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This work and its defense approved by:

Chair: Michael A. Riley, Ph.D.

Kevin D. Shockley, Ph. D.

Peter Chiu, Ph.D.

EFFECTS OF A CONCURRENT MEMORY TASK ON THE MAINTENANCE OF UPRIGHT POSTURE

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by

Veronica C. Ramenzoni
Licenciatura en Psicología, Universidad de Buenos Aires, 1998

Committee Chair: Michael A. Riley, Ph.D.
Committee: Peter C-Y. Chiu, Ph.D.
Kevin D. Shockley, Ph.D.

Abstract

Recent evidence suggests that the control of posture is not simple and automatic, and that the postural control system and the cognitive system interact during the performance of dual tasks (see Woollacott, & Shumway-Cook, 2002, for a review). However, the literature is inconsistent with regard to: whether cognitive activity degrades or facilitates postural control and whether distinct types of cognitive activity differentially affect postural control. The aims of this project were to: avoid methodological confounds identified in previous studies, and provide information concerning the effects on postural control during the performance of distinct cognitive tasks. The tasks varied along the following three dimensions: a) type of information (verbal and visual) the participant is presented with, b) primary cognitive process (encoding and rehearsal), and c) working memory component (phonological loop, visual sketchpad and central executive) believed to be responsible for task performance.

Twenty-three participants were instructed to perform simultaneously a posture task with different working memory tasks (tasks varied along the aforementioned dimensions). Results showed a general tendency for postural sway to decrease during rehearsal of cognitive information and to increase during encoding of cognitive information, but these effects were not specific to the working memory component. An interaction between type of information and cognitive process provides some evidence that postural control might be sensitive to the type of the cognitive task performed. However, in general the results of this study suggest instead that the interaction between postural control and cognitive activity may be due to more general factors. Thus, its still unclear whether postural control and cognition interact at a general level or share specific

mechanisms and processes. Regardless of the issue of general versus specific cognitive influences on postural control, the results of this study are inconsistent with traditional assumptions about the functional separation between sensory-motor and cognitive functions. In turn, the results are consistent with an emerging view that postural control reflects the task-specific organization of neuromotor and cognitive elements (Riley et al., 2003; Riley et al., in press).

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CHAPTER I

Introduction

Postural control and cognition

In everyday situations we routinely engage in activities that require the online integration of multiple tasks. For instance, while standing at the entrance of a movie theater we might read the name of the movies that are showing, observe the posters advertising the coming attractions, and carry on a conversation with somebody else. Performing a sensory-motor task (e.g., standing) simultaneously with a cognitive task (e.g., talking or reading) is a very common occurrence. Traditionally, cognitive psychologists have assumed that maintaining an upright posture is a reflexive and highly practiced task that does not involve substantial cognitive processing demands, and thus can be performed perfectly in combination with other cognitive tasks. Two assumptions underlie traditional accounts of the simultaneous performance of cognitive and sensory-motor tasks. First, "lower" sensory-motor functions and "higher" cognitive functions rely on the workings of functionally independent systems. Second, as a consequence, the sensory-motor task and the cognitive task can be functionally separated for their respective investigations.

However, a rapidly growing body of evidence has challenged these assumptions. The evidence suggests that not only is the control of posture not simple and automatic, but also the processes involved in the control of posture and in the performance of concurrent cognitive activities are intertwined (see Shumway-Cook & Woollacott, 2000, for a review). The relation between postural control and cognition has been investigated using dual-task paradigms, in which participants are requested to perform a postural task simultaneously with a cognitive task. A large spectrum of postural tasks —ranging from unperturbed stance (Maylor, Allison, & Wing, 2001) to upright stance on foam surfaces or while receiving calf electrical stimulation (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002)— and cognitive tasks —ranging from simple reaction time tasks (Lajoie, Teasdale, Bard, & Fleury, 1996; Teasdale, Bard, LaRue, & Fleury, 1993; Yardley, Gardner, Leadbetter, & Lavie, 2001) to more complex working memory tasks (Dault, Frank, & Allard, 2001a; Maylor et al., 2001; Maylor & Wing, 1996) — has been explored in both young and elderly populations. Two findings have been documented. First, with increasing postural demand performance of the cognitive task declines. Second, the introduction of a cognitive task affects postural control. The reciprocity of the effect on postural control suggests that postural control is not an automatic activity, but is sensitive to processes occurring in the cognitive system. However, the nature of postural responses during dual-task conditions is still uncertain. The effects of cognitive task performance on postural control that have been documented in the literature vary depending on the study. While some studies showed less postural stability (Maylor et al., 2001; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Simoneau, Teasdale, Bourdin, Bard, Fleury, & Nougier, 1999) others showed increased stability (Andersson, 2002; Dault et al., 2001a), and others showed no significant changes in postural stability measures (Kerr, Condon, & McDonald, 1985).

