I Can’t Stand Thinking Anymore: An Analysis of Directed Attention on Posture

by

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ABSTRACT

Maintaining upright balance and postural control is a task that most individuals perform everyday with ease and without much thought. Although it may be a relatively easy task to perform, research has shown that changes in cognitive (or "attentional") processes are reflected in the movements of sway. The purpose of this dissertation is to understand the relationship between attention and posture when attention is directly or indirectly shifted away from posture. Using a dual-task paradigm, attention was shifted directly by instructing participants to prioritize the balance task (minimize sway in a unipedal stance) or prioritize the cognitive task (minimize errors in an auditory *n*-back task) and indirectly by changing the difficulty level of the cognitive task (0-back vs. 2-back task). Postural sway was assessed using sample entropy (SampEn), standard deviation, (SD) and sway path (SP) of trunk movements to measure the regularity, variability, and overall distance of sway travelled, respectively. Dual-task behavior was examined when participants were in a controlled (i.e., non-fatigued) state (Experiment 1), in a state of physical fatigue (Experiment 2), and in a state of mental fatigue (Experiment 3). Across all three experiments, indirectly shifting attention away from posture in the more difficult 2-back task induced less regularity (higher SampEn) and variability (smaller SD) in postural sway. Directly shifting attention away from posture, by prioritizing the cognitive task, induced less regularity (higher SampEn) and a longer path length (higher SP) in Experiment 1, however this effect was not significant for the fatigued participants in Experiments 2 and 3. Neither physical fatigue (Experiment 2) or mental fatigue (Experiment 3) negatively affected postural sway or cognitive performance. Overall, the findings from this dissertation contribute to the relationship between movement regularity and attention in posture, and that the postural behavior that emerges is sensitive to methods in which attention is manipulated (direct, indirect) and fatigue (physical, mental).

This work is dedicated to all of my family and friends that have supported me throughout this process. I never could have reached this point without the love and support you have all given me, especially my loving and wonderful mom and stepdad. Thank you both for all of your help that allowed me to focus on my education. I would also like to dedicate this work to Marion Todd Gibbons, my dad, who taught me to always strive to continue learning, and importantly, shared with me his passion to teach what I have learned to others. I love you all so much!

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Postural control is traditionally considered to be an automatic process that requires minimal attentional (or cognitive) resources. However, research has shown that maintaining or regaining postural stability requires considerable attentional resources (Stins & Beek, 2012; Woollacott & Shumway-Cook, 2002). Dual-task paradigms are commonly used to investigate the extent to which cognitive resources are allocated between two tasks. The assumptions of this paradigm are that (1) attentional capacity is limited; (2) performing a task requires some portion of this attentional capacity; and (3) if two tasks performed concurrently require more attention than the total capacity, then performance quality on one or both tasks will decline (Kahneman, 1973; Siu & Woollacott, 2007). Performance declines are particularly pronounced in older (Brown, Shumway-Cook, & Woollacott, 1999; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997) and balance-impaired adults (Brown, Sleik, & Winder, 2002; Marchese, Bove, Abbruzzese, 2003), compared to young adults and healthy controls. Because it is well known that physical and balance abilities decline with age (Maki, Holliday, & Fernie, 1990; Winter, 1995), the presumption is that healthy adults require fewer attentional resources to maintain posture and can therefore attend fully to the secondary cognitive task without destabilizing posture (Müller, Redfern, & Jennings, 2007). In other words, postural control is put on "auto-pilot". Research suggests that the postural system needs to be sufficiently challenged to fully understand the relation between attention and posture in healthy adults. This dissertation is focused on examining the effect of shifting attention on posture when participants are explicitly instructed to attend to the balance task or a secondary task.

Posture and Cognition

There is an imbalance in the literature on the interaction between posture and cognition in healthy adults: Many studies have shown impairments in cognitive performance as a function of posture but fewer studies have observed impairments in posture as a function of cognition (e.g., Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fluery, 1993; see Stins & Beek, 2012 for a review). In one of the first studies on posture and attention, Kerr et al. (1985) asked young participants to control their posture in different balance conditions (sitting and standing in the tandem stance with and without vision) while performing spatial and non-spatial memory tasks. Results showed no effect of cognitive task on postural sway, but participants did make more cognitive errors when standing with the eyes closed. In another early study, Lajoie et al. (1993) used a reaction time task to examine whether attentional demands vary as a function of the postural task. Participants performed the task while sitting, standing in a "normal" feet-apart stance, standing with a reduced base of support (i.e., feet together), and walking (single vs. double support phase). Results showed that reaction time was fastest for sitting and slowed when participants were standing or walking. Reaction times were slower when standing in the more challenging feet together position compared to standing with the feet separated. Reaction times were also slower during the single-leg support phase of waking (reduced base of support) compared to the double support phase. The authors also reported that there was no change in postural sway or gait cycle while performing the secondary task. The findings from both Kerr et al. (1985) and Lajoie et al. (1993), regarding performance declines in the secondary task suggest - *indirectly* - that postural control requires some attentional resources and that even more resources are needed for more complex balance tasks.

The above studies are significant because they demonstrate that concurrent postural and cognitive tasks seem to “compete” for attentional resources, but they do not show that postural control is affected in any way. Research on the effects of a secondary task on posture in young adults have shown mixed results. For example, Pellechia (2003) observed an increased sway variability when participants stood on a foam surface while performing a concurrent arithmetic task (e.g., digit recall, counting backwards). This finding has been replicated using similar arithmetic tasks in different balance tasks (Cyte et al., 2014; Gibbons, Amazeen, & Jondac, 2019). Spatial and non-spatial memory tasks have also been shown to increase postural sway (Raymakers, Sampson, & Verhaar, 2005). In contrast, sway has been shown to decrease when participants are engaged in other secondary tasks. For example, Stoffregen, Pagulayan, Bardy, and Hettinger (2000) examined postural sway in a dual task paradigm in which participants performed a visual search for near and far targets. Results showed that sway variability decreased when participants were engaged in the dual task compared to the single task, and that variability was especially low when targets were near rather than far. The researchers proposed that postural sway may have decreased in order to facilitate performance in the secondary task. Overall, these studies demonstrate that engagement in a secondary cognitive task can influence postural behavior but that the direction of change is mixed and very task specific. The current study will compare both the effect of postural control on cognition and the effect of cognition on posture.

Direction of Attention and Control

A major issue in the dual-task literature concerns the instructions regarding the direction of attention. One type of instruction given to the participant is to try to perform both tasks equally well (Albertsen, Ghédira, Gracies, & Hutin, 2017; Cavanaugh, Mercer, & Stegiou, 2007; Müller et al., 2007). If attentional focus changes at all, this type of instruction makes it difficult to determine exactly where the participant's attention is directed. Results then may be a function of the direction of attention to one of the two tasks or to a general inability to allocate attentional resources evenly between the two tasks. A number of studies have directed participants to focus attention primarily on only one of the two tasks (Donker, Roerdink, Greven, & Beek, 2007; Frazier & Mitra, 2008; Stins, Roerdink, & Beek, 2011). By explicitly directing the participant's attention to one task researchers can eliminate the confound of not knowing which task that participant attends to during dual-task situations. The current study will follow this latter approach by instructing participants to attend, on any given trial, to either the balance or cognitive task.

Researchers have begun to suggest that different control strategies exist because different tasks place different demands on information-processing (Borel & Alescio-Lautier, 2014; Müller et al., 2007). Minimal attentional resources are needed to maintain postural control in non-demanding tasks, such as sitting or standing under normal conditions (e.g., both feet shoulder-width apart on stable ground), whereas more resources are needed as the difficulty of the postural task increases. For both the primary balance task and secondary cognitive task to be performed optimally, it is important for an individual to flexibly and appropriately allocate attention between the two tasks (Siu & Woollacott, 2007).

Müller et al. (2007) proposed two control strategies that may play a role in understanding the interaction between cognitive and postural task process in dual-task situations: (1) postural prioritization and (2) cognitive prioritization. For example, in demanding postural tasks that challenge the participant's ability to remain stable, the participant prioritizes posture because the threat of failure (e.g., falling) is more severe than making an error on the cognitive task. Müller et al. (2007) showed that performance on a secondary task (choice reaction time task) declined when participants stood in anticipation of a perturbation to posture (platform translation). Performance then improved significantly after the perturbation. Researchers interpreted this finding as evidence of a prioritization strategy in which participants attend to the cognitive task fully only after the appropriate postural response has been executed. In other words, responding to the secondary task is "put on hold" until a stable posture is ensured. Conversely, participants are presumed to adopt a cognitive prioritization strategy when there is no perceived threat to posture and their balance abilities exceed the demand of the balance task. The current proposal will examine prioritization strategies on postural behavior when the system's physical and mental abilities are challenged.

Analysis of Postural Sway

Researchers have generally relied upon linear measures to identify degradations in postural control. For example, increases in sway variability or sway range are often interpreted as a decline in postural stability (Doyle, Hsiao-Wecksler, Ragan, & Rosengran, 2007; Shumway-Cook et al., 1997; Vuillerme et al., 2001). These measures, however, have not consistently revealed changes in postural control when balance is cognitively perturbed (Albertsen et al., 2017; Woollacott & Shumway-Cook, 2002) and, as identified earlier, the direction of the effect can depend on the type of cognitive tasks used. In addition, movement variability has been shown to change for different reasons. For example, variability has been shown to increase as a result of negative (e.g., injury; de Haart, Geurts, Huidekoper, Fasotti, & van Limbeek, 2004) or positive (e.g., skill acquisition; Wilson, Simpson, van Emmerik, & Hamill, 2008) states of the motor system. Because of these contradictory findings, it has been suggested that linear measures are limited in their ability to identify the source of variation and sensitivity to changes in postural behavior (Cavanaugh et al., 2007; Stergiou & Decker, 2011; van Emmerik & van Wegen, 2002). Alternative nonlinear approaches that examine the structure of variability in a signal may be more reliable in detecting subtle changes in movement.

The inherent fluctuations observed in postural sway provide a complex signal of the postural control system in which cognitive, perceptual, and motor processes are reflected. Nonlinear measures that examine the dynamical structure or pattern of those fluctuations capture the complexity of the postural control system and its constituent processes (Collins & De Luca, 1993; Newell, van Emmerik, Lee, & Sprague, 1993; Stergiou & Decker, 2011; van Emmerik & van Wegen, 2002 Yamada, 1995). Several nonlinear measures have been used to characterize postural control, such as: correlation dimension, scaling exponent, recurrence quantification analysis, largest Lyapunov exponent, and entropy (e.g., Donker et al., 2007; Gibbons, Amazeen, & Jondac, 2019; Gibbons, Amazeen, & Likens, 2019a, 2019b; Murata & Iwase, 1998; Riley, Baker, Schmit, & Weaver, 2005; Roerdink et al., 2006; Yamada, 1995). Entropy provides an index of the regularity in a complex signal, with low values indicating more regularity and higher values indicating less regularity (Pincus, 1991).

Researchers have suggested that regularity in postural sway fluctuations relates to the amount of attention invested in postural control (Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2006; Roerdink, Hlavackova, & Vuillerme, 2011; Stins, Michielsen, Roerdink, & Beek, 2009; Stins et al., 2011), or similarly, the "automaticity" of the postural control (Borg & Laxåback, 2010). One of the first studies to suggest a direct relationship between entropy and the amount of attention in postural control was by Roerdink et al. (2006), who examined the recovery of postural control in stroke patients and healthy controls. Researchers found that the healthy controls exhibited overall less regularity in sway fluctuations (higher entropy) and lower variability (lower standard deviation) than the stroke patients. Additionally, it was observed that sway became less regular over the course of a 12-week rehabilitation program. The researchers interpreted this decrease in regularity over the course of rehabilitation as a sign that postural control was becoming more automatic and subsequently requiring less cognitive effort (Roerdink et al., 2006). Interestingly, when participants performed a concurrent cognitive task, they exhibited less sway regularity (higher entropy) compared to performing only the balance task. Comparable task effects have since been observed in healthy young adults (Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2011; Stins et al., 2009; Stins et al. 2011). Cavanaugh et al. (2007) observed a significant decrease in anterior-posterior (AP) sway regularity when participants diverted attention away from posture by performing a digit recall task while standing. Similarly, Stins et al. (2009) found that expert dancers exhibited less sway regularity than non-dancers when standing quietly and when performing a secondary cognitive task. The findings from these studies provide support for the direct relationship between the amount of attention directed towards posture and the regularity of the movement signal. Entropy analysis may provide a more direct method of examining the amount of attention in postural control compared to indirectly examining performance declines in a secondary task.

Current Study

The current series of studies were designed to examine the effects of attention on posture. The current studies build heavily on previous research that has suggested that the amount of attention directed at maintaining posture is revealed through the amount of regularity observed in the patterns of postural sway (e.g., Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2006; Roerdink et al., 2011; Stins et al., 2009; Stins et al., 2011). Participants will control postural sway while balancing in a unipedal stance (i.e., balancing on a single leg) and concurrently performing an auditory *n*-back task. Experiment 1 is designed to replicate findings from previous studies (e.g., Cavanaugh et al., 2007; Donker et al., 2007; Stins et al., 2009; Stins et al., 2011) that have shown lower entropy values when attention is directed towards posture and higher values when attention is directed away from posture in dual-task paradigms. The difference between this study and the afore-mentioned studies is that the direction of attention will be explicitly manipulated rather than assuming a change to the direction of attention. Experiments 2 and 3 will examine the relationship between directed attention and posture further by fatiguing the physical (Experiment 2) and cognitive (Experiment 3) abilities of healthy adults using the same dual-task paradigm as Experiment 1.

Experiment 1

The purpose of Experiment 1 was to replicate findings that patterns in postural sway change as a function of the amount of attention being directed at controlling posture. A dual task was used to test that hypothesis by having participants simultaneously maintain a unipedal stance and perform an auditory *n*-back task.

The *n*-back task is a commonly used task in the cognitive literature because of its ability to place continuous demands on attention (Monk, Jackson, Nielsen, Jefferies, & Oliver, 2011). In an auditory *n*-back task, participants listen to a series of items (e.g., single-digit numbers) and repeat the items at a lag of *n*. In a 2-back task, for example, after hearing the sequence "2, 7, 9, 1, 5", a participant performing 2-back would stay silent for the first two digits, then say "2" after hearing 9, "7" after hearing 1, and so on. In the current study, participants performed a 0-back task and a more challenging 2-back task. The purpose of the easier 0-back task was to control for the effects of vocalizing on posture because research has suggested that changes in postural sway may be due to articulation effects rather than an increase in cognitive load (Dault, Yardley, & Frank, 2003; Yardley, Gardner, Leadbetter, & Lavie, 1999).

