5,545.65	28
20	115.39	2,408.81	0	969.95	2
21	22,156.07	4,824.08	0	1,805.29	5
22	310.43	1,742.32	0	9,625.29	11
23	168.53	3,399.96	1	1,053.28	3
24	656.65	1,978.09	0	3,982.24	0
25	306.74	1,142.24	0	2,086.40	0
26	2,761.28	1,952.14	1	1,819.97	5
27	205.88	2,911.94	0	1,929.20	1
28	251.22	2,882.09	0	4,025.65	2
29	692.98	2,502.18	2	2,181.59	9
30	7,708.53	11,152.13	3	6,050.32	8
31	584.84	6,540.60	2	5,201.92	6
32	239.03	847.56	0	1,466.76	1
33	261.26	1,202.01	0	42,059.18	6
34	126.59	1,106.75	0	1,647.83	5
35	1,282.38	6,377.39	2	5,405.91	3
36	160.95	8,940.07	1	1,924.40	3
37	485.71	2,273.85	2	8,255.82	5
38	471.10	3,982.88	0	1,081.05	0
39	354.91	2,259.84	0	1,860.11	0
40	193.29	1,345.62	0	1,614.24	0
41	2,575.42	9,515.61	2	4,222.19	3
42	76.60	12,649.04	2	6,756.41	5
43	122.39	865.51	0	1,682.07	2

Note. There were no BESS Errors for any subject in the Double Leg stance condition. COP = Center of Pressure. BESS = Balance Error Scoring System. ACT = Auditory Consonant Trigrams. RASA = Rapid Auditory Sustained Attention

Table 5

Balance Performance Across Conditions

	COP (mm^2)		BESS Errors	
	M (SD)	Range	*M (SD)*	Range
ACT				
Double Leg	2,917.57 (4,035.38)	81.69-19,157.58	0 (0)	0-0
Tandem	6,492.60 (8,735.65)	739.35-50,500.17	1.05 (1.67)	0-6
Single Leg	7,058.46 (8.953.71)	648.48-37,400.19	7.87 (9.94)	0-43
RASA				
Double Leg	1,534.93 (3,911.29)	76.60-22,156.07	0 (0)	0-0
Tandem	3,992.55 (5,354.35)	847.56-33,493.69	0.93 (1.94)	0-9
Single Leg	4,902.78 (8,696.32)	709.00-42,059.18	5.69 (8.98)	0-43

Note. COP = Center of Pressure. BESS = Balance Error Scoring System. ACT = Auditory Consonant Trigrams. RASA = Rapid Auditory Sustained Attention

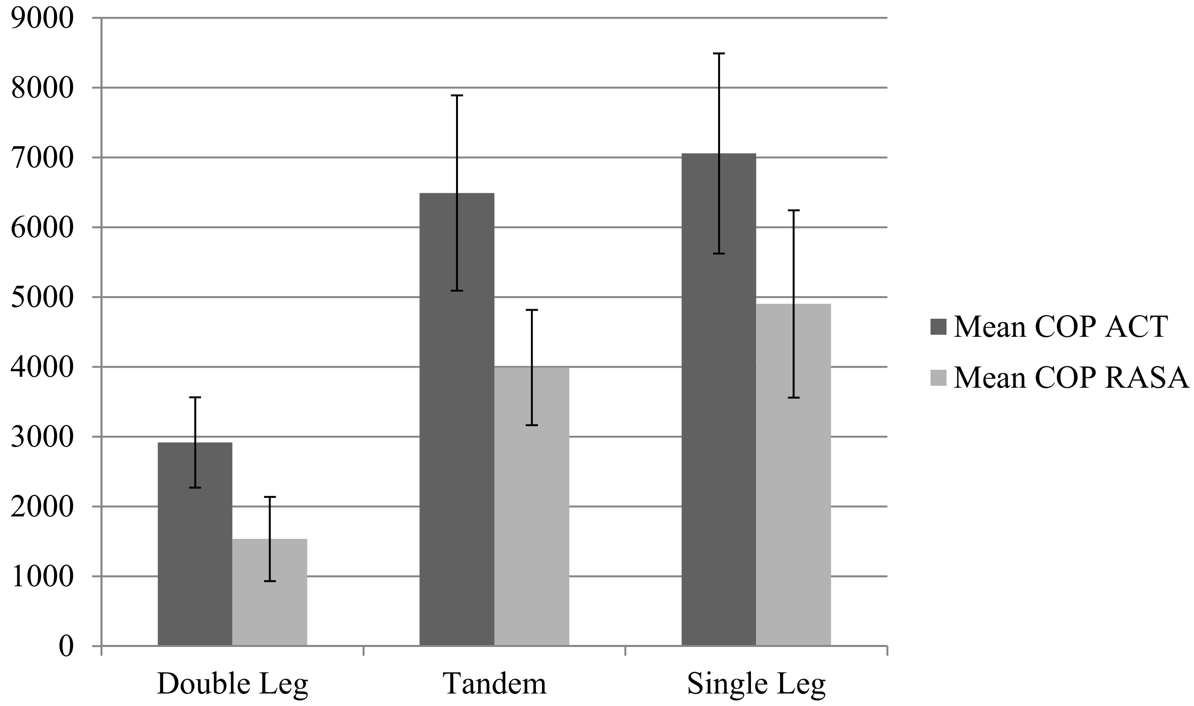

Figure 7. Differences in mean COP (mm^2) across balance conditions. For both the ACT and the RASA, there were statistically significant differences between Double Leg stance and both Tandem stance and Single Leg stance. In neither case was there a statistically significant difference between Tandem stance and Single Leg stance. Error bars represent standard errors.

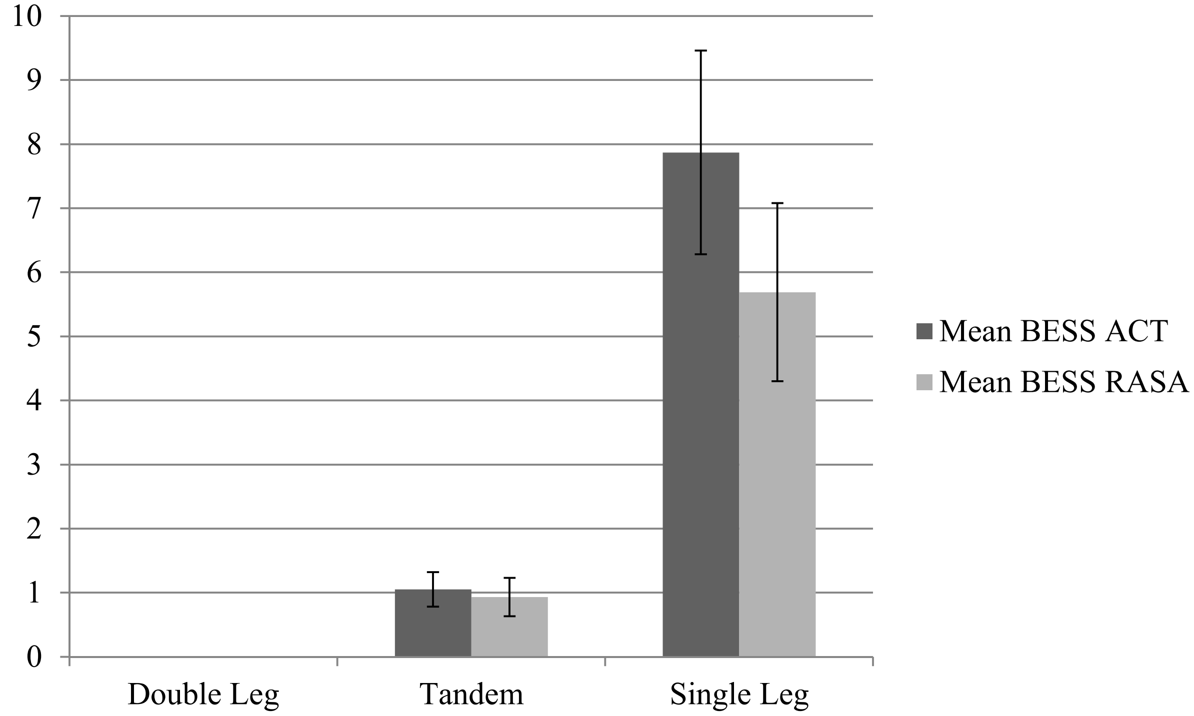

Figure 8. BESS errors across balance conditions for the ACT and the RASA. Error bars represent standard errors.