In this experiment, attention was shifted *directly* by instructing participants to prioritize performance of either the unipedal balance task or the auditory *n*-back task, and attention was shifted *indirectly* by increasing the difficulty of the *n*-back task. Performance in the balance task was measured by the participants' ability to minimize sway in the anteroposterior (AP) direction, and performance in the *n*-back task was measured by the number of errors committed. When the direction of attention (DoA) was towards the balance task, postural sway was expected to exhibit more regularity (small sample entropy, SampEn). In order to examine whether changes in sway variability and the amount of sway accompany changes in SampEn, standard deviation (SD) was used to quantify sway variability and sway path length (SP) was used to quantify the total amount of sway. Participants were expected to be capable of minimizing SD and SP when the DoA was *directly* towards the balance task. Cognitive performance was expected to decline (increased number of errors) when attention was directed away from the cognitive task by prioritizing the balance task. When the DoA was towards the *n*-back task, the regularity in sway was expected to decrease (large SampEn), sway variability and path length were expected to increase (large SD and SP), and performance in the *n*-back task was expected to improve (fewer number of errors).

In addition to measuring postural sway and performance in the cognitive task, electromyography (EMG) data were measured at the lower leg muscles in each trial. Previous research that has examined effects of directed attention on muscle activity has shown that EMG activity is amplified when participants adopt an "internal" focus of attention compared to an "external" focus of attention (e.g., Marchant, Greig, & Scott, 2009; Vance, Wulf, Töllner, McNevin, & Mercer, 2004; Wulf & Dufek, 2009; Wulf, Dufek, Lozano, & Pettigrew, 2010; Zachry, Wulf, Mercer, & Bezodis, 2005). The current study explored whether muscle activity change as a function of DoA. The root mean square error (RMSE) of EMG activity was expected to be greatest when DoA was towards posture.

Method

Participants

Thirty-one introductory psychology students (M_{age} = 19.9 yrs; 16 women; M_{height} = 171.1 cm; M_{weight} = 65.1 kg) from Arizona State University participated in the study in exchange for course credit. Data from four participants were removed from further analysis due to technical difficulties. Therefore, data from twenty-seven participants were included in the analysis. Power analysis following the methods from Anderson, Kelley, and Maxwell (2017) and based on the sample effect size from Cavanaugh et al. (2007) revealed a target sample size of 24 to achieve 0.8 power. Therefore, the sample size was deemed adequate. Informed consent was obtained prior to participation. None of the participants reported any pre-existing injury or disorders that may have affected performance in the task. Participants were treated in accordance to the Declaration of Helsinki.

Apparatus

Postural sway was measured at the trunk by affixing a single marker to the backside of the participants, approximately the midpoint between the shoulder blades at the level of the T5-7 vertebrae (Figure 1), using an adjustable chest strap. A second marker was attached to the backside of the ankle (of the standing leg) to measure movement at the lower body. Movement of the markers was registered at 100 Hz using an Optotrak motion capture system (Northern Digital Inc., Waterloo, Canada).

Surface EMG was recorded from two locations on the lower leg (anterior tibialis, AT, and lateral gastrocnemius, LG) at 1,000 Hz using a single channel, high gain amplifier (Biopac Systems, Inc., Santa Barbara, CA). At each muscle, two disposable electrodes were placed approximately 2-3 cm apart parallel to the muscle fiber (Wulf et al., 2010).

The auditory *n*-back task was delivered using the N-backer software, presented in Monk et al. (2011) and available for download from the Open Lab at Newcastle University (https://openlab.ncl.ac.uk/nback/). The program generated a randomized series of single-digit numbers. The researcher manually recorded correct and incorrect responses during each trial.

Procedure

Participants stood with their backs facing the camera at a distance of approximately 3.5 m and a distance of approximately 4.3 m from the wall in front of them. Participants were instructed to balance on their dominant leg during dual-task performance with their arms hanging relaxed at their side. The leg that the participant would use to kick a ball was selected as the dominant leg. Participants elevated the non-dominant leg by bending the knee until the foot no longer touched the ground. Participants were instructed to refrain from touching the ground with the elevated foot to stabilize balance during the trial. Data collection for each trial began when participants were standing in the unipedal stance and verbally signaled a readiness to begin. The duration of each trial was 20 seconds. Participants were allowed to rest between trials.

Feedback was provided to ensure that participants were directing attention towards the appropriate task. For trials in which attention was directed towards the balance task, participants were given the instruction to "minimize sway by standing as steady as possible". After each trial, only the distance travelled (in the AP direction) was written a whiteboard. For trials where attention was directed towards the cognitive task, participants were instructed to "minimize errors in the *n*-back task" and only the number of errors were written on the whiteboard after each trial.

Participants completed 12 trials in each condition of directed attention (6 trials in of each *n*-back condition) for a total of 24 trials. Direction of attention trials were counter-balanced across participants in order to minimize order effects. The order of *n*-back task condition was randomized across trials.

Design and Analysis

Due to a substantial amount of marker occlusion at the ankle, ankle movements were not analyzed. Postural sway measures (SampEn, SD, SP) were computed from the position data of the trunk marker in both the AP and ML directions.

Sample entropy was estimated using the algorithm developed by Goldberger et al. (2000) and available from PhysioNet (https://physionet.org). As an index of regularity, sample entropy was estimated as the logarithmic probability that a portion of the time series of length N will repeat itself of for M points within a tolerance range r (Lake, Richman, Griffin, & Moorman, 2002; Richman & Moorman, 2000; Pincus, 1991). Trunk movements were mean-centered. A pattern window of M=2 was chosen to coincide with recommendations from the literature that suggests window sizes of 2-3 be used for biological data (Lake et al., 2002; Richman & Moorman, 2000; Roerdink et al., 2011; Stergiou, 2016; Stins et al., 2011). The tolerance window r was chosen as 20% the signal variability (Pincus & Goldberger, 1994; Stergiou 2016). SD was computed for each trial following conventional methods. SP was operationalized as the total Euclidean distance travelled (in mm).

EMG time series for both LG and AT muscle locations were mean-centered and bandpass filtered with cutoffs at 10 and 400 Hz. Signals were then full-wave rectified and enveloped using a moving average filter with a window size corresponding to 1 sec. RMSE of the EMG activity was then determined for each muscle.

The six postural sway measures (SampEn, SD, SP – two for each direction), two EMG measures (RMSE – one for each muscle), and cognitive measure (number of errors) were analyzed in separate 2 $\times$ 2 repeated measures analyses of variance with (1) DoA (towards balance, towards cognition) and (2) *n*-back (0-back, 2-back) as the factors.

Results

Manipulation Check

Mean performance data serve as manipulation checks that participants followed instructions to minimize sway or *n*-back errors, depending on the DoA condition. Figure 2 shows the change in mean SP when DoA across the 12 trials in which the DoA was towards posture and towards cognition. Because participants were given feedback about their SP in the AP direction *only* when the DoA was towards posture, we focus on the changes in AP sway in those trials only. From the figure we can see an overall decrease in AP sway across trials when participants were instructed minimize sway and given feedback after each trial. Results from a repeated-measures ANOVA revealed that the change across trials was significant ($F(11, 220) = 3.51$, $p < 0.001$, $\eta_p^2 = 0.15$). This confirms that participants accomplished the goal of prioritizing posture and minimize sway.

Figure 3 depicts mean number of errors (in the 2-back task) across the six trials in which participants were instructed to minimize errors in the cognitive task. Importantly, this analysis does not include data from the six 0-back trials (in each DoA condition) because participants did not make any errors. Results from a repeated-measures ANOVA revealed that cognitive performance changed significantly across trials ($F(5, 115) = 6.01$, $p < 0.001$, $\eta_p^2 = 0.21$) where DoA was towards cognition. This confirms that cognitive performance changed across trials when the cognitive task was prioritized.

Sample Entropy

The top panels of Figure 4 depict mean SampEn in the (A) AP and (B) ML directions as a function of DoA and *n*-back task. In the AP direction, results from the repeated-measures ANOVA revealed significant main effects of DoA, $F(1, 26) = 4.49$, $p = 0.04$, $\eta_p^2 = 0.15$, and *n*-back task, $F(1, 26) = 5.29$, $p = 0.03$, $\eta_p^2 = 0.17$. The same main effects were significant in the ML direction (DoA: $F(1, 26) = 4.88$, $p = 0.04$, $\eta_p^2 = 0.16$; *n*-back task: $F(1, 26) = 20.52$, $p < 0.001$, $\eta_p^2 = 0.44$). The DoA × *n*-back interaction was not significant in either the AP or ML direction. In both the AP and ML directions, SampEn was smaller, indicating more regular movements, when attention was directed towards posture than when the DoA was towards the cognitive task. Similarly, SampEn was smaller when participants performed the easier 0-back task than the more challenging 2-back task in both directions of sway.

Standard Deviation

The middle panels of Figure 4 depict mean SD in the (C) AP and (D) ML directions as a function of DoA and *n*-back task. In the AP direction, results revealed a significant main effect of *n*-back task only, $F(1, 26) = 15.38$, $p < 0.001$, $\eta_p^2 = 0.38$. From Figure 4C we can see that, regardless of DoA condition, SD was smaller in the more challenging 2-back condition than the 0-back condition. In the ML direction, there was a significant DoA × *n*-back interaction, $F(1, 26) = 6.04$, $p = 0.02$, $\eta_p^2 = 0.20$, and a significant main effect of *n*-back task, $F(1, 26) = 13.14$, $p < 0.001$, $\eta_p^2 = 0.35$. Post hoc tests revealed that SD did not change between the 0-back and 2-back task when DoA was toward posture ($p > 0.05$). However, SD decreased significantly between the 0-back and 2-back task when DoA was toward the cognitive task, $t(25) = 4.20$, $p < 0.001$.

Sway Path

The bottom two panels of Figure 4 depict mean SP in the (E) AP and (F) ML directions as a function of DoA and *n*-back task. In the AP direction, results revealed significant main effects of DoA and *n*-back task only ($F(1, 26) = 6.07$, $p = 0.02$, $\eta_p^2 = 0.20$; $F(1, 26) = 5.50$, $p = 0.03$, $\eta_p^2 = 0.19$, respectively). Participants swayed less overall (smaller SP) when DoA was toward posture than DoA toward the cognitive task. SP was smaller, as well, when participants performed the 2-back task in comparison to the 0-back task. In the ML direction, there was a significant DoA × *n*-back interaction, $F(1, 26) = 4.47$, $p = 0.04$, $\eta_p^2 = 0.16$, and a significant main effect of DoA, $F(1, 26) = 5.90$, $p = 0.02$, $\eta_p^2 = 0.20$. Similar to the trends found in SD (Figure 4D), post hoc tests revealed no difference in SP between *n*-back task conditions when DoA was toward posture ($p > 0.05$). However, SP was significantly smaller in the 2-back task when DoA was toward the cognitive task, $t(25) = 2.37$, $p = 0.03$.

EMG

Figure 5 depicts mean EMG RMSE for the (A) anterior tibialis and (B) lateral gastrocnemius. In both figures it is evident that muscle activity did not change as function of DoA and *n*-back task. Results from the repeated-measures ANOVA confirmed that there was no significant interaction or main effects ($p > 0.05$).

Cognitive Performance

Figure 6 depicts mean number of errors in the *n*-back task as a function of DoA and *n*-back task. Results from the ANOVA revealed a significant main effect of *n*-back task only ($F(1, 28) = 39.75$, $p < 0.001$, $\eta_p^2 = 0.59$). Not surprisingly, performance was worse in the more challenging 2-back task condition. Because participants made no errors in the 0-back task the significant main effect of *n*-back task is likely due to floor effects in the 0-back condition.

Discussion

The purpose of this experiment was to investigate changes in postural sway when attention was explicitly directed towards either a postural or cognitive task in a dual-task paradigm. Attention was diverted towards the respective task through instruction to prioritize one task over the other. Participants were instructed to minimize sway when prioritizing the postural task and minimize errors when prioritizing the cognitive task. We found that shifting attention towards each task had significant effects on the regularity in sway movements (SampEn) and the sway path length (SP). Both SampEn and SP decreased significantly when attention was directed towards the posture task compared to when attention was directed towards the cognitive task. The SampEn results replicate previous studies that have suggested that the amount of attention invested in posture is reflected in the regularity of sway fluctuations (e.g., Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2006; Roerdink et al., 2011; Stins et al., 2009, Stins et al., 2011). The SP results mirror a study from Reynolds (2010) that found an overall reduction in sway when participants intentionally stood still or stood relaxed.

Prioritization of the posture task was expected to decrease sway variability (SD) as well. SP and SD both provide assessments of the overall *magnitude* of postural movements: SP quantifies the total Euclidean distance that the upper body travelled during stance, and SD quantifies how much the upper body moved around a "mean" position of posture (i.e., the variation in the distribution of body position). Although they measure different aspects of sway variability, they were both expected to decrease when participants were instructed to minimize sway. Sway path and sway variability have been shown be positively correlated when posture is perturbed (Chiari, Rocchi, & Cappello, 2002; Corbeil, Blouin, Bégin, Nougier, & Teasdale, 2002; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). SD, however, did not change significantly as a function of directed attention. On the whole, the reduction in SampEn and SP show that the shift in attention, caused by prioritizing the motor or cognitive task, is reflected in changes in the regularity and magnitude of postural sway and supports the interpretation that the regularity in sway movements reflect the amount of attention invested in postural control.

Directed vs. Indirect Manipulations of Attention

Although attention was *directly* manipulated (or "forced") by instructing participants to focus on each task separately, manipulating the difficulty of the *n*-back task provided an *indirect* (or "unforced") way of shifting attention away from posture. The 0-back task was included to control for the effects of articulation because it has been found that sway variability can increase when participants are required to verbally respond (e.g., count-backwards aloud) compared to no verbal response (e.g., count-backwards silently) despite the cognitive demands remaining the same (Dault et al., 2003; Yardley et al., 1999). Because the articulation requirements were identical in both the 0-

back and 2-back tasks in the current study, we can conclude that the changes to SampEn, SD, and SP are the result of the difference in attentional demands between the two cognitive task conditions and not articulation effects. In the current study, sway was less regular (larger SampEn) when participants performed the more difficult 2-back task. The SampEn results replicate previous studies that have shown larger entropy values when cognitive demands increased with the addition of a secondary task (e.g., Cavanaugh et al., 2007; Donker et al., 2007; Stins et al., 2009; Stins et al., 2011).

Sway was also less variable, as reflected by the significant decrease in SD and SP, when participants performed the more challenging 2-back task. The findings replicate previous studies that reported an overall decrease in sway variability measures when cognitive demands increase in comparisons of single and dual task performance and performance of easy and hard secondary tasks during the dual task (e.g., Albertsen et al., 2017; Huxhold, Li, Schmiedek, & Lindenberger, 2006; Lajoie, Richer, Jehu, & Tran, 2016; Richer, Saunders, Polskaia, & Lajoie, 2017; Stoffregen et al., 2000). The finding across these studies collectively show that sway is minimized as the cognitive demands increase by different means of task manipulation. It has been suggested that minimizing movement variability may be the cognitive-motor system's automatic response to increased demands in the secondary task (Albertsen et al., 2017; Frazier & Mitra, 2008; Richer et al., 2017; Riley, Stoffregen, Grocki, & Turvey, 1999; Riley et al., 2005; Stins et al., 2011; Stoffregen, et al., 2000; Siu & Woollacott, 2007). The findings from the current study support the hypothesis of a sway minimization strategy.

Cognitive Performance

Postural performance improved when participants were instructed to prioritize the posture task, but cognitive performance was not affected by the instruction to prioritize the cognitive task. Cognitive performance was affected only by the level of difficulty in the cognitive task. Not surprisingly and in support of many previous studies (Baddeley, Hitch, & Allen, 2009; Ragland et al., 2002; see Redick & Lindsey, 2013 for a review), participants committed more errors in the 2-back task than the 0-back task. We expected that cognitive performance would suffer when attention was directed towards posture, but the overall number of errors did not change across the different conditions of directed attention. The implication is that cognitive performance was not affected by allocating some cognitive effort towards the motor task.

Attention and Muscle Activity

Muscle activity was measured at the AT and LG muscles to extend the findings from the literature that have observed effects of attention on muscle activity (e.g., Marchant et al., 2009; Vance et al., 2004; Waddell & Amazeen, 2019; Wulf & Dufek, 2009; Wulf et al., 2010; Zachry et al., 2005). Based on those studies, more muscle activity (as indexed by EMG RMSE) was expected when participants were instructed to prioritize balance. However, results showed that activity in the muscles did not change in either muscle as a function of directed attention or cognitive task difficulty. One possible explanation is that the static nature of the unipedal balance task may not demand sufficient muscle activity to detect differences in attentional focus. Studies that have observed differences in task relevant muscle activity have generally involved motor tasks that are arguably more “physically demanding” than maintaining balance, such as: bicep curls (Marchant et al. 2009; Vance et al., 2004; Waddell & Amazeen, 2019); free-throw shooting (Zachry et al., 2005); and jump-and-reach task (Wulf & Dufek, 2009; Wulf et al., 2010). Another possibility is that there are many muscles along the body that are involved in maintaining balance and the AT and LG muscles my not be sensitive enough to reflect shifts in attention in isolation of the other muscles in the abdominals, hips, and upper leg that are involved in balance. Research could examine changes in a collection of muscles across the body that are apart of maintaining upright balance.

This is the first known study to find effects of shifted attention on the regularity of sway when individuals are in a unipedal stance. We chose the unipedal stance to ensure that the balance was moderately challenging and something "apparent" that the participants could attend to and prioritize. Overall, sway became less regular when attention was diverted away from posture when participants (1) prioritized the cognitive task and (2) performed the difficult 2-back task. These findings contribute to an understanding of the relationship between regularity and attention and provide a foundation to examine how the relation between attention and posture change when posture is physically challenged, as in Experiment 2.

Experiment 2

Examining dual-task performance when individuals are in a state of physical fatigue provides a way to further examine the attentional requirements involved in performing the motor tasks. Physical fatigue (or muscle fatigue) occurs when the motor system performs strenuous or repetitive motor actions (e.g., lifting heavy objects, running) that result in decreased force output and tension capacity of the muscles (Gribble & Hertel, 2004a; 2004b; Hiemstra, Lo, & Fowler, 2001). In procedures designed to induce fatigue in balance, researchers have targeted muscles in the hips (Bisson, McEwen, Lajoie, & Bilodeau, 2011; Gribble & Hertel, 2004a; 2004b; Salavati, Moghadam, Ebrahimi, & Arab, 2007), quadriceps/hamstrings/knee (Bizid et al., 2009; Gribble & Hertel, 2004a; 2004b) and or lower legs/calf/ankles (Bisson et al., 2011; Bizid et al., 2009; Gribble & Hertel, 2004; Salavati et al., 2007; Vuillerme, Burdet, Isableu, & Demetz, 2006; Vuillerme, Forestier, & Nougier, 2002). The general finding is that sway measures (e.g., range, SD, velocity) are amplified when participants balance in a state of fatigue (Bisson et al., 2011; Bizid et al., 2009; Gribble & Hertel, 2004a, 2004b; see Paillard, 2012 for a review; Nardone, Trantola, Giordano, & Schieppati, 1997; Salavati et al., 2007; Simoneau, Bégin, & Teasdale, 2006; Vuillerme et al., 2006; Vuillerme et al., 2002) which researchers have interpreted is a sign that balance is compromised. Because posture will always be prioritized over cognition when balance is threatened (Müller et al., 2007; Siu & Woollacott, 2007) it is reasonable to expect that the attentional resources invested in maintaining/stabilizing posture will increase when participants are physically fatigued. The current study will use the same dual-task paradigm as Experiment 1 to examine changes in sway regularity when attention is *directly* and *indirectly* manipulated by instructing participants to prioritize either the balance or cognitive task and by increasing the difficulty in the cognitive task, respectively.

In the fatigue/depletion literature there are differing theories about the source of the depletion effects (or performance declines) that are observed in the task at hand. Broadly speaking, one perspective assumes performance declines occur because of the physical and/or mental metabolic resources, needed to perform the physically and/or cognitively demanding task, are depleted (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Baumeister, Vohs, & Tice, 2007; Griffith, Kerr, Mayo, & Topal, 1950; Persson, Larsson, & Reuter-Lorenz, 2013). An alternative perspective proposes that performance declines are not solely the result of depleted metabolic resources, but rather the result of a depletion of the individual's motivation to continue to perform well in the task (Brewer, Lau, Wingert, Ball, & Blais, 2017; Dorris, Power, & Kenefick, 2012, , Inzlicht & Schmeichel, 2012; Hagger et al., 2016; Hopstaken, van der Linden, Bakker, Kompier, & Leung, 2016; Muraven & Slessareva, 2003). For example, an individual's motivation to perform a task well will decline if there is no perceived incentive to continue peak performance and, therefore, performance in the task declines as well (this is known as "ego depletion"). The disagreement between these two perspectives has led researchers to examine variables that can be incorporated in a study's methods to ameliorate the effect of ego depletion. One method that has been shown to reduce ego depletion effects is to increase the task rewards (Brewer et al., 2017; Hopstaken et al., 2016; Muraven & Slessareva, 2003). The current experiment incorporated this method by adding a monetary incentive ($5 Amazon gift card) to maintain performance on the balance and cognitive task per the respective DoA instructions. It is important to note that participants in Experiment 1 were not offered a monetary incentive because the study was still awaiting funding for the incentive. We acknowledge this is a methodological concern and we consider the potential effects of the incentive into the discussion of the results.

The purpose of Experiment 2 was to examine *direct* and *indirect* manipulations to attention on postural sway when the muscles involved in balance are fatigued. The same within experiment predictions were expected as Experiment 1: postural sway was expected to be more regular (small SampEn), less variable (small SD), and minimized (small SP) when participants were instructed to *directly* prioritize the balance task by minimize sway. Cognitive performance was expected to be worse (more errors) when the balance task was prioritized and, subsequently, less attentional resources can be devoted to the cognitive task. EMG activity was also expected to be amplified (larger EMG RMSE) when participants were directed to prioritize the balance task. Sway was expected to be less regular (larger SampEn) and less variable (small SD) when attention was *indirectly* shifted away from posture by increasing the difficulty in the *n*-back task. The findings from Experiment 2 will also be compared to the data from Experiment 1 in order to investigate the effects of physical fatigue vs. no fatigue. If being in a state of physical fatigue draws more attention towards maintaining posture compared to no fatigue, then we expect sway to exhibit more overall regularity (smaller SampEn) compared to no fatigue. Additionally, and consistent with the reported results of physical fatigue on sway, sway was expected to exhibit more overall variability (larger SD) and a larger sway path (larger SP) when participants are fatigued compared to no fatigue.

Method

Participants

Twenty-seven introductory psychology students (M_{age} = 19.8 yrs; 12 women; M_{height} = 175.0 cm; M_{weight} = 73.9 kg) participated in this study in exchange for course credit and a $5 Amazon gift card.

Apparatus

The same materials and techniques were used for data collection as in Experiment 1. Physical fatigue was induced by having participants perform seated calf-raises using the Inspire M2 Home Gym (Inspire Fitness, CA).

Procedure

Participants performed seated calf-raises before every experimental trial to ensure posture and cognitive behaviors were measured in a true state of fatigue. Following a similar fatigue protocol from Bisson et al. (2011) and Vuillerme et al. (2006), participants were asked to perform as many seated calf-raises as possible following the beat of a metronome at 40 bpm. All participants performed the calf-raise exercise against 50 lbs of weighted resistance with the exception of two participants who requested 70 lbs of resistance. The fatigue level was reached when participants felt exhausted in the lower leg muscles and verbally reported that they could no longer perform the exercise. Once the fatigue level was reached, participants were immediately guided to the designated standing area by the researcher in order to begin data collection. All other experimental procedures were identical to Experiment 1. The experiment consisted of 12 trials: six trials with attention directed towards the balance task, and six trials with attention directed towards the cognitive task.

Design and Analysis

The same 2 × 2 repeated-measures ANOVA design was used for SampEn, SD, SP, EMG RMSE, and cognitive performance (number of errors) as in Experiment 1 with (1) direction of attention (DoA: towards balance, towards cognition) and (2) *n*-back (0-back, 2-back) as the factors.

Results

Manipulation Check

Figure 7 shows the mean number of calf-raises during the fatigue task across trials. Overall, participants were unable to perform the same number of calf-raises the more they experienced fatigue in the lower leg muscles. This figure lends support that the muscles in the lower legs were fatigued during the experimental trials. Figure 8 depicts mean SP across each of the six trials when the DoA was toward posture and when DoA was toward cognition. Similar to the performance observed in Experiment 1 (Figures 2 & 3), SP in the AP direction decreased across trials per the instructions (and feedback) given to participants. Results from the repeated-measures ANOVA revealed that the change across trials was not significant ($p > 0.05$). However, it is important to note that the SP value in the last trial (100.5 mm) was approximately similar to the value observed in the last trial from Experiment 1 (100.2 mm; see Figure 2) and therefore the non-significant change over trial may have been due to a floor effect. Figure 9 depicts the mean number of errors (in the 2-back task) across the trials in both DoA conditions. Results from a repeated-measures ANOVA revealed that cognitive performance changed significantly across trials ($F(2, 46) = 20.56$, $p < 0.001$, $\eta_p^2 = 0.47$). This result suggests the same adherence to minimize errors in the *n*-back task when DoA was toward the cognitive task.

Sample Entropy

The top two panels in Figure 10 depict mean SampEn in the (A) AP and (B) ML directions as a function of DoA and *n*-back task. Results revealed a significant main effect of *n*-back task, $F(1, 26) = 13.14$, $p = 0.001$, $\eta_p^2 = 0.34$, in the AP direction only.

SampEn values were smaller in the 0-back task compared to the 2-back task regardless of DoA condition. This replicates the significant effect main effect of *n*-back task in the AP direction from Experiment 1. None of the interaction or main effects were significant in the ML direction.

Standard Deviation

The middle panels of Figure 10 depict mean SD in the (C) AP and (D) ML directions as a function of DoA and *n*-back task. In the AP direction, results revealed that only the main effect of *n*-back task was significant, $F(1, 26) = 17.44$, $p < 0.001$, $\eta_p^2 = 0.40$. SD was smaller in the more challenging 2-back task than the 0-back task regardless of DoA condition. None of the interaction or main effects were significant in the ML direction.

Sway Path

The bottom two panels in Figure 10 depict mean SP in the (E) AP and (F) ML directions as a function of DoA and *n*-back task. None of the interaction or main effects were significant in the AP direction. In the ML directions, there was a significant DoA × *n*-back interaction, $F(1, 26) = 5.18$, $p = 0.03$, $\eta_p^2 = 0.17$, and a significant main effect of DoA, $F(1, 26) = 5.40$, $p = 0.03$, $\eta_p^2 = 0.18$. Post-hoc tests revealed that SP was significantly larger in the 2-back task than 0-back task when DoA was toward posture, $t(26) = -2.37$, $p = 0.02$. SP did not change significantly between the 0-back and 2-back tasks when DoA was toward the cognitive task ($p > 0.05$).

EMG

Similar to the Experiment 1 findings, EMG RMSE did not change as function of DoA and *n*-back task. Therefore, no figure was included. Results from the repeated-measures ANOVA confirmed that there was no significant interaction or main effects for both the AT and LG muscles ($p > 0.05$).

Cognitive Performance

Figure 11 depicts mean number of errors in the *n*-back task as a function of DoA and *n*-back task. ANOVA results replicated the findings from Experiment 1. Results revealed a significant main effect of *n*-back task only ($F(1, 27) = 48.75$, $p < 0.001$, $\eta_p^2 = 0.64$). Participants performed worse in the *n*-back task (increased errors) in the more challenging 2-back task than the 0-back task. As mentioned previously, this significant effect is likely due to the floor effect in the 0-back condition.

Non-fatigue (Exp. 1) vs. Fatigue (Exp. 2)

Figure 12 depicts the combined (A, B) SampEn, (C, D) SD, and (E, F) SP results from Experiment 1 (Figure 4) with the current results (Figure 10) in order to examine difference in postural measures as a function of physical fatigue. A mixed-design ANOVA was used to examine the effects of fatigue (i.e., Experiment 1 vs. Experiment 2) as the between-subjects factor. For the SampEn measure, results revealed a significant interaction between Experiment × *n*-back ($F(1, 52) = 7.25$, $p = 0.01$, $\eta_p^2 = 0.12$) for the ML direction only. No other significant effects were found for the ML and AP directions. From Figure 12B, we can see that values of SampEn were smaller when performing the 0-back task in Experiment 1 but did not change between *n*-back task conditions in Experiment 2. This suggests that the change between *n*-back task conditions had a larger effect on SampEn when participants were not fatigued (Experiment 1) than when they were fatigued (Experiment 2). The same significant Experiment × *n*-back effect was found for SD in the ML direction (Figure 12D) only

($F(1, 52) = 4.39$, $p = 0.04$, $\eta_p^2 = 0.08$). In Experiment 1, SD was smaller in the 0-back task than the 2-back task but did not change between *n*-back task conditions in Experiment 2. The same significant Experiment × *n*-back effect also was found for SP in both the (Figure 12E) AP and (Figure 12F) ML directions ($F(1, 52) = 4.96$, $p = 0.03$, $\eta_p^2 = 0.09$; $F(1, 52) = 4.21$, $p = 0.04$, $\eta_p^2 = 0.07$, respectively). Similar to the significant effects for SampEn and SD, SP changed significantly between *n*-back task conditions when participants were not in a state of fatigue (Experiment 1) compared to when they were fatigued (Experiment 2). No other effects on SP or SD were significant.

Discussion

The purpose of Experiment 2 was to examine the interaction between attention and posture in a dual-task when participants were physically fatigued. The results of Experiment 1 showed that postural sway became more regular (decreased SampEn) and sway path (SP) decreased when participants prioritized the postural task, but cognitive performance did not change when participants prioritized the cognitive *n*-back task. Indirect shifts of cognitive attention through manipulation of the difficulty of the *n*-back task (0-back vs 2-back) had the same effect as previous studies that manipulated the presence or absence of a cognitive task (e.g., Cavanaugh et al., 2006; Donker et al., 2007; Stins et al., 2009; Stins et al., 2011). The results of Experiment 2 replicated some findings from Experiment 1 and failed to replicate others.