A one-way repeated measures ANOVA was performed to determine if there was a statistically significant difference in COP across stances. Due to the presence of several outliers and non-normal distributions in each condition as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively, a logarithmic transformation was applied to all COP calculations. Following the log transformation, outliers remained in each level of the dependent variable for the RASA and in Tandem stance during the ACT; however, after inspection of each of these, it was determined that they are genuine values rather than data entry or measurement errors. Also, while they are greater than 1.5 box-lengths from the edge of the box, they are not extreme data points (i.e., greater than 3 box-lengths from the edge of the box), and were thus kept in for subsequent analyses. The assumption of normality was met for each measurement of COP during the RASA after the data was transformed, while COP distributions vastly improved but remained non-normal during the ACT. Non-normality does not affect Type I error rate substantially, and the one-way repeated measures ANOVA can be considered robust to non-normality.

During ACT administration, Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 3.11$, $p = .211$. COP was statistically significantly different across balance conditions, $F(2, 76) = 23.23$, $p < .001$, partial $\eta^2 = .38$. Post hoc analysis with a Bonferroni adjustment revealed a statistically significant increase in COP between Double Leg stance ($M = 2{,}917.57$, $SD = 4{,}035.38$) and both Tandem stance ($M = 6{,}492.60$, $SD = 8{,}735.65$) and Single Leg stance ($M = 7{,}058.46$, $SD = 8{,}953.71$), but not between Tandem stance and Single Leg stance. Graphical representations are available in Figure 7.

During RASA administration, Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 5.66$, $p = .059$. COP was statistically significantly different across balance conditions, $F(2, 82) = 50.22$, $p < .001$, partial $\eta^2 = .55$. Again, post hoc analysis with a Bonferroni adjustment revealed a statistically significant increase in COP between Double Leg stance ($M = 1{,}534.93$, $SD = 3{,}911.28$) and both Tandem stance ($M = 3{,}992.55$, $SD = 5{,}354.35$) and Single Leg stance ($M = 4{,}902.78$, $SD = 8{,}696.32$), but not between Tandem stance and Single Leg stance. Graphical representations are available in Figure 7.

Two independent-samples t-tests were run to determine if there were differences in COP between females and males. There was homogeneity of variances for COP during both the ACT and the RASA, as assessed by Levene's test for equality of variances (*p* = .901; *p* = .561, respectively). On the ACT, there was no difference in COP between males (*M* = 19,770.69, *SD* = 12,756.79) and females (*M* = 15,983.03, *SD* = 19,408.49), *t*(37) = .42, *p* = .677. The same was true during the RASA administration. There was no difference in COP between females (*M* = 10,033.98, *SD* = 10,391.57) and males (*M* = 12,807.96, *SD* = 13,682.67), *t*(40) = .58, *p* = .566. Refer to Table 6 for additional correlations among balance variables. Of note, also shown in Table 6, both height and exercise involvement were unrelated to both BESS errors and COP.

Balance Condition Effects on Cognitive Performance

Mean cognitive performances across balance conditions can be found in Table 5. Correlations among cognitive variables are reported in Table 7. A series of one-way repeated measures analyses of covariance (ANCOVA) were conducted to determine whether there were differences in cognitive performance across balance conditions controlling for estimated intelligence using the WTAR raw score.[1]

Variables for the ACT included ACT Total Score, ACT 9-second delay, and ACT 36-second delay. These values were derived from the total number of correct letters recalled, regardless of order. Assumption testing was performed for each ACT ANCOVA. This included box-plot inspections for outliers, Shapiro-Wilk's test of normality, and Mauchley's test of sphericity. The assumption of sphericity was met for all analyses. Occasional outliers greater than 1.5 box-lengths from the edge of the

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[1] There was no systematic difference when WTAR standardized scores rather than raw scores were used in the analyses due to the small range in participants' age.

Table 6

Correlations Among Balance Variables

	M (SD)	BESS RASA	BESS ACT	COP RASA	COP ACT	Height	Exercise
BESS RASA (sum of trials)	6.62 (9.91)		.91**	.64**	.26	.05	-.02
BESS ACT (sum of trials)	8.87 (10.82)			.61**	.34*	.07	-.03
COP RASA (mm^2)	10,430.26 (10,769.22)				.59**	-.03	-.15
COP ACT (mm^2)	16,468.62 (18,598.41)					.05	-.18
Height (inches)	65.59 (3.98)						.21
Exercise (hours/week)	1.71 (.926)						

Note. *N*'s range from 39 to 42 due to occasional missing data. BESS = Balance Error Scoring System. RASA = Rapid Auditory Sustained Attention. COP = Center of Pressure.
* Correlations are significant at the $p < .05$ level
** Correlations are significant at the $p < .001$ level

Table 7

Correlations Among Cognitive Variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. WTAR		.41**	.47**	.32*	.45**	.45**	.39**	-.03	-.17	.31*	.20	-.11	-.03
2. ACT-TS			.94**	.95**	.96**	.89**	.91**	-.17	-.07	-.17	.22	.20	.10
3. ACT-9				.78**	.93**	.97**	.77**	-.24	-.03	.19	.24	.30	.07
4. ACT-36					.89**	.73**	.94**	-.07	-.09	.14	.20	.08	.10
5. ACT-TS-CO						.93**	.94**	-.16	-.09	.15	.24	.20	.12
6. ACT-9-CO							.76**	-.21	-.02	.17	.24	.29	.10
7. ACT-36-CO								-.09	-.15	.12	.23	.08	.13
8. RASA Number Correct									.39*	-.32*	-.49**	-.88**	.02
9. RASA Percent Correct										-.05	-.33*	-.09	-.70**
10. RASA RTT											.73**	.14	-.37*
11. RASA RTV												.24	-.03
12. RASA Omissions													-.04
13. RASA Commissions													

Note. *N*'s range from 31 to 42 due to occasional missing data. ACT = Auditory Consonant Trigrams. TS = Total Score. CO = Correct Order. RASA = Rapid Auditory Sustained Attention. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.
* *p* < .05. ** *p* < .01.

boxplots were identified; however, each was inspected, determined to be a true outlier, and subsequently left in the analysis. None were greater than 3 box-lengths from the edge of the boxplots. The assumption of normality was violated for ACT Total Score in Single Leg Stance as well as 9-second delay in all stances, but was met in all other analyses. Again, non-normality does not affect Type I error rate substantially, and the one-way repeated measures ANOVA can be considered robust to non-normality.

Variables for the ACT included ACT Total Score, ACT 9-second delay, and ACT 36-second delay. These values were derived from the total number of correct letters recalled, regardless of order. Assumption testing was performed for each ACT ANCOVA. This included box-plot inspections for outliers, Shapiro-Wilk's test of normality, and Mauchley's test of sphericity. The assumption of sphericity was met for all analyses. Occasional outliers greater than 1.5 box-lengths from the edge of the boxplots were identified; however, each was inspected, determined to be a true outlier, and subsequently left in the analysis. None were greater than 3 box-lengths from the edge of the boxplots. The assumption of normality was violated for ACT Total Score in Single Leg Stance as well as 9-second delay in all stances, but was met in all other analyses. Again, non-normality does not affect Type I error rate substantially, and the one-way repeated measures ANOVA can be considered robust to non-normality.

When controlling for estimated intelligence, there were no significant differences in performance on ACT Total Score ($F(2, 74) = 0.35$, $p = .705$, partial $\eta^2 = .01$), 9-second delay ($F(2, 74) = 0.89$, $p = .414$, partial $\eta^2 = .02$), or 36-second delay ($F(2, 74) = 0.67$, $p = .514$, partial $\eta^2 = .02$) across balance conditions (Table 8). Each of these scores were also derived using more stringent accuracy guidelines, by counting as correct *only* those

Table 8

Mean ACT and RASA Performance Across Balance Conditions

	Double Leg		Tandem		Single Leg		*F* value	p	Partial η^2
Measure	*M*	SD	*M*	SD	*M*	SD			
ACT (N=39)									
Total Score	35.77	6.43	36.18	5.56	36.05	6.01	0.35	.705	.009
9-s Delay	10.74	3.73	11.18	2.99	11.00	3.18	0.89	.414	.024
36-s Delay	10.05	3.28	10.05	3.45	10.13	3.28	0.67	.514	.018
Total Score CO	33.36	7.39	33.31	7.07	33.69	7.31	0.29	.748	.008
9-s CO	9.51	4.29	9.90	3.77	9.72	3.84	0.33	.722	.009
36-s CO	8.87	3.86	8.46	4.22	9.05	3.89	0.73	.486	.019
RASA (N=31)									
Number Correct	86.10	10.51	83.35	11.80	81.52	13.71	0.34	.711	.012
Percent Correct	90.00	6.18	89.19	5.71	89.26	6.79	0.25	.778	.009
RTT	120.17	9.89	121.58	11.98	122.95	9.84	0.34	.716	.011
RTV	37.93	7.48	38.23	6.68	38.63	9.44	0.16	.855	.005
Omissions	17.16	9.33	20.74	11.55	21.32	13.66	0.28	.759	.009
Commissions	7.94	4.74	9.61	9.82	8.10	5.80	0.22	.740	.007

Note. WTAR score was used as a covariate in all analyses. ACT = Auditory Consonant Trigrams. CO = Correct Order. RASA = Rapid Auditory Sustained Attention. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.

letters recalled in the order in which they were presented. These include ACT Total Correct Order, ACT 9-second delay correct order, and ACT 36-second delay correct order. Regarding Correct Order variables, there were no significant differences in performance on Total Score ($F(2, 74) = 0.29$, $p = .748$, partial $\eta^2 = .01$), 9-second delay ($F(2, 74) = 0.33$, $p = .722$, partial $\eta^2 = .01$) or 36-second delay ($F(2, 74) = 0.73$, $p = .486$, partial $\eta^2 = .02$) across balance conditions. Thus, stance, itself, did not elicit statistically significant changes in ACT performance.

With regard to the RASA, accuracy variables included Number Correct and Percent Correct. Response latency variables included Reaction Time to Targets (RTT) and Reaction Time Variability (RTV). Error variables included Omissions and Commissions. The assumption of sphericity was met in each ANCOVA, except for that examining differences in RASA Commissions for which Mauchly's test of sphericity indicated that the assumption of sphericity had been violated, $\chi^2(2) = 11.93$, $p = .003$. Epsilon (ε) was 0.74, as calculated according to Greenhouse & Geisser (1959), and was used to correct the one-way repeated measures ANCOVA. There were non-normal distributions for Number Correct in Tandem stance and for both Commissions and Omissions in all three stances. Once again, one-way repeated measures ANOVA can be considered robust to non-normality, and analyses were continued without adjustment. There were no significant differences in performance on Number Correct ($F(2, 58) = 0.34$, $p = .711$, partial $\eta^2 = .01$), Percent Correct ($F(2, 58) = 0.25$, $p = .778$, partial $\eta^2 = .01$), RTT ($F(2, 58) = 0.34$, $p = .716$, partial $\eta^2 = .01$), or RTV ($F(2, 58) = 0.16$, $p = .855$, partial $\eta^2 = .01$), Omissions ($F(2, 58) = 0.28$, $p = .759$, partial η2 = .01), or Commissions ($F(1.48, 43.06) = 0.22$, $p = .740$, partial $\eta^2 = .01$) across balance conditions (Table 8).

Like with the ACT, the stance manipulation itself did not result in statistically significant changes in ACT performance. A summary of results can be found in Table 8.

Balance Performance Effects on Cognitive Performance

COP and cognitive performance. Multiple regression was used to predict cognitive performance from both *actual* balance performance as measured by the force platform as well as estimated intelligence. Broadly, predictor variables included COP and WTAR raw score. In all instances, both variables were entered into the regressions simultaneously. Simultaneous entry was chosen because predictors are not correlated with one another and there is no theoretical argument for accounting for incremental validity of one predictor over another (Lewis, 2007). Unless noted below, all assumptions for multiple regressions were met, including independence of residuals, homoscedasticity, multicollinearity, and multivariate normality. Outliers are noted for specific regressions below. In each regression analysis in which COP was used as a predictor variable, a logarithmic transformation was performed on the COP variable due to strongly positively skewed relationships with the dependent variable resulting in non-linear relationships.

Analyses were completed in two different ways. First, regressions were run for each trial of the RASA and each trial of the ACT, using as predictors only the WTAR and the COP for that particular trial. Second, regressions were run with balance and cognitive performance combined across trials to result in outcome and predictor variables that would reflect total performance across the duration of each cognitive task. This allows for examination of two different questions: (1) within each individual balance trial, does postural stability predict cognitive performance on that trial, and (2) does postural stability across balance trials predict cognitive performance (on either the ACT or the RASA) across balance trials?

Predicting cognitive performance on individual ACT and RASA trials. Performance on individual ACT trials will be reported first. In regard to the most basic stance trial, the Double Leg stance, the multiple regression model significantly predicted Total Correct 9-second delay ($F(2, 36) = 4.54$, $p = .017$, adj. $R^2 = .16$) as well as both Correct Order Total Score ($F(2, 36) = 3.29$, $p = .049$, adj. $R^2 = .11$), and Correct Order 9-second delay ($F(2, 36) = 3.79$, $p = .032$, adj. $R^2 = .13$). In each instance, only the WTAR raw score was a statistically significantly predictor of ACT performance, $p < .05$. In Tandem stance, the multiple regression model significantly predicted Total Score ($F(2, 36) = 4.33$, $p = .021$, adj. $R^2 = .15$) and 9-second delay score ($F(2, 36) = 3.70$, $p = .035$, adj. $R^2 = .12$). Regarding Correct Order variables, the multiple regression model significantly predicted Total Score ($F(2, 36) = 5.32$, $p = .009$, adj. $R^2 = .19$) and 9-second delay score ($F(2, 36) = 3.48$, $p = .041$, adj. $R^2 = .12$). Again, only WTAR raw score, but not balance, aided prediction of ACT performance, $p < .05$. In Single Leg stance, none of the multiple regressions statistically significant predicted ACT performance. Regression coefficients and standard errors can be found in Tables 9-11. In summary, COP did not predict performance on the ACT in any of the balance conditions.

In regard to the RASA, it should first be noted that for a number of regressions predicting cognitive performance for each particular trial, one participant (though not the same participant) was removed from individual analyses due to having a residual greater than 3 standard deviations from the mean during assumption testing (Field, 2005). In the case of Double Leg stance trial and the Tandem stance trial, the multiple regression

Table 9

Predicting ACT Double Leg Performance from Double Leg Sway Area and Estimated Intelligence

Predictor	*b*	SE_b	β
ACT-TS			
WTAR Raw Score	.35	.15	.37*
COP	.98	1.66	.09
Adjusted R^2		.09	
F		2.91	
ACT-9			
WTAR Raw Score	.25	.08	.45*
COP	.20	.93	.03
Adjusted R^2		.16	
F		4.54*	
ACT-36			
WTAR Raw Score	.10	.08	.21
COP	.72	.89	.13
Adjusted R^2		.002	
F		1.04	
ACT-TS-CO			
WTAR Raw Score	.43	.17	.35*
COP	.11	1.89	.01
Adjusted R^2		.11	
F		3.29*	
ACT-9-CO			
WTAR Raw Score	.26	.10	.41*
COP	-.18	1.09	-.03
Adjusted R^2		.13	
F		3.79*	
ACT-36-CO			
WTAR Raw Score	.17	.09	.29
COP	.23	1.03	.04
Adjusted R^2		.03	
F		1.61	

Note. *$p < .05$. ACT = Auditory Consonant Trigrams. ACT-TS = ACT Total Score. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure during Double Leg ACT. ACT-9 = ACT 9-second delay. ACT-36 = ACT 36-second delay. ACT-CO = ACT Total Correct Order. ACT-9-CO = ACT Total Correct Order 9-second delay. ACT-36-CO = ACT Total Correct Order 36-second delay.

Table 10

Predicting ACT Tandem Performance from Tandem Sway Area and Estimated Intelligence

Predictor	b	SE_b	β
ACT-TS			
WTAR Raw Score	.36	.12	.43*
COP	-.70	2.13	-.05
Adjusted R^2		.15	
F		4.33*	
ACT-9			
WTAR Raw Score	.18	.07	.41*
COP	.07	1.16	.01
Adjusted R^2		.12	
F		3.70*	
ACT-36			
WTAR Raw Score	1.74	.08	.34*
COP	-.91	1.37	-.10
Adjusted R^2		.08	
F		2.73	
ACT-TS-CO			
WTAR Raw Score	.47	.15	.45*
COP	-2.70	2.66	-.15
Adjusted R^2		.19	
F		5.32*	
ACT-9-CO			
WTAR Raw Score	.22	.09	.39*
COP	-.83	1.48	-.09
Adjusted R^2		.12	
F		3.48*	
ACT-36-CO			
WTAR Raw Score	.25	.09	.40*
COP	-2.01	1.61	-.19
Adjusted R^2		.16	
F		4.56*	

Note. *$p < .05$. ACT = Auditory Consonant Trigrams. ACT-TS = ACT Total Score. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure during tandem ACT. ACT-9 = ACT 9-second delay. ACT-36 = ACT 36-second delay. ACT-TS-CO = ACT Total Correct Order. ACT-9-CO = ACT Total Correct Order 9-second delay. ACT-36-CO = ACT Total Correct Order 36-second delay.