In contrast to Experiment 1, sway regularity (SampEn) did not change as a function of *directly* shifting attention by prioritizing each task; that is, SampEn was the same when participants prioritized the balance task or cognitive task. The finding that *directly* manipulating attention had no effect on sway regularity in the current study suggests that physical fatigue eliminates the effects of direction of attention in a dual task. We will investigate the replication of that effect with the manipulation of cognitive fatigue in Experiment 3. Sway was less regular (larger SampEn) when attention was diverted away from posture *indirectly* by increasing the cognitive demands in the *n*-back task (0-back vs. 2-back). This finding replicates the results of Experiment 1 and previous studies that have shown less sway regularity (larger entropy values) when cognitive demands increased from the addition of a secondary task (e.g., Cavanaugh et al., 2007; Donker et al., 2007; Stins et al., 2009; Stins et al. 2011). Sway variability (SD) and sway path (SP) results also replicated the results of Experiment 1: SD was smaller overall when the cognitive demands increased in the 2-back task but not when participants were instructed to prioritize the balance task and minimize sway; conversely, SP was smaller overall when participants prioritized the balance task but not when the cognitive demands increase in the 2-back task. The changes in SD and SP are discussed further below.

Studies that have examined fatigue effects in dual-task performance have only ever instructed participants to prioritize the balance task over the secondary cognitive task (Bisson et al., 2011; Vuillerme et al., 2002). This is the first known study to instruct participants to prioritize the cognitive task over maintaining balance in a challenging unipedal stance. This is also the first known study to compare direct and indirect methods of manipulating attention on movements when participants are in a state of physical fatigue. More research is first required to understand the systematic differences between direct and indirect methods of shifting attention in dual-task situations and why they *would* affect the cognitive-motor system differently.

Direct vs. Indirect Effects on SP and SD

Directly manipulating attention by prioritizing either the balance task or the cognitive task had the same effects on sway path as observed in Experiment 1. When participants prioritized the posture task by attempting to minimize sway, SP was significantly smaller compared to when the cognitive task was prioritized. SP did not change significantly as a function of the *indirect* manipulation to attention (0-back vs. 2-back). It is notable that participants in the current study were able to significantly minimize sway path when instructed to despite the fatigue in the standing leg. This suggests that participants could still exert enough control in the body to intentionally reduce sway to the same extent as participants who were not fatigued in Experiment 1. Results from Reynolds (2010) support this general finding that participants are able to minimize sway when explicitly instructed to compared to studies that have reported no effects of explicitly instructing participants to minimize sway on posture (Siu & Woollacott, 2007).

Similar to the results in Experiment 1, SD did not change significantly when attention was *directly* manipulated by prioritizing either the postural or cognitive task but was significantly affected when attention was *indirectly* manipulated by increasing the difficulty in the cognitive *n*-back task. SD was smaller overall when the cognitive demands increased in trials with the 2-back task. This result is also notable because *indirectly* manipulating attention by increasing the difficulty of the cognitive task showed the same minimization in SD as was observed in the non-fatigued participants in Experiment 1. When the cognitive demands increased in the 2-back task conditions SD was reduced. This significant decrease in sway variability is consistent with the general finding from the literature that the magnitude of sway (as indexed by variability measures – SD, variance, range, etc.) decreases when the cognitive demands increase by the inclusion of a secondary task (i.e., single-task vs. dual-task) or by increasing the difficulty of the secondary cognitive task (Albertsen et al., 2017; Frazier & Mitra, 2008; Riley et al., 1999; Riley et al., 2005; Stins et al., 2011; Stoffregen, et al., 2000; Siu & Woollacott, 2007). It has been suggested that this minimization strategy is an automatic reduction in degrees of freedom so that more attention can be directed towards the additional challenge.

Fatigue Effects on Sway

Surprisingly, balancing in a unipedal stance after the lower leg was fatigued did not have a significant overall effect on the sway measures. A cross-experiment comparison showed that SampEn, SD, and SP were not significantly different between the non-fatigued and fatigued participants. The null-finding in both the SD and SP measures is inconsistent with general finding from the literature that have reported sway to be amplified and more variable after undergoing a fatigue task (Bisson et al., 2011; Bizid et al., 2009; Gribble & Hertel, 2004a, 2004b; Salavati et al., 2007; Simoneau et al., 2006; Vuillerme et al., 2006; Vuillerme et al., 2002). Because the fatigued participants in the current study showed significant effects of *direct* and *indirect* methods of manipulating attention (discussed above) on SP and SD, respectively, it may explain why SP and SD were not amplified overall as a function of fatigue. Participants may have been able to maintain sufficient control of posture and subsequently mitigate the effect of fatigue in the lower leg muscles. Similarly, studies have reported more pronounced effects of fatigue on sway variability when different muscles in the hips and upper leg (quadriceps, hamstrings, knee) are fatigued compared to muscles in the lower legs and ankles (Bisson et al., 2011; Gribble & Hertel, 2004a, 2004b; Salavati et al., 2007). Future research could use the same dual-task paradigm but target upper leg and hip muscles to challenge the postural-system further.

Participants in Experiments 2 and 3 received an additional $5 gift card as a methodological way of mitigating effects of ego depletion, a phenomenon in which fatigue effects are caused by the decrease in a person's motivation to maintain performance rather than depletion of metabolic energy and reduced muscle effectiveness (Brewer et al., 2017; Dorris et al., 2012; Hagger et al., 2016; Inzlicht & Schmeichel, 2012). That incentive was not available to participants in Experiment 1. The monetary incentive may have increased the motivation to minimize SP when participants were *directly* instructed to minimize sway despite the feelings of fatigue. This is consistent with recent research on "mental fatigue" (discussed further below) that has shown improvements in cognitive performance after fatigued participants were motivated by an increase in task reward (e.g., Brewer et al., 2017; Hopstaken et al., 2016; Muraven & Slessareva, 2003).

Cognitive Performance

As in Experiment 1, cognitive performance was not impaired by directing participants attention away from the cognitive task, but it was worse when the n-back task difficulty was increased. The latter effect replicates the findings of previous studies (Baddeley et al., 2009; Ragland et al., 2002; see Redick & Lindsey, 2013 for a review). A cross-study analysis confirmed that the number of errors committed in the *n*-back task was similar across experiments. The relationship between physical fatigue/exercise and cognitive functioning is complex, and there is not a clear understanding of the effects of physical exercise/fatigue on cognitive performance in the literature (see Abd-Elfattah, Abdelazeim, & Elshennawy, 2015 for a review). Studies have reported positive (Hancock & McNaughton, 1986), negative (Côté, Salmela, & Papathanasopoulu,1992; Covassin, Weiss, Powell, & Womack, 2007), and even no effects (Cian Barraud, Melin, & Raphel, 2001) of physical activity on cognitive performance. More recently, it has been proposed that the effects of physical activity on cognitive functioning follow an inverted-U trend that depends on the intensity and duration of the physical fatigue, whereby a moderate amount of physical exercise has the most positive effects on cognitive functioning compared to no physical exercise and exhaustion from physical exercise (Chang, Labban, Gapin, & Etnier , 2012; Kamijo, Nishihira, Higashuira, & Kuroiwa, 2007; Lambourne, & Tomporowski, 2010; Tomporowski, 2003). The intensity of the fatigue from the calf-raises may not have been significant enough to affect cognitive functioning.

Attention and Muscle Activity

The current EMG results replicated the results from Experiment 1. Activity in the AT and LG muscles did not change as a function of direct and indirect manipulations of attention. The replication of this null-finding suggests that shifts in attention are not reflected in the AT and LG muscles even when the lower leg is fatigued. A cross-study analysis also confirmed that the AT and LG muscles did not perform any differently in the dual-task in the participants from the current study (physical fatigue) compared to the non-fatigued participants in Experiment 1. The implication is that the fatigue the participants experienced from performing calf-raises was not reflected in the AT and LG muscles during unipedal quiet standing. As proposed in the discussion of EMG results in Experiment 1, the AT and LG muscles may not be sensitive enough to reflect shifts in attention in isolation of other muscles in the abdominals, hips, and upper leg that are involved in balance. The studies that have found more pronounced effects of fatigue in other muscles in the leg on overall postural sway (Bisson et al., 2011; Gribble & Hertel, 2004a, 2004b; Salavati et al., 2007) may lend credence to this. The more pronounced effect fatiguing the muscle has on sway may indicate a more prominent role in postural control and therefore may reflect changes in attention.

Overall, the findings from Experiment 2 replicate the significant *indirect* effect of shifting attention on sway regularity (SampEn) but showed that the *direct* effect of shifting attention no longer induced changes in sway regularity when participants were balancing while physically fatigued. Sway variability and sway path were largely unaffected as a result of physical fatigue. Experiment 3 will investigate the effects that mental fatigue may have on postural sway, cognitive performance, and muscle activity in a dual-task situation.

Experiment 3

The purpose of Experiment 3 was to examine changes in dual-task performance when the demands of the task change by fatiguing the cognitive system. Working on a cognitively demanding task for a considerable time often leads to feelings of "cognitive fatigue". Cognitive (or mental) fatigue is generally defined as the psychological state induced by sustained periods of a demanding cognitive activity and characterized by feelings of tiredness and lack of energy (Marcora, Staiano, & Manning, 2009; Smith et al., 2016a). Therefore, cognitive fatigue is thought to compromise the ability to maintain attentional focus and regulate perceptual and motor processes for goal-directed behavior (van der Linden, Frese, & Meijman, 2003). Research that has examined effects of cognitive fatigue on physical performance is limited (see van Cutsem et al., 2017 for a review). Marcora et al. (2009) conducted one of the first studies to examine cognitive fatigue on motor performance. In that study, participants were mentally fatigued by performing a choice reaction time task continuously for 90 minutes before performing a cycling task until exhaustion. Results showed that the fatigued participants reached exhaustion significantly quicker than controls. Similar findings from Dorris et al. (2012) showed that athletes reached physical exhaustion sooner following a difficult counting and balance task that required participants to count backwards from 1,000 by intervals of seven (until the final number is reached) while simultaneously keeping a bubble-level, held with both hands, level. Duncan, Fowler, George, Joyce, and Hankey (2015) showed that manual-dexterity performance declined following a mentally fatiguing 40-minute vigilance task. Smith et al. (2016a) found that experience soccer players made more errors in a skilled-passing task after the players had performed a 30-minute Stroop task. However, Pageaux, Marcora, and Lepers (2013) did not find negative effects of mental fatigue on maximal muscle activation in a knee extension exercise but did find the same negative effect in knee extension *endurance*. The findings from these studies indicate a general negative effect of mental fatigue on motor performance, however the results vary depending on the type of motor task that performance is measured on. There are no known studies that have directly examined the effects of mental fatigue on postural control.

After participants complete a taxing cognitive task, we expected postural sway to be more regular (smaller SampEn), more variable (larger SD), and have a larger sway path (SP) compared to the non-fatigued participants from Experiment 1. The same within experiment predictions were expected as in Experiments 1 and 2: postural sway was expected to be more regular (small SampEn), less variable (small SD), and minimized (small SP) when attention was manipulated *directly* by prioritizing the posture task. Cognitive performance was expected to be worse (higher number of errors) when attention was directly manipulated towards the posture task and subsequently drawing more attention away from the cognitive task. EMG activity was also expected to be amplified (larger EMG RMSE) when participants were directed to prioritize the balance task. We expected sway to be less regular (larger SampEn) and less variable (small SD) when attention was *indirectly* shifted away from posture by increasing the difficulty in the *n*-back task that were found in both Experiments 1 and 2.

Method

Participants

Thirty introductory psychology students (M_{age} = 19.6 yrs; 13 women; M_{height} = 169.6 cm; M_{weight} = 67.4 kg) participated in this study in exchange for course credit and a $5 gift card.

Apparatus

The same materials and techniques were used for data collection as in Experiment 1. To assess cognitive fatigue, participants completed the visual analogue scale for fatigue (VAS-F). The VAS-F is an 18-item questionnaire that assess the perception overall mental fatigue, mental effort, and motivation. The VAS-F has been used in the previous studies that have applied mental fatigue tasks (e.g., Smith et al., 2016a, 2016b). Each item in the questionnaire consists of a line with bipolar anchors relating to the descriptors of fatigue. Participants are instructed to mark the location on the line that represents his/her perceived level of fatigue "at the moment". The questionnaire was designed using the Qualtrics XM survey software (SAP, Walldorf, Germany) and administered using a laptop computer. The cumulative VAS-F score for each participant ranges from 0-180 points with larger scores indicating higher levels of fatigue.

Procedure

Prior to the start of the experimental trials, participants completed the VAS-F questionnaire in order to assess levels of mental fatigue prior to performing the fatigue task. The approximate time to complete the questionnaire was 5 minutes. In order to fatigue the cognitive system, we used the fatigue task from Dorris et al. (2012). In the task, participants were instructed to count backwards from 1,000 by seven while attempting to balance a bubble-level with both hands. Participants were instructed to count backwards "as accurately as possible" while keeping the bubble-level "as level as possible". The fatigue task terminated when participants reached the final number (specifically "6" if the participants had counted correctly). Participants took an average of 25 minutes to complete the task. Participants completed the VAS-F questionnaire a second time to assess levels of fatigue post-fatigue task. Participants were then positioned in the designated target area in order to begin data collection in the dual-task. All other experimental procedures were identical to Experiment 1. The experiment consisted of 12 trials: six trials with attention directed towards the balance task, and six trials with attention directed towards the cognitive task.

Design and Analysis

The same 2 $\times$ 2 repeated-measures ANOVA design was used for SampEn, SD, SP, EMG RMSE, and cognitive performance (number of errors) as in Experiment 1 with (1) direction of attention (DoA: towards balance, towards cognition) and (2) *n*-back (0-back, 2-back) as the factors.

Results

Manipulation Check

The scores from the VAS-F questionnaire pre- and post-fatigue task served as a manipulation check that participants felt more fatigued after performing the fatigue task. Figure 13 depicts the mean VAS-F scores pre- and post-fatigue task. A paired-samples *t*-test confirmed ($t(26) = 6.62$, $p < 0.001$) that participants reported stronger feelings of fatigue after performing the fatigue task. VAS-F scores from two participants were not included in the analysis due to technical difficulties with the electronic survey.

Figure 14 depicts mean SP across each of the six trials in which the DoA was toward posture and when the DoA was toward the cognitive task. Although there is a negative overall trend in SP (in the AP direction) across trial, results from a repeated-measures ANOVA revealed that the change across trials was not significant ($p > 0.05$). However, the mean SP (in the AP direction) observed in the current study (113.4 mm) was approximately similar to the mean SP from Experiments 1 and 2 (105.8 mm, 110 mm, respectively), and therefore the non-significant change over trial may have been due to a floor effect. Figure 15 depicts the mean number of errors (in the 2-back task) across the trials when the DoA was towards posture and towards cognition. Results from a repeated-measures ANOVA revealed that cognitive performance changed significantly across trials ($F(2, 60) = 8.41$, $p = 0.001$, $\eta_p^2 = 0.22$). This result suggests the same adherence to minimize errors in the *n*-back task when DoA was toward the cognitive task.

Sample Entropy

The top two panels in Figure 16 depict mean SampEn in the (A) AP and (B) ML directions as a function of DoA and *n*-back task. ANOVA results revealed a significant main effect of *n*-back task in the ML direction only ($F(1, 29) = 21.81$, $p < 0.001$, $\eta_p^2 = 0.43$). SampEn values were smaller in the 0-back task than the 2-back task regardless of DoA condition. None of the interaction or main effects were significant in the AP direction.