Table 11

Predicting ACT Single Leg Performance from Single Leg Sway Area and Estimated Intelligence

Predictor	b	SE_b	β
ACT-TS			
WTAR Raw Score	.26	.14	.30
COP	-.34	2.22	-.03
Adjusted R^2		.04	
F		1.79	
ACT-9			
WTAR Raw Score	.15	.08	.32
COP	.06	1.12	.01
Adjusted R^2		.05	
F		1.98	
ACT-36			
WTAR Raw Score	.12	.08	.26
COP	-.42	1.17	-.06
Adjusted R^2		.02	
F		1.46	
ACT-TS-CO			
WTAR Raw Score	.36	.17	.33*
COP	-.58	2.56	-.04
Adjusted R^2		.07	
F		2.34	
ACT-9-CO			
WTAR Raw Score	.20	.09	.35*
COP	.11	1.34	.01
Adjusted R^2		.07	
F		2.40	
ACT-36-CO			
WTAR Raw Score	.17	.09	.29
COP	-.71	1.37	-.08
Adjusted R^2		.05	
F		2.02	

Note. *$p < .05$. ACT = Auditory Consonant Trigrams. ACT-TS = ACT Total Score. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure during single leg ACT. ACT-9 = ACT 9-second delay. ACT-36 = ACT 36-second delay. ACT-TS-CO = ACT Total Correct Order. ACT-9-CO = ACT Total Correct Order 9-second delay. ACT-36-CO = ACT Total Correct Order 36-second delay.

models did not significantly predict performance on any of the RASA variables of interest. Regression coefficients and standard errors can be found in Tables 12 and 13, respectively. For Single Leg stance, the multiple regression model trended toward predicting both Number Correct ($F(2, 28) = 3.28$, $p = .053$, adj. $R^2 = .13$) and Reaction Time Variability ($F(2, 28) = 3.52$, $p = .092$, adj. $R^2 = .04$). In each case, Single Leg balance performance statistically improved prediction of cognitive performance, $p < .05$ (Figure 9), while general intelligence did not. Regression coefficients and standard errors can be found in Table 14.

Predicting performance across trials. Next, the question of whether or not postural stability across balance trials predicted cognitive performance across balance trials was addressed. For the ACT, the multiple regression model significantly predicted Total Score ($F(2, 36) = 3.74$, $p = .033$, adj. $R^2 = .17$) and 9-second delay score ($F(2, 36) = 5.08$, $p = .011$, adj. $R^2 = .22$). With respect to Correct Order variables, the Total Score ($F(2, 36) = 4.91$, $p = .013$, adj. $R^2 = .21$), 9-second delay score ($F(2, 36) = 4.87$, $p = .013$, adj. $R^2 = .21$), and 36-second delay score ($F(2, 36) = 3.62$, $p = .037$, adj. $R^2 = .12$) were all predicted. Again, in each instance, only WTAR raw score, but not the total COP value, significantly predicted performances, $p < .05$. Regression coefficients and standard errors can be found in Table 15.

For the RASA, when considering total balance performance combined across stances, there were two instances in which a case was removed due to residuals greater than 3 standard deviations from the mean. These were for the regressions predicting Percent Correct and Omissions. The multiple regression model did not significantly predict any of the RASA outcome variables. Noteworthy, both Number Correct ($F(2, 28)$

Table 12

Predicting RASA Double Leg Performance from Double Leg Sway Area and Estimated Intelligence

Predictor	b	SE_b	β
Number Correct			
WTAR Raw Score	-.16	.25	-.12
COP	-5.29	2.91	-.33
Adjusted R^2		.04	
F		1.68	
Percent Correct			
WTAR Raw Score	-.04	.11	-.06
COP	-.15	1.27	-.02
Adjusted R^2		-.07	
F		.06	
RTT			
WTAR Raw Score	.41	.23	.32
COP	2.22	2.74	.15
Adjusted R^2		.04	
F		1.63	
RTV			
WTAR Raw Score	.32	.17	.32
COP	3.61	2.04	.31
Adjusted R^2		.09	
F		2.59	
Omissions			
WTAR Raw Score	.14	.22	.12
COP	4.62	2.58	.32
Adjusted R^2		.04	
F		1.62	
Commissions			
WTAR Raw Score	-.02	.09	-.04
COP	-.31	1.07	-.06
Adjusted R^2		-.07	
F		.05	

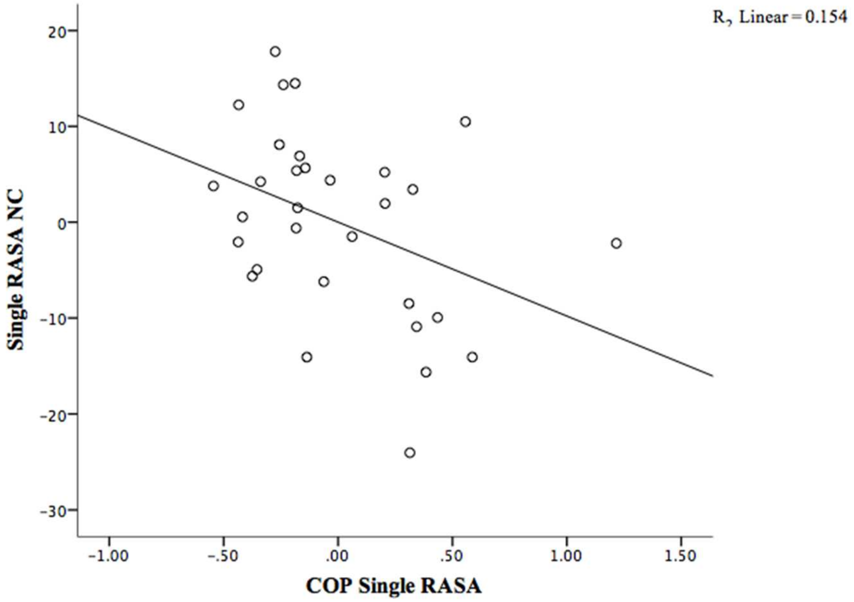
Note. $^*p < .05$. RASA = Rapid Auditory Sustained Attention. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.

Table 13

Predicting RASA Tandem Performance from Tandem Sway Area and Estimated Intelligence

Predictor	*b*	SE_b	β
Number Correct			
WTAR Raw Score	-.24	.29	-.15
COP	-3.22	6.10	-.10
Adjusted R^2		-.04	
F		.40	
Percent Correct			
WTAR Raw Score	-.15	.11	-.24
COP	-.40	2.33	-.03
Adjusted R^2		-.01	
F		.86	
RTT			
WTAR Raw Score	.40	.28	.25
COP	2.00	5.95	.06
Adjusted R^2		.00	
F		1.00	
RTV			
WTAR Raw Score	.26	.16	.28
COP	3.20	3.32	.17
Adjusted R^2		.03	
F		1.56	
Omissions			
WTAR Raw Score	-.16	.28	-.10
COP	3.76	5.93	.11
Adjusted R^2		-.04	
F		.44	
Commissions			
WTAR Raw Score	.11	.12	.17
COP	1.03	2.45	.08
Adjusted R^2		-.03	
F		.47	

Note. $^*p < .05$. RASA = Rapid Auditory Sustained Attention. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.