Standard Deviation

The middle panels of Figure 16 depict mean SD in the (C) AP and (D) ML directions as a function of DoA and *n*-back task. In the AP direction, results revealed a significant DoA × *n*-back interaction, $F(1, 29) = 7.11$, $p = 0.01$, $\eta_p^2 = 0.21$, and a significant main effect of *n*-back task, $F(1, 26) = 7.25$, $p = 0.01$, $\eta_p^2 = 0.21$. Post hoc tests revealed that SD did not change between the 0-back and 2-back task conditions when DoA was toward posture ($p > 0.05$), but decreased significantly in the 2-back task condition when DoA was toward the cognitive task, $t(29) = 3.91$, $p = 0.001$. In the ML direction, results revealed a significant main effect of *n*-back task only, $F(1, 29) = 15.47$, $p = 0.001$, $\eta_p^2 = 0.37$. SD was significantly smaller in the more challenging 2-back task than the 0-back task regardless of DoA condition.

Sway Path

The bottom two panels in Figure 16 depict mean SP in the (E) AP and (F) ML directions as a function of DoA and *n*-back task. In the AP direction, results revealed a significant main effects of DoA and *n*-back task only ($F(1, 29) = 11.04$, $p = 0.003$, $\eta_p^2 = 0.29$; $F(1, 29) = 5.44$, $p = 0.03$, $\eta_p^2 = 0.17$, respectively). These results replicate the results in the AP direction from Experiment 1: SP was smaller overall when DoA was towards posture (regardless of *n*-back condition) and smaller overall (regardless of DoA condition) in the 2-back task. In the ML direction, there was a significant main effect of DoA only ($F(1, 29) = 8.99$, $p = 0.006$, $\eta_p^2 = 0.25$) whereby SP was smallest overall when DoA was toward posture.

EMG

Similar to the findings from both Experiment 1 and Experiment 2, EMG activity did not change as function of DoA and *n*-back task (figure not shown). Results from the repeated-measures ANOVA confirmed that there was no significant interaction or main effects for both the AT and LG muscles ($p > 0.05$).

Cognitive Performance

Figure 17 depicts mean number of errors in the *n*-back task as a function of DoA and *n*-back task. ANOVA results replicated the findings from both Experiment 1 and Experiment 2: there was a significant main effect of *n*-back task only ($F(1, 29) = 25.50$, $p < 0.001$, $\eta_p^2 = 0.46$). Participants performed worse in the *n*-back (increased errors) in the more challenging 2-back task than the easier 0-back task.

Non-fatigue (Exp. 1) vs. Fatigue (Exp. 3)

To examine changes in the postural measures as a function of cognitive fatigue, Figure 18 depicts mean SampEn, SD, and SP results from the non-fatigued participants from Experiment 1 (Figure 4) with the fatigued participants from the current study (Figure 16). A mixed design ANOVA was used with Experiment as the between-subjects factor (Experiment 1, Experiment 3) to examine the effects of cognitive fatigue. None of the interaction or main effects were found in the postural measures between Experiment 1 and Experiment 3.

Discussion

The purpose of Experiment 3 was to examine the interaction between attention and posture in a dual-task when participants were mentally fatigued. The results of Experiment 1 showed that postural sway became more regular (decreased SampEn) and sway path (SP) decreased when attention was *directly* manipulated by instructing participant to prioritize postural task, but cognitive performance did not improve significantly when participants prioritized the cognitive *n*-back task. When participants were physically fatigued in Experiment 2, the results showed that sway regularity (SampEn) no longer changed when attention was *directly* shifted by prioritizing the postural task compared to conditions when the cognitive task was prioritized, but SampEn did change when attention was *indirectly* manipulated by increasing the difficulty of the cognitive task (0-back vs. 2-back). SampEn was larger (i.e., less sway regularity) when more attention was shifted away from posture in the more difficult 2-back task. Surprisingly, sway variability (SD) and SP did not increase when participants balanced in the unipedal stance after the lower leg was fatigued (Experiment 2) compared to the non-fatigued participants (Experiment 1). The results of Experiment 3 replicated the findings from Experiment 2.

In the current study, the SampEn results replicated the trends observed in Experiment 2 in that sway regularity was no longer affected when attention was *directly* shifted towards or away from posture by prioritizing either the postural task or the cognitive task, but sway regularity did change when attention was *indirectly* shifted away from posture by the increased cognitive difficulty in the 2-back task. The SampEn results showed that postural sway was less regular (larger SampEn) when more attention was shifted away from posture when the 2-back task was performed. The increase in SampEn when attention was *indirectly* shifted is also consistent with previous studies that have observed less sway regularity when a secondary cognitive task was concurrently performed compared to a single-task condition (e.g., Cavanaugh et al., 2006; Donker et al., 2007; Stins et al., 2009; Stins et al., 2011).

The SampEn results in Experiments 2 and 3 were similar in that the effect of *directly* shifting attention toward or away from the postural task was no longer significant when participants were fatigued physically or mentally, respectively. Sway regularity did not change when participants prioritized the postural task compared to when the cognitive task was prioritized. This is notable because the participants in both the current experiment and Experiment 2 were in a state of mental and physical fatigue, respectively, compared to the non-fatigued participants in Experiment 1. Sway variability (SD) and sway path (SP) results also replicated from both Experiment 1 and Experiment 2: SD was smaller overall when the cognitive demands increased in the 2-back task but not when participants were instructed to prioritize the balance task and minimize sway;

conversely, SP was smaller overall when participants prioritized the balance task but not when the cognitive demands increase in the 2-back task. The SD and SP results were identical to the results observed in Experiment 2 that found SD and SP to be unaffected by feelings of fatigue, in this case mental fatigue. The changes in SD and SP are discussed further below. As mentioned in the Experiment 2 discussion, more research is first required to understand the differences between *direct* and *indirect* methods of shifting attention in dual-task situations. Overall, the results from current study add further evidence that sway regularity increases when the cognitive demands of the dual-task are also increased.

Direct vs. Indirect Effects on SP and SD

The sway path (SP) results in the current study replicated the findings from Experiments 1 and 2 whereby SP was significantly reduced when attention was *directly* shifted towards the postural task by instructing participants to minimize sway and "stand as still as possible" compared to conditions when the cognitive task was prioritized. This significant reduction in SP when the balance task was prioritized was found across all three experiments and suggests that participants were able to intentionally minimize sway despite feelings of physical or mental fatigue. Results from Reynolds (2010) support this general finding that participants are able to minimize sway when explicitly instructed to compared to studies that have reported no effects of explicitly instructing participants to minimize sway on posture (Siu & Woollacott, 2007).

The sway variability (SD) results in the current study did not show any significant change in SD when attention was *directly* manipulated by prioritizing the postural task but did show a significant decrease in SD when attention was *indirectly* shifted away from posture by the increased difficulty in the cognitive task. As mentioned previously, the significant effect of the *indirect* manipulation of attention on posture is notable because SD was found to change similarly as the non-fatigued (Experiment 1) and physically fatigued participants (Experiment 2). The general result that SD was found to decrease when the difficulty of the cognitive task increases lends support to studies that have observed the same minimization strategy in response to increases in cognitive demands (Albertsen et al., 2017; Frazier & Mitra, 2008; Riley et al., 2005; Riley et al., 1999; Stins et al., 2011; Stoffregen, et al., 2000; Siu & Woollacott, 2007). As mentioned previously, the minimization strategy is thought to be an automatic reduction in the physical degrees of freedom so that more attention can be directed towards the increased challenge in the secondary task.

Fatigue Effects on Sway

This is the first known study to investigate whether postural sway was affected by mental fatigue. In addition, the scope of the literature that has examined the effects of mental fatigue on physical performance is small. A cross-study analysis confirmed that performing the mental fatigue task did not have any overall effects on sway regularity (SampEn), sway variability (SD), or sway path length (SP) in dual-task situations compared to participants that were not-fatigued (Experiment 1). Despite the increase in participants' subjective report of mental fatigue in the current experiment these feelings were not reflected in changes to postural sway. The evidence from studies that have reported negative effects of mental fatigue on physical performance have largely been in tasks that test *endurance* performance (e.g., Dorris et al., 2012; Marcora et al., 2009; Pageaux et al., 2013). Pageaux et al. (2013) also assessed the maximal muscle activation in knee extensions but did not find effects of mental fatigue. This suggests that the muscles do not lose the ability to produce maximum force output when feeling “mentally fatigued”. Balance is arguably an endurance task but is considered significantly less strenuous than performing sit-ups or cycling. Maintaining upright balance is also a task in which all healthy children and adults are highly skilled. Overall, the null effect of fatigue in the current study suggest that postural sway is not affected by mental fatigue.

Cognitive Performance

The cognitive performance results in the current study mimic the results from both Experiments 1 and 2. Cognitive performance was impaired overall in the 2-back task than the 0-back task, but performance was not impaired by directing participants attention away from the cognitive task. The increase in errors in the 2-back task compared to the 0-back task was expected and supported in previous studies (Baddeley et al., 2009; Ragland et al., 2002; see Redick & Lindsey, 2013 for a review). Additionally, because participants committed more errors in the 2-back task the significant effect of the *n*-back task may be due to a floor effect in the 0-back task.

A cross-study analysis confirmed that the number of errors committed in the *n*-back task was similar between the non-fatigued participants in Experiment 1 and the mentally fatigued participants in the current experiment. This finding is inconsistent with the general finding from the literature that have shown negative effects of mental fatigue on performance in a variety of cognitive tasks, such as: reaction time tasks (Brewer et al., 2017; Dinges & Powell, 1985; Loh, Lamond, Dorrian, Roach, & Dawson, 2004; Unsworth, Redick, Lakey, & Young, 2010); a visual 2-back task (Hopstaken et al., 2016); visual attention task (Boksem Miejman, & Lortist, 2005); decision making task (Smith et al., 2016b; van der Linden et al., 2003). The methods that have been used in the literature to induce feelings of mental fatigue is also varied, for example: repeated visual 2-back task (Hopstaken et al. , 2016); 30-minute Stroop task (Smith et al., 2016a, 2016b); 40-minute grid task (Duncan et al., 2015); 30- and 90-minute simple reaction time task (Brewer et al., 2017; Marcora et al., 2009, respectively); 90- minute AZ-Continuous Performance Test (Pageaux et al., 2013); 2-hour scheduling-task (van der Linden et al., 2003); 3-hour visual attention task (Boksem et al., 2005). It is important to note the majority of these fatigue tasks require a sufficient length of time to implement. In the current study, it took participants less time (approximately 15-20 minutes) to complete the fatigue task. Future research that investigates the effects of mental fatigue on postural behavior should impose a longer (in duration) fatigue task to ensure that participants are sufficiently fatigued. Even though participants reported more feelings of mental fatigue after completing the fatigue task (compared to pre- fatigue task) the effects did not perturb postural control sufficiently to reveal changes in balance. The fatigue task used in the current study was chosen because it could be implemented within the time limits of the experimental session in addition to the precedent from the literature that had shown a negative effect on physical task performance (Dorris et al., 2012).

Overall, the cognitive performance results suggest that performance in an auditory 2-back task is not impaired after participants counted backwards from 1,000 by seven. One possible reason for this null-finding is that the monetary incentive may have strengthened the participants' resolve to perform well in the cognitive task and balance task regardless of feelings of fatigue, as was proposed in Experiment 2. Support for this comes from studies that have mitigated depletion effects when participants were offered an increase in task reward (Brewer et al., 2017; Hopstaken et al., 2016; Muraven & Slessareva, 2003).

Attention and Muscle Activity

The current EMG results replicated the null effects found in both Experiments 1 and 2. See discussions above.

Overall, the findings from Experiment 3 replicate the significant *indirect* effect of shifting attention on sway regularity (SampEn) but showed that the *direct* effect of shifting attention no longer induced changes in sway regularity when participants were balancing in state of mental fatigue compared to non-fatigued participants. Sway variability (SD) and sway path (SP) were largely unaffected as a result of mental fatigue. These findings are novel and contribute to the literature on the effects of mental fatigue on postural sway.

General Discussion

The current set of experiments sought to investigate the interaction between attention and posture when the focus of attention was shifted between the cognitive and motor task. Using a dual-task paradigm, participants maintained balanced in a unipedal stance while performing a concurrent auditory *n*-back task. Attention was shifted *directly* by instructing participants to prioritize the balance task or prioritize the cognitive task and *indirectly* by changing the difficulty level of the cognitive task (0-back vs. 2-back task). These manipulations of attention in dual-task performance were examined when participants were in a controlled state (i.e., non-fatigued) state (Experiment 1), in a state of physical fatigue (Experiment 2), and in a state of mental fatigue (Experiment 3). Sample entropy (SampEn) was used to measure the regularity in postural sway fluctuations, and standard deviation (SD) and sway path length (SP) were used to quantify the overall magnitude of sway movements.

Across all three experiments we tested the overall prediction of the direct relationship between sway regularity and the amount of attention invested in postural control, whereby sway would exhibit more regularity in conditions when more attention was allocated towards maintaining balance and relatively less regularity when attention was diverted away from posture. SampEn results across all three experiments showed that postural sway became less regular (larger SampEn) and less variable (smaller SD) overall when attention was *indirectly* shifted away from posture when the cognitive task was made more difficult (0-back vs. 2-back). Overall, both SampEn and SD results contribute to the posture and attention literature that has observed the same increase in SampEn when attention was shifted away from posture as a result of engagement in a secondary cognitive task (e.g., Roerdink et al., 2006; Stins et al., 2009, Stins et al., 2011) and decrease in SD (e.g., Albertsen et al., 2017; Huxhold, Li, Schmiedek, & Lindenberger, 2006; Lajoie, Richer, Jehu, & Tran, 2016; Richer, Saunders, Polskaia, & Lajoie, 2017; Stoffregen et al., 2000).

When attention was *directly* manipulated by prioritizing the postural task, sway was more regular (smaller SampEn), as expected, for the participants that were not fatigued (Experiment 1). However, that effect was no longer produced when participants were fatigued in both Experiment 2 and Experiment 3, nor were sway variability (SD) and sway path length (SP) affected by the effects of physical (Experiment 2) and mental (Experiment 3) fatigue. Possible reasons for these null effects of fatigue on SD and SP were already discussed in Experiments 2 and 3. Further research is needed to (1) replicate these differential effects of fatigue on SampEn between the *direct* and *indirect* methods of manipulating attention using alternative methods from the fatigue literature (discussed above), and (2) to have a more exact understanding of the different effects that the *direct* and *indirect* methods *could* have on motor control. By continuing to explore the differences in behavior that emerge from the different methods utilized in dual-task research, we can shed more light on the complexity of how the effects of attention are reflected in postural sway.