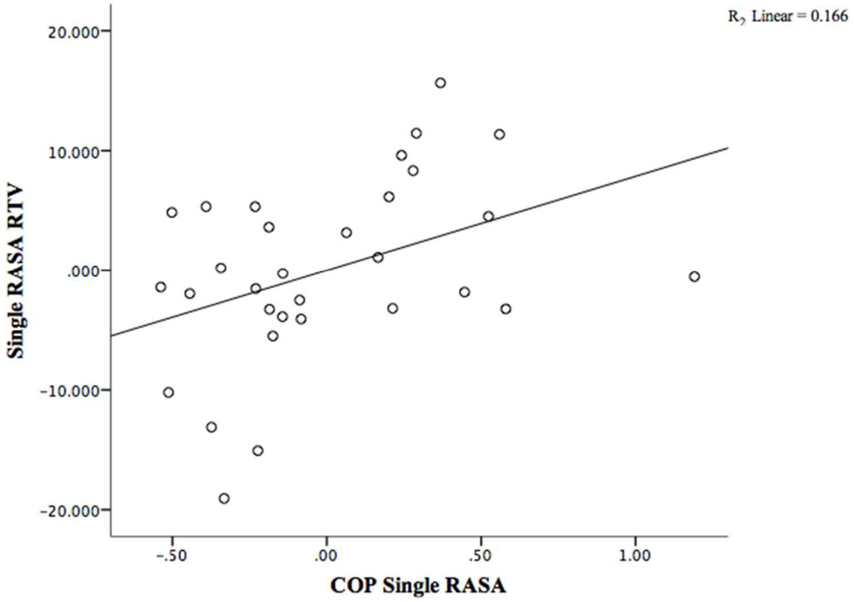


Figure 9. Scatterplots depicting the relationship between RASA Number Correct (NC) and balance (COP; Graph A) and between RASA Reaction Time Variability (RTV) and balance (Graph B) during the Single Leg trial. Logarithmic transformation was applied to the COP data.

Table 14

Predicting RASA Single Leg Performance from Single Leg Sway Area and Estimated Intelligence

Predictor	*b*	SE_b	β
Number Correct			
WTAR Raw Score	-.29	.23	-.21
COP	-9.80	4.34	-.38*
Adjusted R^2		.13	
F		3.28	
Percent Correct			
WTAR Raw Score	-.08	.17	-.08
COP	-1.26	3.10	-.08
Adjusted R^2		-.06	
F		.17	
RTT			
WTAR Raw Score	.49	.23	.37*
COP	3.46	4.19	.14
Adjusted R^2		.09	
F		2.55	
RTV			
WTAR Raw Score	.26	.18	.24
COP	7.86	3.33	.40*
Adjusted R^2		.14	
F		3.52	
Omissions			
WTAR Raw Score	.22	.22	.18
COP	6.93	4.15	.30
Adjusted R^2		.06	
F		1.87	
Commissions			
WTAR Raw Score	-.02	.11	-.04
COP	-.71	2.11	-.06
Adjusted R^2		-.07	
F		.07	

Note. *$p < .05$. RASA = Rapid Auditory Sustained Attention. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.

Table 15

Predicting Combined ACT Performance from Estimated Intelligence and Combined Sway Area

Predictor	b	SE_b	β
ACT-TS			
WTAR Raw Score	.95	.36	.41*
COP	-2.00	6.46	-.05
Adjusted R^2		.13	
F		3.74*	
ACT-9			
WTAR Raw Score	.57	.18	.46**
COP	-.86	3.29	-.04
Adjusted R^2		.18	
F		5.08*	
ACT-36			
WTAR Raw Score	.39	.20	.31
COP	-1.32	3.62	-.06
Adjusted R^2		.05	
F		2.08	
ACT-TS-CO			
WTAR Raw Score	1.22	.42	.43**
COP	-6.14	7.58	-.12
Adjusted R^2		.17	
F		4.91*	
ACT-9-CO			
WTAR Raw Score	.66	.23	.44**
COP	-2.65	4.02	-.10
Adjusted R^2		.17	
F		4.87*	
ACT-36-CO			
WTAR Raw Score	.56	.24	.37*
COP	-3.64	4.22	-.13
Adjusted R^2		.12	
F		3.62*	

Note. $*p < .05$, $**p < .01$. ACT = Auditory Consonant Trigrams. ACT-TS = ACT Total Score. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure. ACT-9 = ACT 9-second delay. ACT-36 = ACT 36-second delay. ACT-TS-CO = ACT Total Correct Order. ACT-9-CO = ACT Total Correct Order 9-second delay. ACT-36-CO = ACT Total Correct Order 36-second delay.

= 2.79, $p = .079$, adj. $R^2 = .11$) and Reaction Time Variability ($F(2, 28) = 2.68$, $p = .086$, adj. $R^2 = .10$) trended toward significance, with balance performances predicting aspects of RASA performance (Figure 10). Regression coefficients and standard errors can be found in Table 16.

BESS errors and cognitive performance. Multiple regression was used to predict cognitive performance from balance performance as quantified by number of BESS errors (i.e., lifting hands above the waist, taking a step, stumbling/stepping/falling, remaining out of the testing position for more than 5 seconds, moving hip into more than 30° of either flexion or abduction, and lifting any part of the foot or feet off of the floor) and estimated intelligence. For the ACT, the multiple regression model significantly predicted Total Score ($F(2, 36) = 3.93$, $p = .029$, adj. $R^2 = .13$) and 9-second delay score ($F(2, 36) = 5.42$, $p = .009$, adj. $R^2 = .19$). Regarding the Correct Order variables, the regression model predicted Total Score ($F(2, 36) = 4.59$, $p = .017$, adj. $R^2 = .16$), 9-second delay score ($F(2, 36) = 4.79$, $p = .014$, adj. $R^2 = .17$), and 36-second delay score ($F(2, 36) = 3.19$, $p = .053$, adj. $R^2 = .10$). Again, in each instance, only WTAR raw score, but not the all-trial combined BESS sum errors significantly added to the prediction, $p < .05$. Regression coefficients and standard errors can be found in Table 17.

For the RASA, when considering total performance combined across trials, there was only one instance in which a case was removed due to due to having a residual greater than 3 standard deviations from the mean during assumption testing. The multiple regression model significantly predicted Number Correct ($F(2, 28) = 5.42$, $p = .010$, adj. $R^2 = .23$) and Omissions ($F(2, 28) = 3.94$, $p = .031$, adj. $R^2 = .16$). In each of these cases,

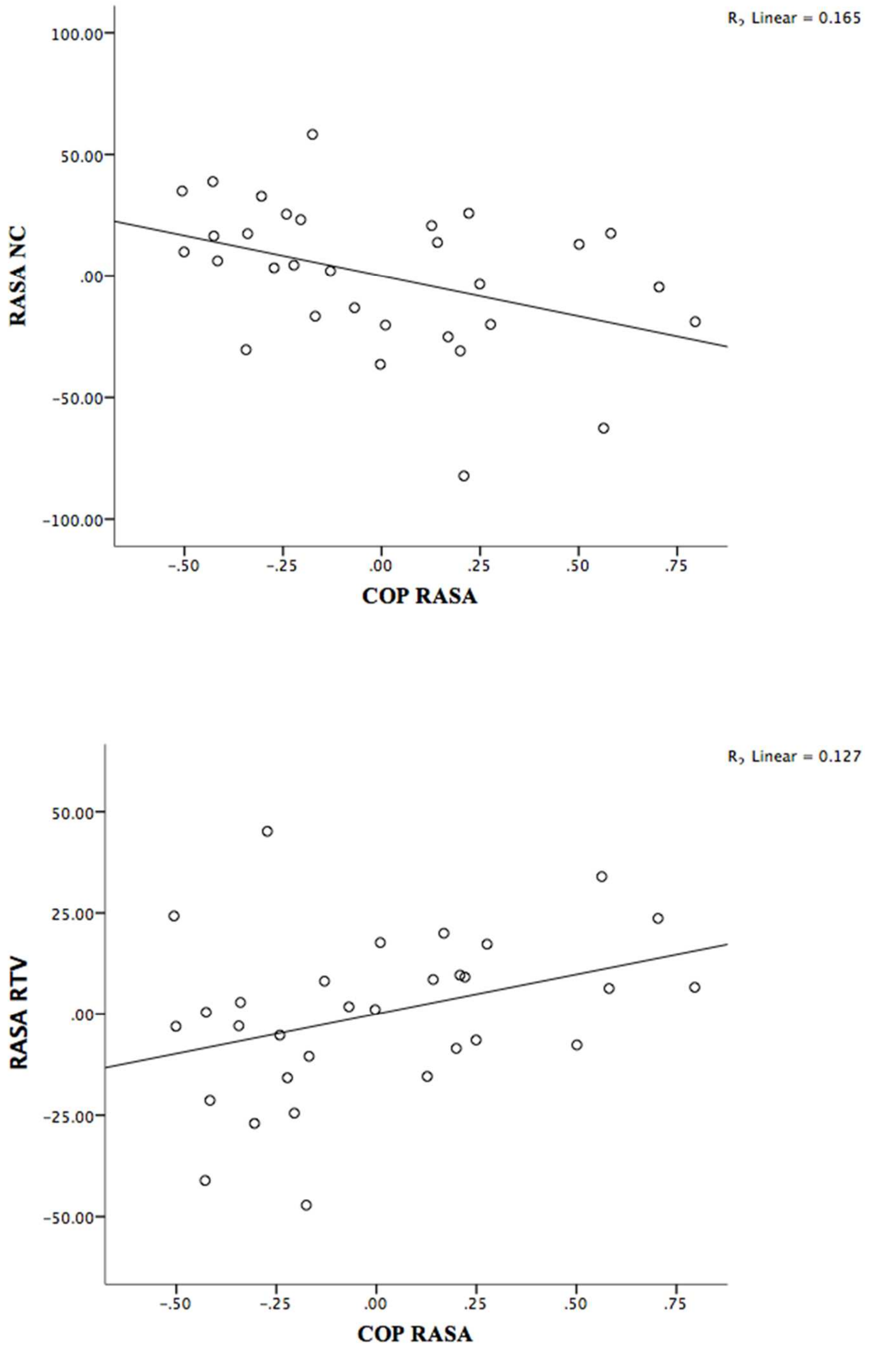


Figure 10. Scatterplots depicting the relationship between RASA Number Correct and COP (Graph A) and between RASA RTV and COP (Graph B) during all three RASA trials combined. Logarithmic transformation was applied to the COP data.

Table 16

Predicting Combined RASA Performance from Estimated Intelligence and Combined Sway Area

Predictor	*b*	SE_b	β
Number Correct			
WTAR Raw Score	-.37	.70	-.09
COP	-33.26	14.13	-.41*
Adjusted R^2		.11	
F		2.79	
Percent Correct			
WTAR Raw Score	-.08	.10	-.15
COP	-3.06	1.98	-.29
Adjusted R^2		.03	
F		1.37	
RTT			
WTAR Raw Score	1.23	.69	.32
COP	6.39	14.00	.08
Adjusted R^2		.040	
F		1.60	
RTV			
WTAR Raw Score	.68	.48	.25
COP	19.63	9.73	.35*
Adjusted R^2		.10	
F		2.68	
Omissions			
WTAR Raw Score	.30	.50	.11
COP	19.37	9.86	.36
Adjusted R^2		.06	
F		2.00	
Commissions			
WTAR Raw Score	-.01	.36	-.01
COP	4.81	7.31	.13
Adjusted R^2		-.05	
F		.23	

Note. *$p < .05$. RASA = Rapid Auditory Sustained Attention. WTAR = Wechsler Test of Adult Reading. COP = Center of Pressure. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.

Table 17

Predicting Combined ACT Performance from Estimated Intelligence and BESS Errors

Predictor	*b*	SE_b	β
ACT-TS			
WTAR Raw Score	1.01	.36	.43**
BESS Errors	.15	.23	.10
Adjusted R^2		.13	
F		3.93*	
ACT-9			
WTAR Raw Score	.60	.18	.49**
BESS Errors	.09	.12	.12
Adjusted R^2		.19	
F		5.42**	
ACT-36			
WTAR Raw Score	.42	.20	.33*
BESS Errors	.06	.13	.07
Adjusted R^2		.056	
F		2.12	
ACT-TS-CO			
WTAR Raw Score	1.30	.43	.46**
BESS Errors	.10	.27	.06
Adjusted R^2		.16	
F		4.59*	
ACT-9-CO			
WTAR Raw Score	.70	.23	.47**
BESS Errors	.08	.14	.08
Adjusted R^2		.17	
F		4.79*	
ACT-36-CO			
WTAR Raw Score	.60	.24	.39*
BESS Errors	.02	.15	.02
Adjusted R^2		.10	
F		3.19*	

Note. *$p < .05$, **$p < .01$. ACT = Auditory Consonant Trigrams. ACT-TS = ACT Total Score. WTAR = Wechsler Test of Adult Reading. BESS = Balance Error Scoring System. ACT-9 = ACT 9-second delay. ACT-36 = ACT 36-second delay. ACT-TS-CO = ACT Total Correct Order. ACT-9-CO = ACT Total Correct Order 9-second delay. ACT-36-CO = ACT Total Correct Order 36-second delay.

the all-trial combined BESS variable, but not the WTAR, added to the prediction, $p < .05$ (Figure 11). Regression coefficients and standard errors can be found in Table 18.

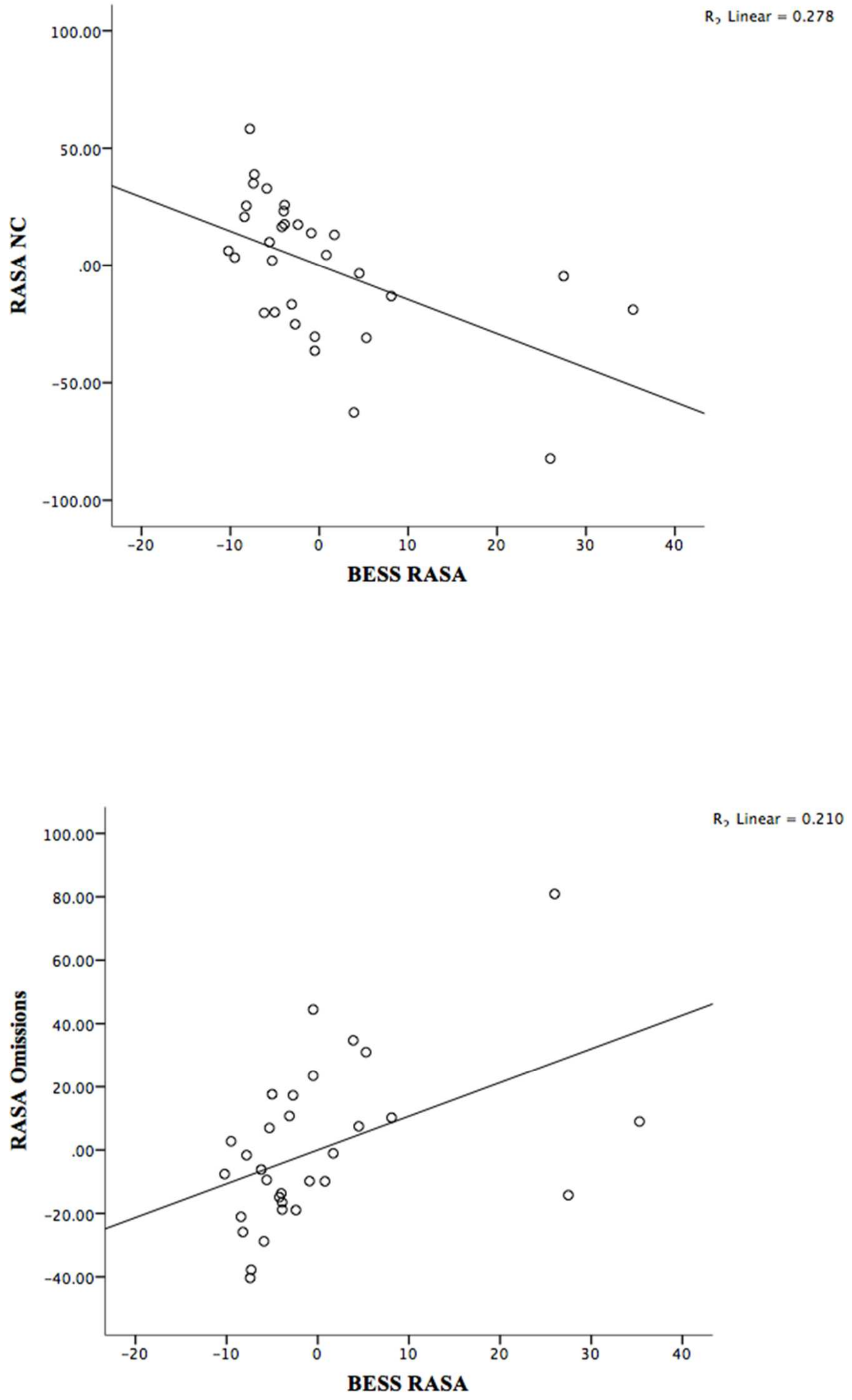


Figure 11. Scatterplots depicting the relationship between RASA Number Correct and BESS Errors (Graph A) and between RASA Omissions and BESS errors (Graph B) during the all three RASA trials combined.