The *magnitude* of sway was shown to decrease overall when the difficulty of the cognitive task increased (0-back vs. 2-back) and, subsequently, *indirectly* shifted attention away from posture. As mentioned earlier, standard deviation (SD) and sway path (SP) are two linear measures from the posture literature that are commonly used to assess the overall magnitude of sway in a variety of experimental comparisons: young vs. old adults (e.g., Prieto et al, 1996; Teasdale Stelmach, & Breunig, 1991); biomechanically/neurologically impaired individuals vs. healthy controls (e.g., Agostini, Chiaramello, Bredariol, Cavallini, & Knaflitz, 2011; de Haart et al., 2004; Dehail, Petit, Joseph, Vuadens, & Mazaux, 2007); novices vs. experts (e.g., Vuillerme et al., 2001; Yaggie & Campbell, 2006); different foot placement strategies (e.g., Chiari et al., 2002; Gibbons et al., 2019b; Kim et al., 2014; Kirby, Price, & MacLoed, 1987); perturbations to the supporting platform (e.g., Gibbons et al., 2019a; Nichols, Glenn, & Hutchinson, 1995); and *indirect* shifts in attention away from posture with a secondary cognitive task (e.g., Albertsen et al., 2017; Gibbons, Amazeen, & Jondac, 2019; Huxhold et al., 2006; Lajoie et al., 2016; Richer et al., 2017; Riley et al., 2005; Stoffregen et al., 2000). The SD results across all three experiments were consistent with the findings from the literature that have observed an overall minimization of sway (in SD and SP) in response to increases in attentional demands in the dual-task by either including a secondary cognitive task condition (single-task vs. dual-task) or increasing the difficulty of the cognitive task (Albertsen et al., 2017; Frazier & Mitra, 2008; Richer et al., 2017; Riley, Stoffregen, Grocki, & Turvey, 1999; Riley et al., 2005; Stins et al., 2011; Stoffregen, et al., 2000; Siu & Woollacott, 2007). SP results showed that sway path similarly decreased when attention was *indirectly* shifted away from posture in the 2-back in Experiment 1. However, this effect was not significant for the fatigued participants in Experiments 2 and 3 (discussed further below).

The general finding that sway is minimized overall when the attentional demands increase has been interpreted as an automatic minimization strategy by the cognitive-motor system so that more attentional resources can be directed towards the more challenging cognitive task in dual-task situations (e.g., Stins et al., 2011; Stoffregen, et al., 2000; Siu & Woollacott, 2007). Some researchers have suggested that this minimization strategy may serve to facilitate performance in the secondary task (Balasubramaniam, Riley, and Turvey, 2000; Stoffregen et al., 2000). For example, Stoffregen et al. (2000) found that mean sway variability (SD) was significantly minimized to aide in the performance of a difficult visual search task while standing. Balasubramaniam et al. (2000) showed that individuals reduced their postural sway below baseline conditions when concurrently performing a manual precision task. The implication for the current results would mean that sway was minimized to help with recall in the *n*-back task. However, follow-up analysis is necessary to determine if a smaller SD was correlated with better performance in the cognitive task. Future research could also compare performance in the *n*-back task when participants are explicitly instructed to amplify their sway movements to cognitive performance when sway is relaxed, or explicitly minimized to determine if performance in memory tasks is impaired when sway is amplified. Overall, the significant SD and partial SP results contribute to this literature that has found changes in sway variability in response to changes to the cognitive demands in dual-task situations.

Regularity in Movement

Postural sway reflects the product of a motor system that is governed by the many interactions within the cognitive, perceptual, and biomechanical properties. Over the last three decades there has been a growing interest identifying how different processes are reflected in postural sway. Dynamical systems analyses have helped to untangle the complexities reflected in biological signals by examining the how the signals evolve overtime. Within the last decade researchers have suggested that the regularity within the movement signal (as indexed by approximate and sample entropy measures) provides a direct measure of the amount of attention that is invested in postural control (Borg & Laxåback, 2010; Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2006; Roerdink, Hlavackova, & Vuillerme, 2011; Stins, Michielsen, Roerdink, & Beek, 2009; Stins et al., 2011). The collective finding across these studies, and the current experiments, is that sway becomes more regular (smaller entropy values) when more attention is directed towards the body and controlling balance compared to less regularity (higher entropy values) when attention is diverted away from posture.

Research has also shown that in an individual's sensory information or emotional state can elicit changes in sway regularity in the same fashion as increasing attentional demands in a secondary task. When visual information is removed by instructing participants to stand with their eyes closed sway becomes more regular (smaller entropy values) compared to when the eyes or opened (Donker et al., 2007; Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009; Stins et al., 2009). Similarly, when anxiety was induced by having participants stand on the ledge of a raised (1 m) platform sway became more regular compared to standing on level ground (Stins et al., 2011). The assumption is that standing with the eyes closed or in a high anxiety state naturally draws more attention to the movements of the body and, thereby, making them more regular. These studies support the finding that differences in sway regularity emerge when attention is shifted by automatic changes in the sensory and emotional systems.

The SampEn results from the current study contribute to the theorized relationship between changes in sway regularity and the amount of attention invested in postural control. Results from the non-fatigued participants in Experiment 1 showed that SampEn was smaller (more sway regularity) when participants were instructed to *directly* attend to controlling his/her posture compared to attending to the cognitive task. Additionally, SampEn was larger overall (less sway regularity) when attention was shifted away from posture *indirectly* by increasing the difficulty of the cognitive task. The *indirect* effect was consistent across all three experiments. Overall, the SampEn results from the current series of experiments support the relation between sway regularity and the amount of attention invested in posture. The current work also adds to the utility of sample entropy in movement signals that may reflect changes within the underlying dynamics of the system.

Movement regularity has also been suggested to be a marker of delays or impairments in the motor system. Entropy measures (approximate, sample) have been used to distinguish the movement patterns of adults and children with different pathologies from their healthy counterparts (e.g., Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Donker et al., 2007; Kaipust, Huisinga, Filipi, and Stergiou, 2012; Lamoth & van Heuvelen, 2012; Roerdink et al., 2006; Schniepp et al., 2013). Children and adults with cerebral palsy have been found to exhibit more regular sway patterns than healthy controls (Donker et al., 2008). Kaipust et al. (2012) observed more regularity (smaller entropy value) in the gait patterns of adults with multiple sclerosis than healthy controls. Lamoth and van Heuvelen (2012) found more regular patterns in sway velocity in elderly adults that are not active in sports than in active elderly and young adults. Collectively, these studies suggest a general increase in movement regularity (smaller entropy values) when the motor system is compromised compared to healthy controls. Combined with other studies that have shown an overall decrease in movement regularity (larger entropy values) in individuals with superior body control (e.g., dancers; Stins et al., 2009), it has been suggest that an "optimal" or "healthy" amount of regularity (and variability) lies between these two limits (Lamoth & van Heuvelen, 2012; Stergiou & Decker, 2011). Though the participants used in the current experiments were all young and healthy adults, the SampEn results suggest that differences in sway regularity can emerge within one demographic in response to cognitive perturbations on posture. Shifting attention away from posture (directly or indirectly) could be a useful strategy to incorporate into clinical and rehabilitation practices to push patients towards an optimal amount of regularity. Additionally, changes in sway regularity may serve as an identifier of the prioritization strategy (posture, cognitive) that individuals adopt in dual-task situations. When balance is threatened and posture is prioritized (c.f., Müeller et al., 2007; Siu & Woollacott, 2007), there should be a significant difference in the sway regularity that emerges compared to when balance is no longer threatened, and participants can prioritize cognition. Future research could examine changes in entropy across time to see if moments when balance is threatened correspond to sudden fluctuations in entropy.

There is evidence from studies that have examined changes in entropy within a trial in which there was a significant change to the cognitive system. Stephen, Dixon, and Isenhower (2009) estimated the Shannon entropy of finger movements while participants solved a cognitive gear-tracing task. Previous work by Dixon and Bangert (2004) found that participants reliably discovered a new strategy or "solution" to solving the task as the number as the number of gears in the task increased. Stephen et al. (2009) found a significant spike in the entropy of finger movements that corresponded to the moment within the trial that participants discovered the new cognitive strategy. Future research could utilize this same approach to examine the emergence of new cognitive or motor "solutions" that arise to meet the motor and/or cognitive demands in the dual-task situation.

Attention plays an important role in the performance of many motor tasks. Previous research that has examined the effects of directed attention in motor performance often involve complex and skilled motor actions, such as: free-throw shooting (Al-Abood, Bennett, Hernandez, Ashford, & Davids, 2002; Zachry et al., 2005); golf putting/swinging (Beilock & Gray, 2011; Wulf & Su, 2007); tennis swinging (Wulf, McNevin, Fuchs, Ritter, & Toole, 2001); baseball batting (Gray, 2004); dart throwing

(Marchant, Clough, & Crawshaw, 2007); jumping (Wulf & Dufek, 2009; Wulf et al., 2010). Postural sway is a complex behavior that is nested within all of those actions, and therefore posture must be controlled in order to execute and perform those tasks well. Though the effects of attention on postural control in dual-task conditions depend on many factors (e.g., cognitive, sensory, motor, emotional), this area of research demonstrates that attention does affect the motor behaviors that emerge in the relatively simple act of standing upright. As we continue to untangle the complexities of the cognitive-motor system we will gain a better understanding of how cognitive and motor processes interact and are assembled into observable motor behavior. We will ultimately gain a better understanding of how individuals can stand to think.

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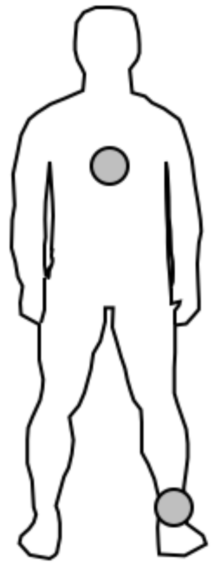

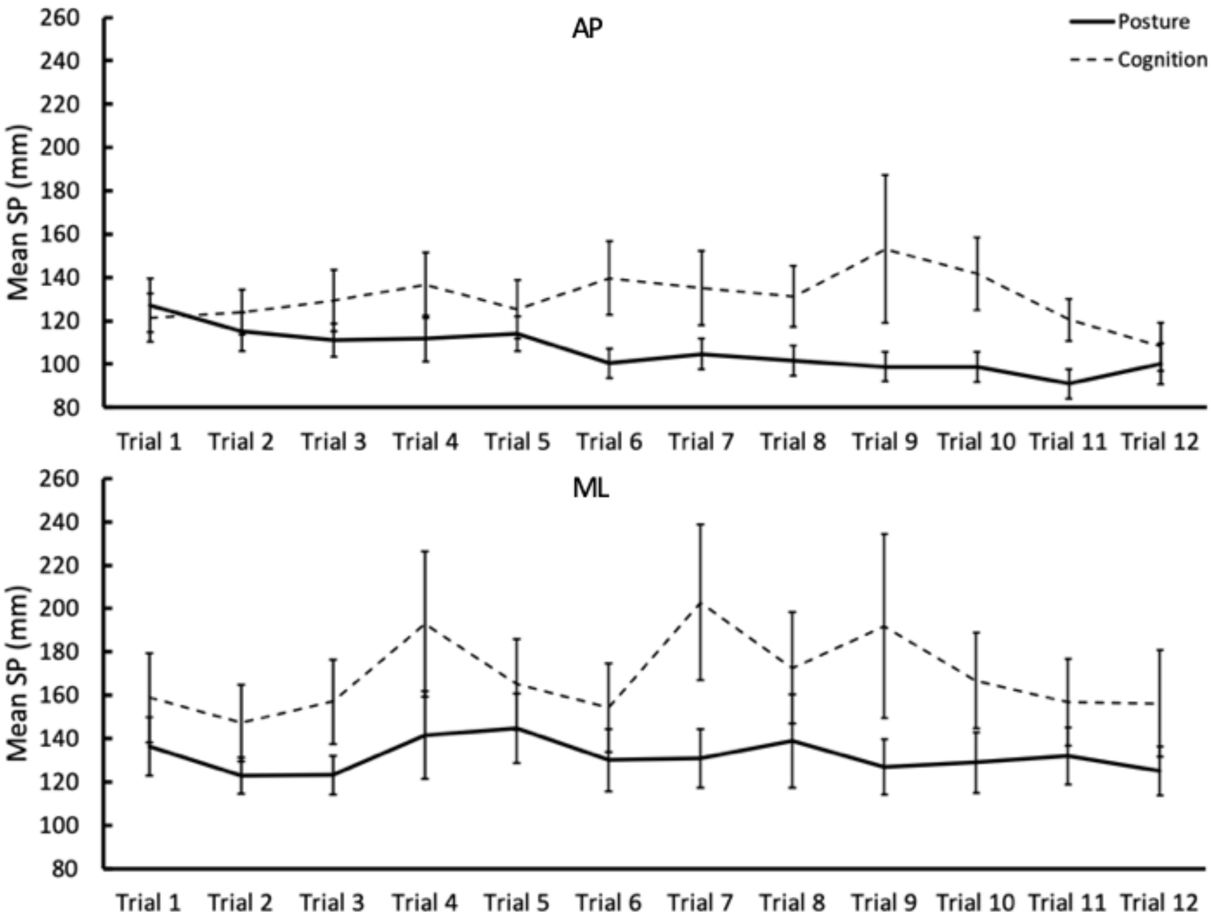
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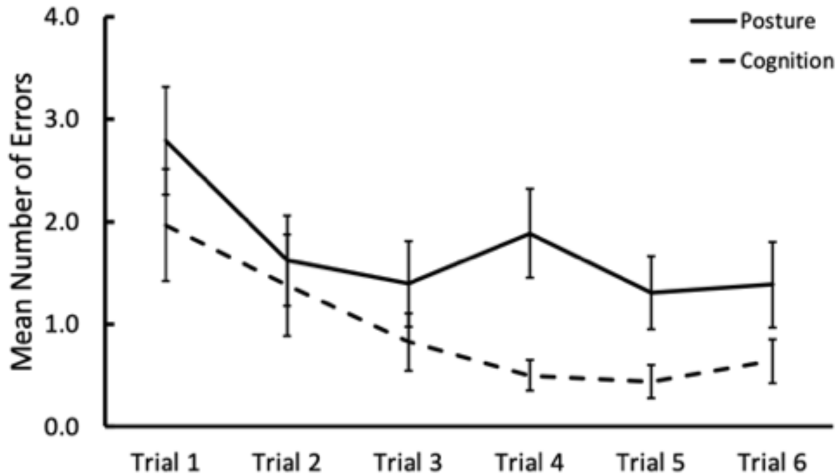
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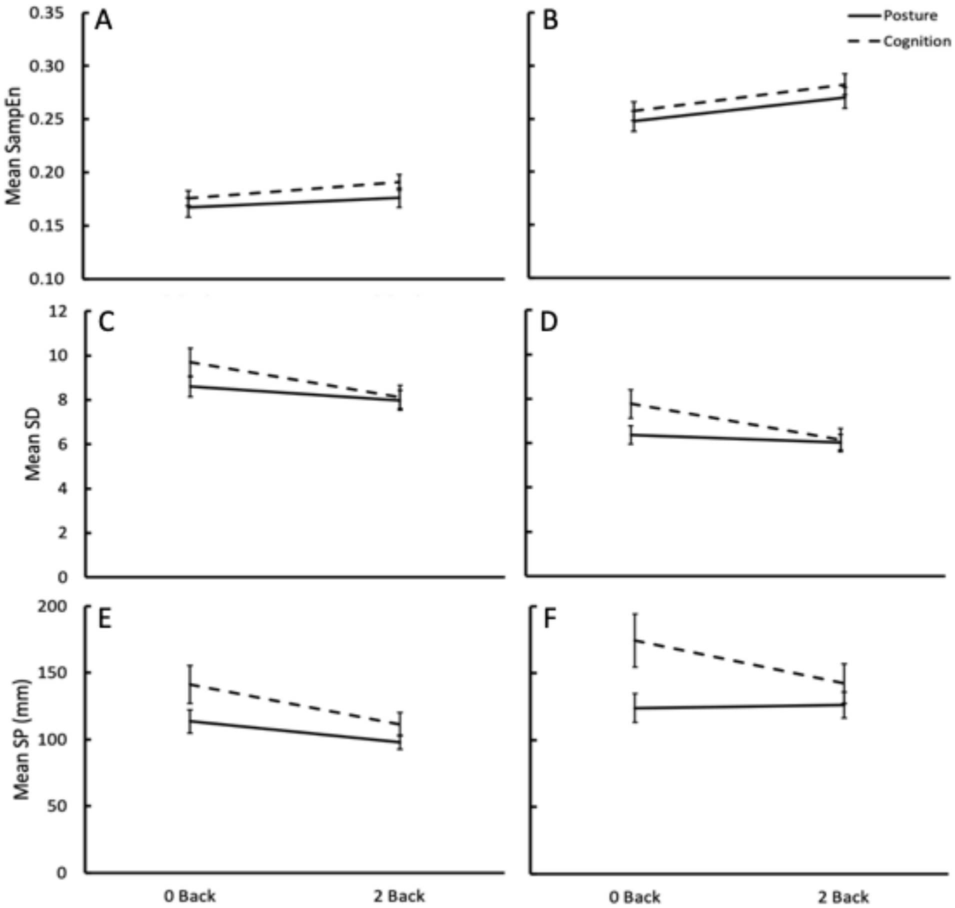