Table 18

Predicting Combined RASA Performance from Estimated Intelligence and BESS Errors

Predictor	*b*	SE_b	β
Number Correct			
WTAR Raw Score	-.56	.66	-.14
BESS Errors	-1.45	.44	-.54**
Adjusted R^2		.23	
F		5.42**	
Percent Correct			
WTAR Raw Score	-.09	.010	-.18
BESS Errors	-.13	.07	-.35
Adjusted R^2		.07	
F		2.01	
RTT			
WTAR Raw Score	1.25	.70	.33
BESS Errors	.21	.47	.08
Adjusted R^2		.04	
F		1.60	
RTV			
WTAR Raw Score	.67	.50	.25
BESS Errors	.44	.34	.24
Adjusted R^2		.03	
F		1.43	
Omissions			
WTAR Raw Score	-.05	.58	-.02
BESS Errors	1.07	.39	.47*
Adjusted R^2		.16	
F		3.94*	
Commissions			
WTAR Raw Score	-.06	.37	-.03
BESS Errors	-.02	.25	-.02
Adjusted R^2		-.07	
F		.01	

Note. *$p < .05$, **$p < .01$. RASA = Rapid Auditory Sustained Attention. WTAR = Wechsler Test of Adult Reading. BESS = Balance Error Scoring System errors during the RASA. RTT = Reaction Time to Targets. RTV = Reaction Time Variability.

Discussion

The present study is among the first documenting a relationship between balance disturbance and cognitive performance using an experimental paradigm developed with cognition as the primary outcome of interest. It is likely the very first within the neuropsychology field to do so, which is meaningful because of our greater familiarity, understanding, and ability to quantify cognition.

There were no statistically significant differences on either the working memory task or the sustained attention task across balance conditions. This was contrary to the prediction that as stances became more challenging, cognitive performance would decline. While unexpected, this is consistent with previous research by Akram and Frank (2009) and Olivier and colleagues (2010) suggesting that experimentally manipulating balance disturbance did not impact cognitive task performance among healthy adult subjects. Akram and Frank (2009) used a rotating platform with varying degrees of amplitude and frequency of perturbation and found no difference between perturbed conditions and a control condition on a silent word identification task. Olivier and colleagues (2010) used a similar design in a pediatric population but with a color identification task. While the latter investigators made no attempt to explain the lack of experimental effect on cognition, it is likely that the cognitive task may have been too easy – that even in the dual task conditions, children between the ages of 7-11 had no difficulty quickly identifying the colors of objects. On the other hand, Akram and Frank (2009) speculated that their balance challenge task was too easy, given that the force platform perturbations did not result in particularly large changes in COP. This was not the case in the present study. Differences in COP emerged between Double Leg stance and both Tandem stance and Single Leg stance, indicating that the balance manipulations were successful in that regard. However, the same was not true between Tandem and Single Leg stance, which likely affected the outcome of the repeated measures analyses when examining performance differences between these two conditions.

Current findings, however, do contrast with those of other researchers who have observed changes in cognitive performance as the result of a balance manipulation (e.g., Swan et al., 2007). Swan and colleagues found that performance on two memory tasks was better when participants were sitting versus standing (except, the authors add, during tandem stance, when performance on one of the memory tasks was greater than when participants were sitting). Brauer and colleagues (2002) found differences in performance on a vocal reaction time task in the dual task condition, with the most pronounced effect observed among balance-impaired older adults. In considering why the current findings contrast with these specific studies, it seems plausible that the length of each trial (approximately 6 minutes) was such that subjects' attention was taxed regardless of condition, reducing the likelihood of observing an effect due to the experimental manipulation. It is also plausible that subjects' balance ability was variable enough that it was not possible to detect a meaningful difference between conditions due to stance manipulation alone. For example, BESS errors and COP calculations suggest that some participants clearly had considerably more trouble standing on one leg than other participants. The present study did, in fact, attempt to identify and control for participant characteristics that might influence variations in balance performance, such as exercise involvement and height. However, no significant correlations emerged between these characteristics and either COP or BESS errors, suggesting that they had little effect on balance performance in this sample.

COP was recorded in order to combat this possibility, and a regression predicting sustained attention revealed that sustained attention performance could in fact be predicted by both postural sway and BESS errors. The greater the sway area, the fewer correctly identified targets and the more variability in reaction time. BESS performance predicted the number of correct responses to targets in addition to the number of omissions. When regressions were run for each position individually, COP predicted the number of correct responses to targets and the Reaction Time Variability in Single leg Stance but not in the two less challenging stances. This is consistent with a recent study documenting worse performance among both older and younger healthy adults on a choice reaction time task in a sway-referenced condition versus a fixed-floor condition (Fuhrman, Redfern, Jennings, and Fuhrman, 2015).

In no case did balance performance predict performance on the working memory task, regardless of whether balance performance was measured by BESS errors or by the COP. There are several plausible reasons for this. One possibility is that the ACT was either too easy or too difficult to result in great variations in performance secondary to balance performance. However, this seems unlikely, given that means and standard deviations of ACT variables showed no indication of floor or ceiling effects. Another possibility is that practice effects on the ACT were such that they “washed out” any possible influence of balance perturbation. Practice effects, while small, do exist with the ACT even when alternate forms are administered (Stuss et al., 1987; Stuss et al., 1989).

Alternate forms were not used in this design. Doing so may or may not have minimized potential practice effects.

A third possibility is that the RASA measures a construct that is simply more susceptible to effects from postural sway than does the ACT. This, too, is plausible. Working memory is a higher order process that is reliant on basic cognitive processes like sustained attention (Baddeley, 2006; Knudsen, 2007). As Knudsen (2007) aptly suggests, "working memory represents the objects of attention." However, working memory also relies on other processes like those mediated by the mesial temporal lobes, especially when working memory tasks are language dependent (Baddeley, 2006; Knudsen, 2007), as is the verbally mediated ACT. It makes some theoretical sense for dual-task deficits to be more easily detected on tasks of basic attention and speed, mediated largely by frontal parietal and frontal subcortical networks (Sarter, Givens, & Bruno, 2001), when other, perhaps unaffected cognitive processes may not be available to contribute in a compensatory way. In other words, perhaps the relative "purity" of the RASA task makes it make it more susceptible to dual-task effects.

This purity does not exist with the ACT. ACT variables were statistically significantly predicted by WTAR performance, suggesting that estimated intelligence exerts a meaningful influence on ACT performance in this sample. Typically, the ACT is understood to be sensitive to the detection of frontal subcortical and mesial temporal lobe dysfunction rather than general estimates of intelligence (Strauss, Sherman, & Spreen, 2006). However, the relationship between WTAR performance and ACT in the present study is not entirely surprising, given that a moderate correlation exists between WTAR performance and the Working Memory Index scale on the Wechsler Memory Scale-III

(Strauss et al., 2006; Wechsler, 1997). It is possible that the relationship between estimated intelligence and ACT obscures the relationship between ACT and balance. This was clearly not true in the case of the RASA. In fact, WTAR performance was in no way associated with RASA performance in the present sample.

The findings that emerge from the present study – namely that postural sway is related to impairments in sustained attention – are compatible with a limited capacity theory (Kahneman, 1973; Moray, 1967; Wickens, 1980). Detriments in cognitive performance in the present study illustrate the limits of attentional capacity and the necessity to divide and allocate attention among different neurologic processes. While there is nothing in this design to test task-switching models directly (Bonnel & Hafster, 1998; Pashler, 1994; Sperling & Melchner, 1978), they are also compatible with the findings that emerged here. It is plausible that executive control networks function as a self-propelling bottleneck where attention is switched between the competing tasks resulting in the response variability and errors documented on the RASA with greater balance challenge. The models also offer potential explanations for opposing findings that emerged on the working memory task versus the basic sustained attention task. Perhaps there exists greater overlap or mental resource sharing between central nervous system components of balance maintenance and sustained attention than between working memory and balance maintenance, which fits with Baldwin (2012) and Wickens' (1984) assumptions that greater similarity between processing modality and greater sharing of resources may result in greater performance impairment.

A particularly noteworthy strength of this design is its unique comprehensiveness in terms of measurement techniques. We chose to measure cognition using two different tasks, one that assesses sustained attention and has greater value as a basic experimental measure and one that is more complex and reliant on a broader range of networks and is also used by neuropsychologists clinically to measure working memory. Balance performance also was measured in two different ways, using highly precise COP data provided by a force platform and using a tally of BESS errors. By including multiple methods of measurement of both constructs of interest, we were able to evaluate the ability of each to detect the effect of balance disturbance on cognition. Doing so also provides suggestions for methodological considerations when proceeding with this type of research in the future. Taken together, study findings suggest that a relationship certainly exists between balance and cognition, but that this effect may be more visible when *actual* balance performance rather than group membership or assumed theoretical difficulty of an imposed balance challenge task is used to predict performance. Had this research used only a single measure of cognition, different and incomplete conclusions would have been reached.

While the present study sample included healthy individuals with no disturbances either in balance or in cognition, the results are applicable for clinical populations for whom balance and cognition are impaired. When neuropsychologists receive referral questions about impaired cognition, it is standard practice to assess for possible contributing factors, such as medication side effects, psychosocial stressors and mood disturbance, sleep disruption, or pain. Each of these is (or should be) given weight when interpreting test results and when making recommendations in the hopes of managing or alleviating cognitive symptoms. As it is now, the contribution of balance impairment, despite how pervasive it is among patient populations seen by neuropsychologists, is essentially ignored. In doing, patients are deprived of treatment recommendations addressing balance that, given the findings seen here, could potentially positively impact cognitive functioning.

The present research carries relevance even for healthy older adults. Balance impairment is common among healthy older adults, due to both peripheral weakness and to an aging brain (Liu, Chan, & Yan, 2014). There is evidence to support the conclusion that even within an older population aging healthily, balance and cognition can interact in detrimental ways. For example, Hawkes and colleagues (2012) identified task-switching deficits in balance impaired older adults in comparison to healthy older adults, indicating that balance impairment alone can impact cognition. In another study, older adults had more difficulty than did younger adults on an auditory Stroop task while also performing a walking obstacle avoidance task (Sui, Chou, Mayr, van Donkelaar, & Woollacott, 2008). This evidence, coupled with the findings of the present study, suggests that greater balance impairment puts these individuals at risk for reduced performance on attention and executive functioning tasks. Together, this body of research strongly supports the argument that neuropsychologists should be regularly asking patients and families and scouring medical record for evidence balance impairment, just as they do for medications associated with cognitive impairment, for example, and making treatment recommendations to combat it. Just as neuropsychologists frequently recommend that patients be referred for behavioral health treatment of depression and anxiety to alleviate contributions to actual or perceived cognitive impairment, so should they consider and address balance deficits. An obvious option would be recommending physical therapy when appropriate. Various evidence-based physical therapy approaches are effective in targeting gait and balance in Parkinson's disease (Morris, Martin, & Schenkman, 2010) and multiple sclerosis (Haselkorn et al., 2015). For example, one such therapy involving training in repetitive, high-amplitude movements has been shown to improve motor performance in Parkinson's disease patients above and beyond walking or at-home exercise (Brooks, 2010).

Despite this sample consisting of healthy young adults, this project has considerable implications for individuals with mTBI. Previous research suggests that balance impaired adults are especially susceptible to dual-task interference (e.g., Brauer et al., 2002; Negahban et al., 2011). There is a scarcity of dual-task balance and cognition research with individuals who have sustained a mTBI, and the overwhelming majority of it focuses on the impact of a simultaneous cognitive task on postural control rather than the reverse (e.g., Catena et al., 2009a; Parker et al., 2006). This is a glaring gap in what is otherwise a very comprehensive mTBI literature, and clearly deserves more attention. If balance performance is related to sustained attention in healthy young adults, it is logical to assume a similar or even more pronounced relationship between balance and cognitive functioning in individuals in the acute recovery phase of mTBI.

It is important to recognize that this research gap is not unique to studies with healthy adults and individuals with mTBI. The authors of a recent review examining balance and cognition dual-task research in a sample of patients with MS lamented that 12 of 14 of the studies available failed to even compute cognitive task performance during dual-task conditions (Wajda & Sosnoff, 2015). This illustrates that neuropsychologists, the individuals who are both most adept at studying cognition and who are involved in the care of a broad range of patient groups with both deficits in both balance and cognition, have remarkably remained all but absent when it comes to conducting investigations of cognition and balance dual-task effects. The question has also been raised in studies investigating both stroke patients (Patel & Bhatt, 2014) and patients with movement disorders (Bloem, Grimberg, van Dijk, & Munneke, 2006), though again the research is remarkably sparse.

Limitations and Directions for Future Research

Although this project addresses a notable gap in the literature and does so with a sound and comprehensive methodological approach, it is not without limitation. First, the long duration of trials may have introduced error into the repeated measures analyses testing the experimental manipulation based on balance condition through either postural or cognitive fatigue or both. Fatigue is clearly evident in the difference that can be seen in mean postural sway between the two cognitive tasks (see Figure 2). All ACT trials were administered after all RASA trials, and sway area is visibly greater for all ACT trials. While shorter trials may have made the manipulations "cleaner," longer trials were chosen to achieve greater reliability for the intrasubject reaction time variability variable on the RASA. Variation in reaction time requires more trials to achieve reliability than measures of central tendency, like mean reaction time (Saville et al., 2012). Nevertheless, this variable was viewed as particularly important during study design as it has been shown to generalize across sensory modalities and cognitive tasks (Saville et al., 2012), to reflect intermittent interruption of task relevant brain activity by task irrelevant activity (Tamm et al., 2012), and to increase after head injury (Makdissi et al., 2001; Segalowitz, Dywan, & Unsal, 1997; Stuss et al., 1989). Despite this, the impact of fatigue on performance is clearly not negligible, and it deserves further consideration. In ongoing investigations with the present data it would be possible to examine the impact of fatigue on performance by comparing performance across the first third, second third, and final third of each trial, for example. This would help guide future study design using similar paradigms.

An additional limitation involves the decision to not use alternative ACT forms across balance conditions. Alternative forms theoretically may have resulted in greater variability in ACT performance, which in turn may have made a relationship between ACT and balance performance more likely. However, this is merely speculative, and test-retest reliability on the ACT indicates that practice effects exist on the ACT, even when alternate forms are used (Stuss et al., 1987; Stuss et al., 1989). We did attempt to protect against this by pseudorandomly altering the order in which the balance tasks were administered. Additionally, it is possible that fatigue may have introduced greater error on the ACT than on the RASA, given that all ACT trials were administered following all RASA trials. To quantify this limitation, participants had been engaging in challenging cognitive tasks for nearly 20 minutes before a single ACT trial was administered.

The sample in the present study included 37 women and 6 men, which may be an additional limitation given such a considerable imbalance in sex representation. Evidence in animals and humans links estrogen and working memory (Rosenberg & Park, 2002), which may be mediated by the impact of estrogen level on dopamine (Jacobs & D’Esposito, 2011). Given this, it is worth considering the impact that cyclical differences in women’s estrogen level might have on attention and working memory in the present study that have no impact on the men. In the future, a sample with an equivalent sex representation between women and men or one that includes only members of one sex or the other would allow for identification of (in the former case) or protection against (in the latter case) this potential confound.

Finally, the sample size is relatively small for the current study. Although it is fairly standard when considering other dual-task studies of balance and cognition, a larger sample size may have been beneficial in detecting a smaller effect, especially considering that there were predictions that trended toward statistical significance (see Table 14 and Figure 5). The regression analyses in the present study had sufficient power only to predict a large effect between cognition and balance. A larger sample would have allowed detection of less substantial effect.

A number of avenues exist for extending and improving this work in future research. Additional experiments with healthy adults might include increasing the balance challenge in various ways, such as having participants close their eyes or stand on a rotating platform. It would also be worthwhile to consider adjusting cognitive tasks and exploring implementation of additional tasks. One possibility would be to have shorter trials to minimize possible error introduced by fatigue. Another would be to use alternate forms of the ACT or to use another task altogether, such as an auditory Stroop task, as was done with older adults by Sui and colleagues (2008). Extending research to healthy adults of various age ranges also has utility, as it can be argued that the relative youth of our sample resulted in smaller effects than would be expected with older adults.

In regards to future research with clinical populations, an obvious direction would be to repeat aspects of the same experiment with various patient populations, beginning with individuals in the acute or subacute phase of mTBI. Other populations of interest might include patients with MS, movement disorders, and complicated medical conditions. Doing so would increase the applicability of the findings and provide more precise guidance for management of cognitive impairment in the context of balance disturbance.

Finally, research examining treatment outcomes is also imaginable. One option would be to repeat cognitive testing for individuals whose balance impairment has improved. For example, individuals with both balance impairment and cognitive impairment could receive balance or vestibular rehabilitation therapy. Cognitive performance could be compared pre- and post-treatment or between possible treatment and control groups.

Conclusion

In conclusion, the present study reveals a significant relationship between balance performance and sustained attention but not between balance performance and working memory, suggesting that impairments in balance may contribute to attentional impairments, even among healthy individuals. This highlights the importance of considering balance impairment as a contributing factor in cognitive symptoms among individuals with mTBI and, more broadly, among patients with various other neurologic and complex medical conditions or even among healthy older adults. Additionally, the present study provides support for including recommendations to address balance concerns in the hopes of alleviating cognitive symptoms among these patient groups.

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