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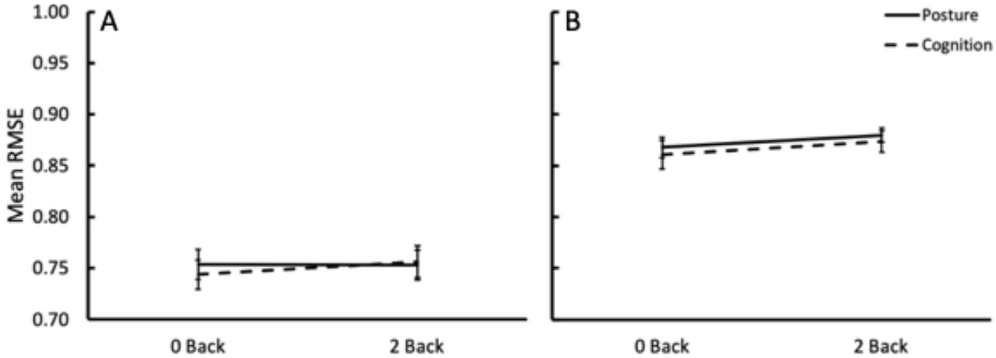
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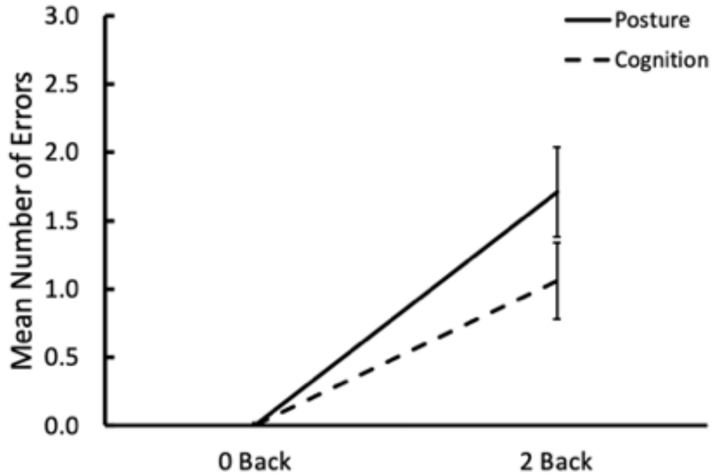
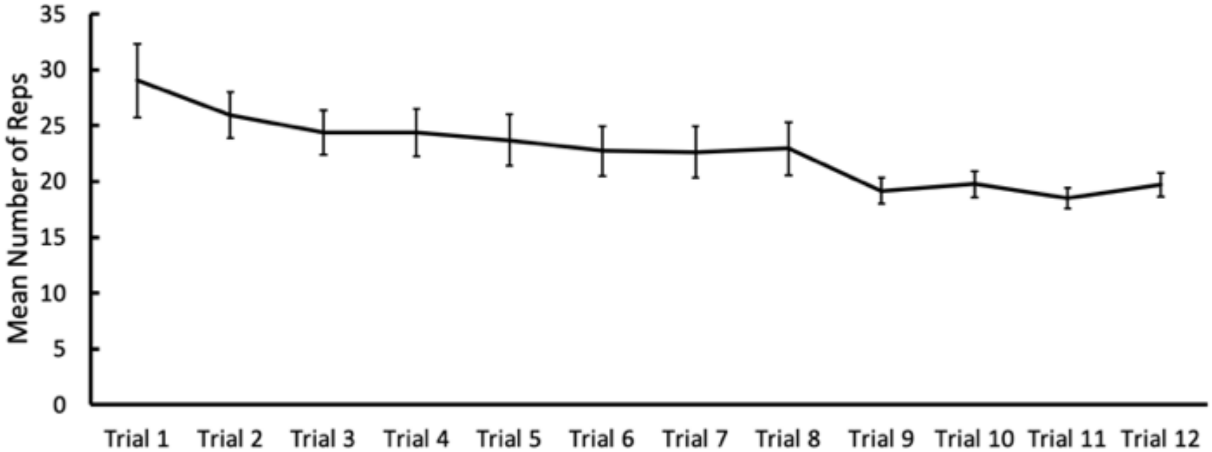
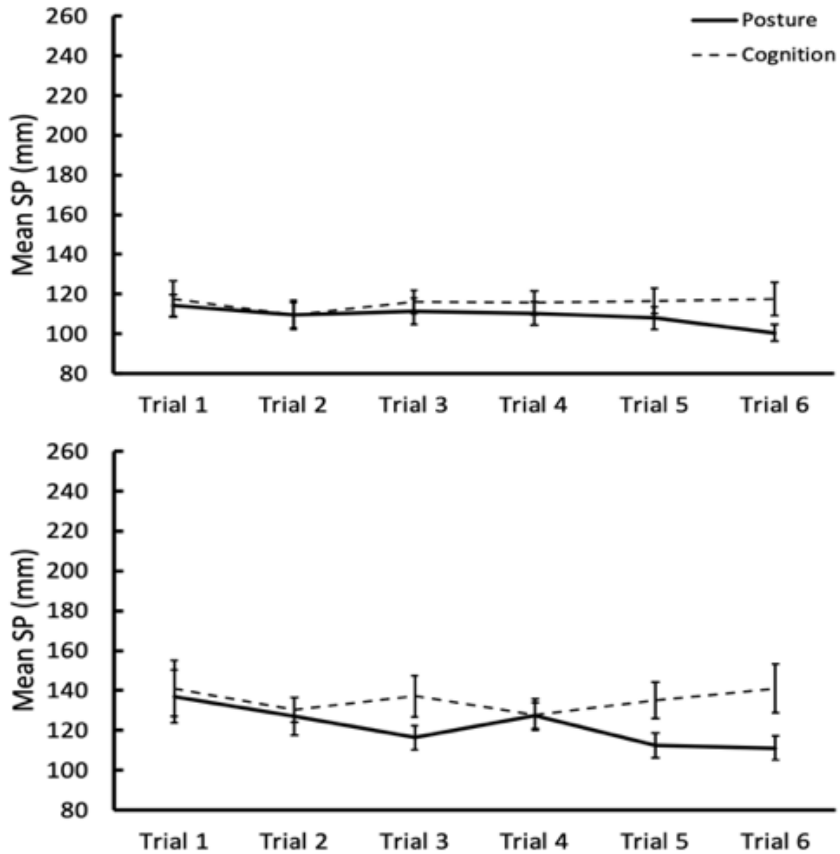
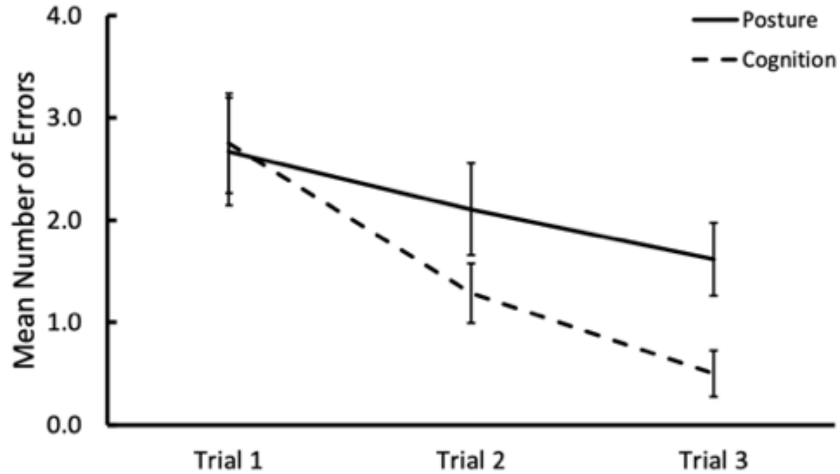
0 Back
2 Back

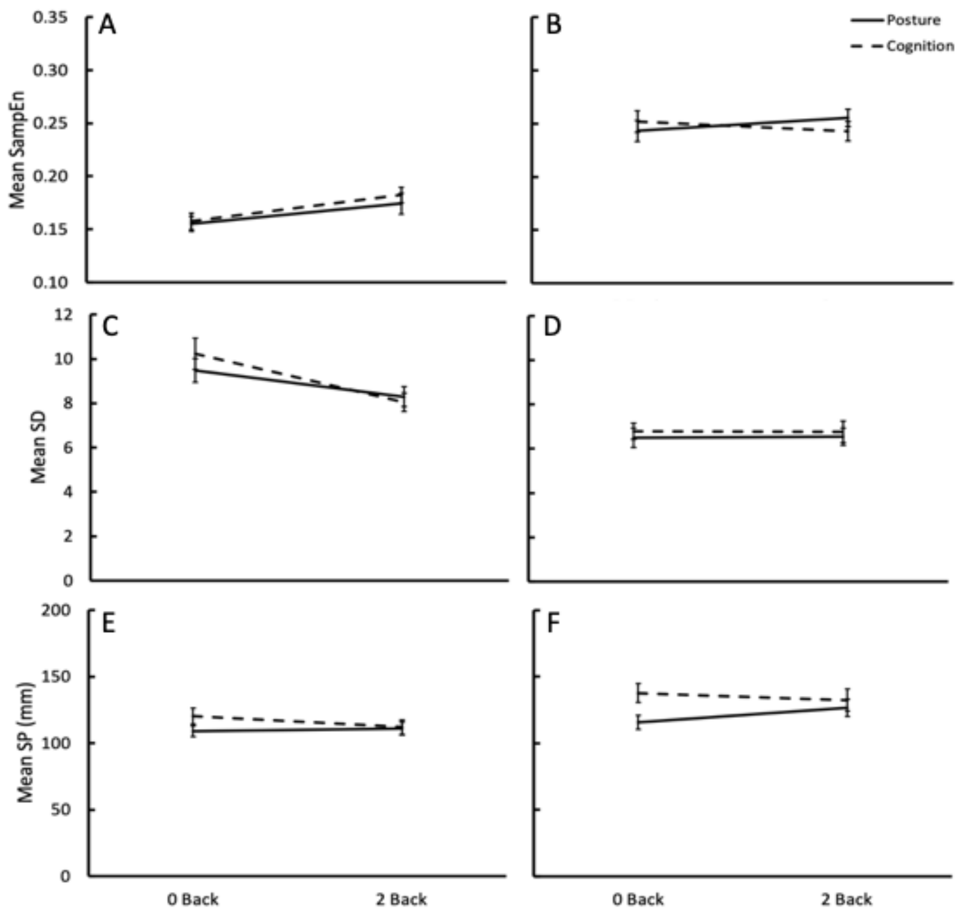

Mean Number of Errors
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Posture
Cognition
0 Back
2 Back

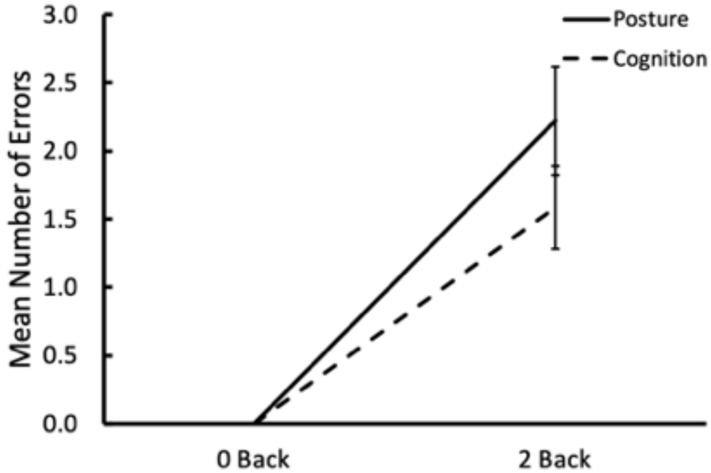

Mean Number of Reps
35
30
25
20
15
10
5
0
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 6
Trial 7
Trial 8
Trial 9
Trial 10
Trial 11
Trial 12

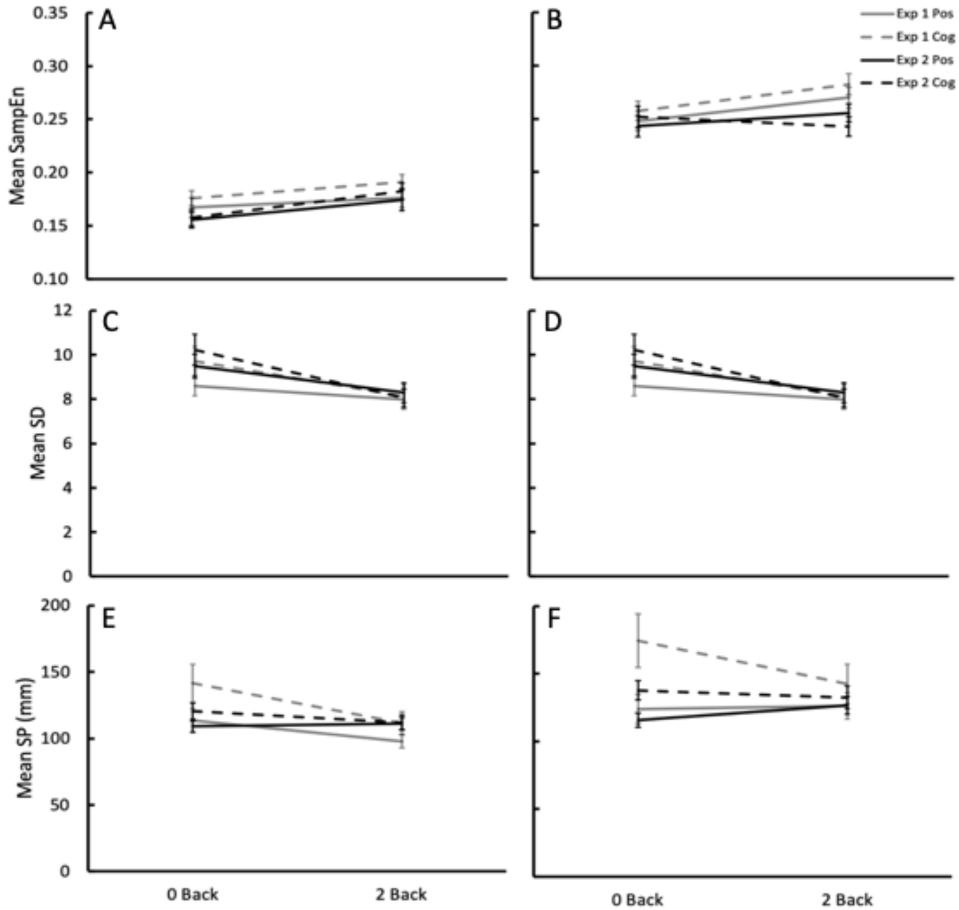

Posture
Cognition
Mean SP (mm)
260
240
220
200
180
160
140
120
100
80
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 6
Mean SP (mm)
260
240
220
200
180
160
140
120
100
80
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 6

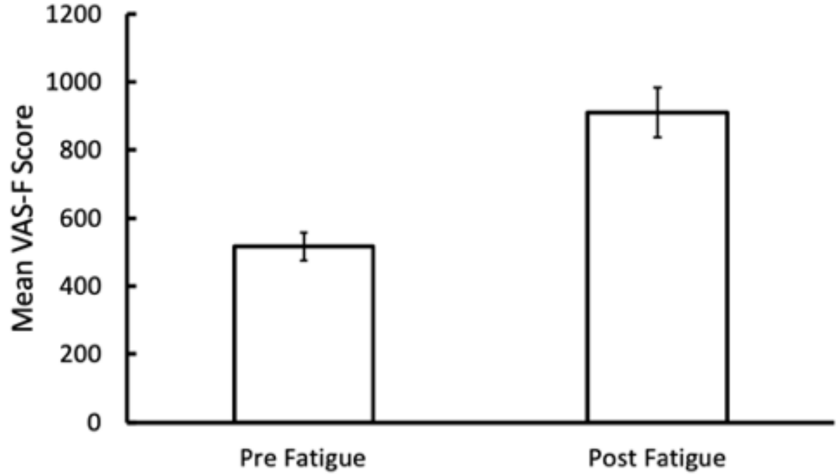


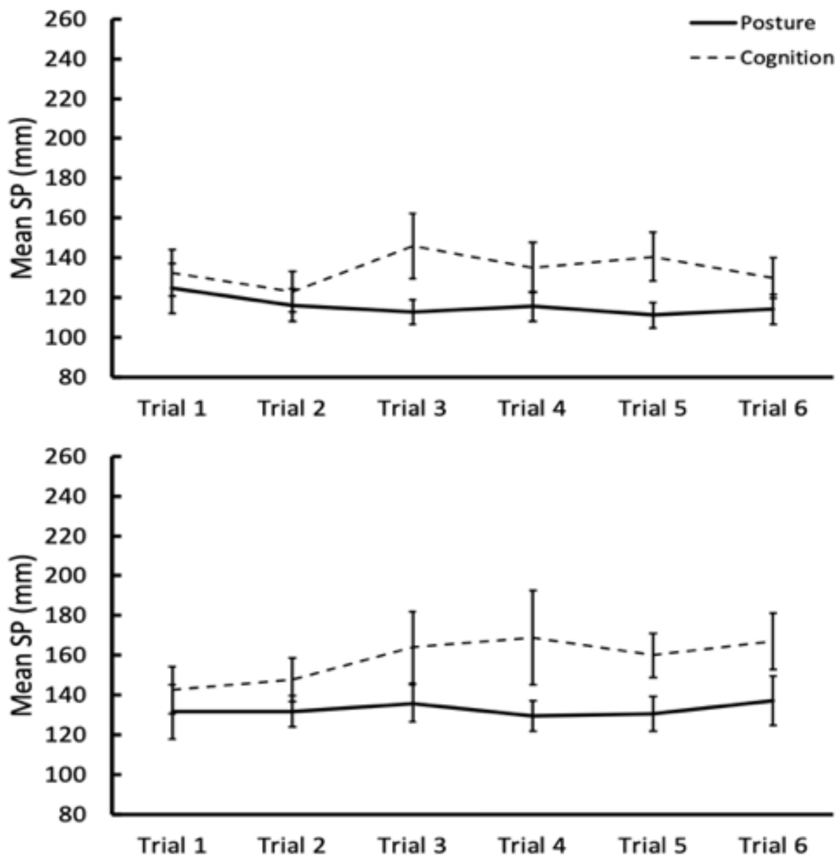
Posture
Cognition
Mean Number of Errors
4.0
3.0
2.0
1.0
0.0
Trial 1
Trial 2
Trial 3

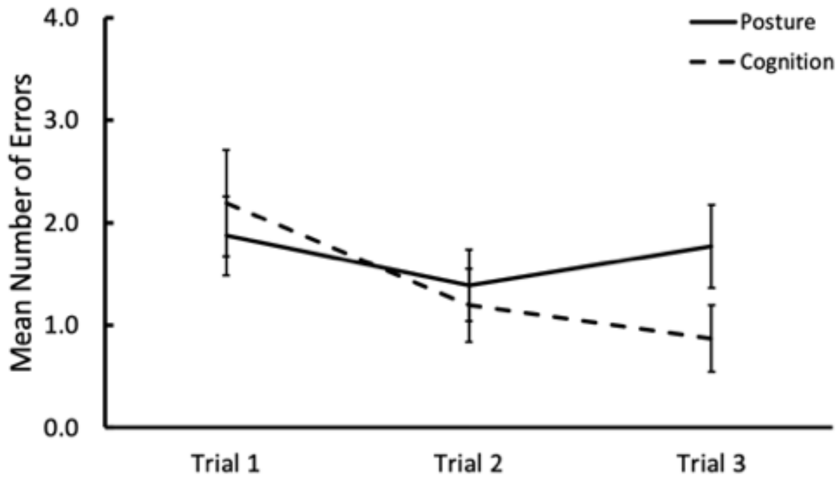

A
B
C
D
E
F
Posture
Cognition
Mean SampEn
Mean SD
Mean SP (mm)
0.35
0.30
0.25
0.20
0.15
0.10
12
10
8
6
4
2
0
200
150
100
50
0
0 Back
2 Back
0 Back
2 Back

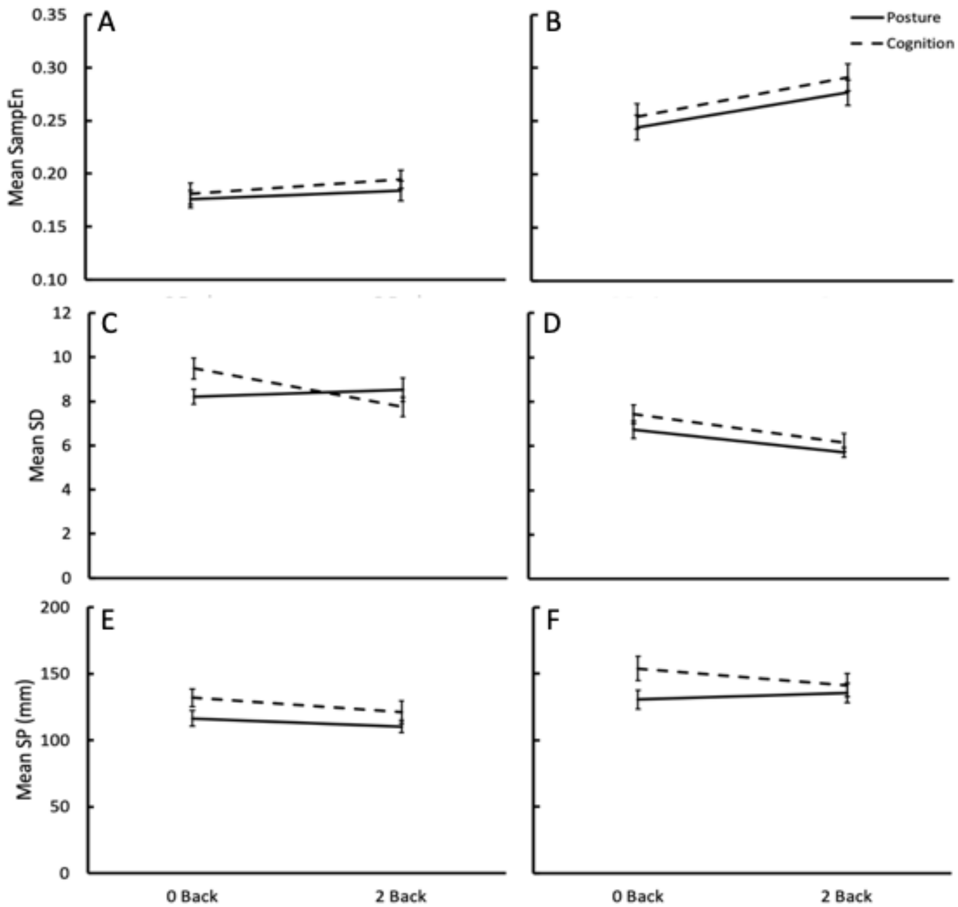

3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mean Number of Errors
Posture
Cognition
0 Back
2 Back

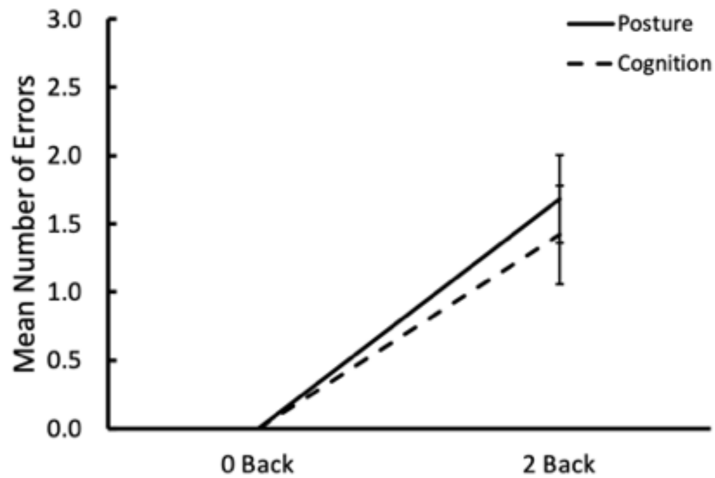

A
B
C
D
E
F
Exp 1 Pos
Exp 1 Cog
Exp 2 Pos
Exp 2 Cog
Mean SampEn
0.35
0.30
0.25
0.20
0.15
0.10
Mean SD
12
10
8
6
4
2
0
Mean SP (mm)
200
150
100
50
0
0 Back
2 Back
0 Back
2 Back

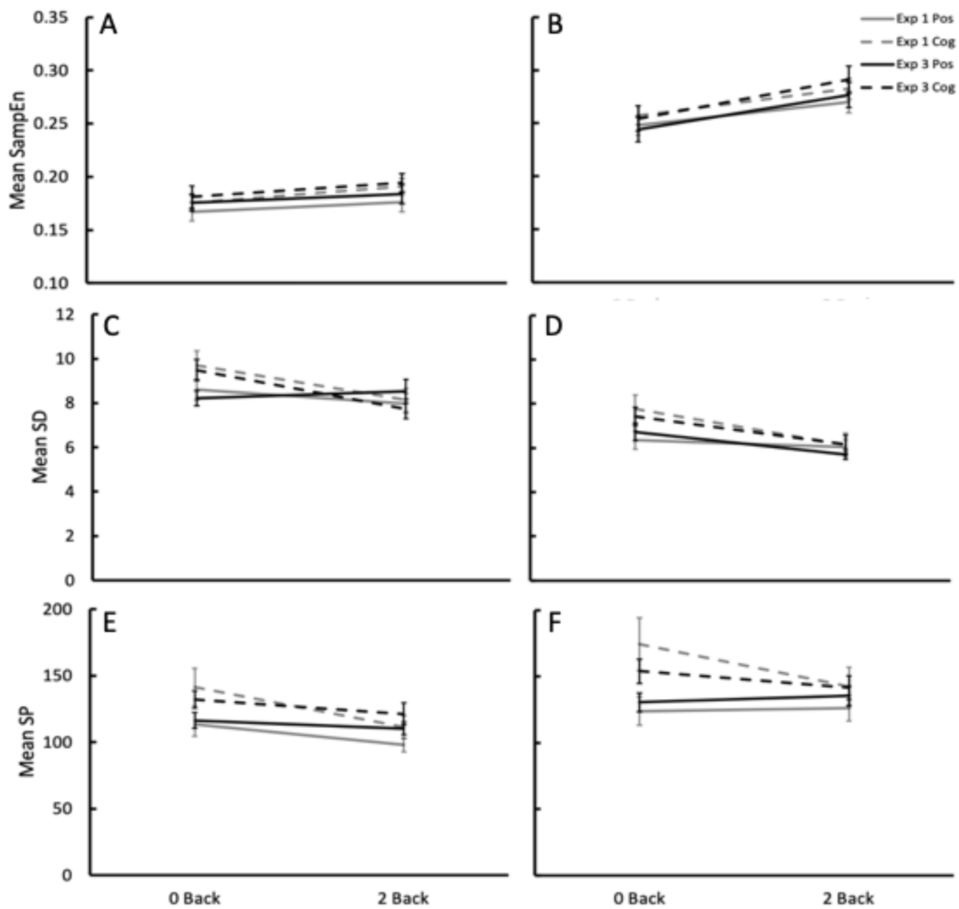

1200
1000
800
600
400
200
0
Mean VAS-F Score
Pre Fatigue
Post Fatigue


Posture
Cognition
Mean SP (mm)
260
240
220
200
180
160
140
120
100
80
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 6
Mean SP (mm)
260
240
220
200
180
160
140
120
100
80
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 6


4.0
3.0
2.0
1.0
0.0
Mean Number of Errors
Posture
Cognition
Trial 1
Trial 2
Trial 3


A
B
C
D
E
F
Posture
Cognition
Mean SampEn
Mean SD
Mean SP (mm)
0.35
0.30
0.25
0.20
0.15
0.10
12
10
8
6
4
2
0
200
150
100
50
0
0 Back
2 Back
0 Back
2 Back


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mean Number of Errors
Posture
Cognition
0 Back
2 Back



A
B
C
D
E
F
Exp 1 Pos
Exp 1 Cog
Exp 3 Pos
Exp 3 Cog
Mean SampEn
0.35
0.30
0.25
0.20
0.15
0.10
Mean SD
12
10
8
6
4
2
0
Mean SP
200
150
100
50
0
0 Back
2 Back
0 Back
2 Back