Methodological inconsistencies and differences in secondary and primary tasks used, the dependent measures chosen, and the populations surveyed render it difficult to describe the relation between postural control and cognition. As noted, the literature is inconsistent with regard to whether cognitive activity degrades or facilitates postural control. The literature is also inconsistent with regard to whether distinct types of cognitive activity differentially affect postural control. Due to these inconsistencies, detailed explanations of the relation between sensory-motor functions and cognitive functions are still lacking. More importantly, despite the amount of empirical data, the research on the interaction between postural control and cognition has failed to clearly illuminate the characteristics of the system(s) involved in the control of posture. These concerns motivated the present research. This project aims to provide important information about the effects of the performance of distinct cognitive tasks on postural control. The cognitive tasks were manipulated in terms of the type of information (verbal vs. visual), the memory processes involved (encoding vs. rehearsal), and the hypothetical working memory components believed to be associated with encoding and rehearsing verbal and visual information (phonological loop, visuo-spatial sketchpad, and central executive).

Postural control System

At first glance the maintenance of upright stance appears to be a simple and automatic behavior. When requested to stand still a person seems to show almost no movements and to invest little effort in the task. Nevertheless, closer examination of this behavior reveals the presence of small and continuous forward-backward and side-to-side movements of the body. The omnipresent motion of the center of mass of the body during upright stance is termed postural sway. Postural sway reflects the online interaction of neuromotor control, musculoskeletal biomechanics, and environmental factors (such as the destabilizing force of gravity and characteristics of the support surface). Postural sway is usually measured as the trajectory of the center-of-pressure (COP), which is the average location of the point of force application on the support surface plane.

All activities have postural requirements. Those requirements vary with the task and the environment. The postural control system adapts to these demands by developing perceptual-motor strategies. These strategies vary across the individual's life span and are a critical factor in the acquisition and loss of functional abilities (Williams & Ho, 2004). For this reason, postural control is conceived as an adaptive system and postural sway as an adaptive behavior (or at least as a reflection of adaptive behavior) (Riccio, 1993). Important clues about how the postural control system generates adaptive strategies may be found in the spatiotemporal structure and online evolution of postural sway (e.g., Collins & De Luca, 1993; see Riley, 2001). Studies have documented the adaptation of postural control to changing sensory and motor conditions (see Shumway-Cook & Woollacott, 1995, for a review). In recent years the spectrum of manipulations has expanded to include observations of how postural sway changes in response to tasks involving higher-level cognitive demands (see Woollacott & Shumway-Cook, 2002, for a review).

Posture-cognition dual-task research: Overview of empirical findings

In studies on the relation between the control of posture and the performance of cognitive tasks, posture is usually considered the primary task and the secondary task is any task that requires cognitive processing, ranging from simple reaction time tasks to more demanding working memory tasks. Impairments in cognitive performance in response to increasing difficulty of the posture task have been consistently documented in the literature (Andersson et al., 2002; Lajoie et al., 1993; Marsh & Geel, 2000; Mitra, 2003; Mitra & Frazier, 2004; Muller, Jennings, Redfern, & Furman, 2004; Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Shumway-Cook, & Woollacott, 2000). Findings regarding changes in the pattern of postural sway observed in dual-tasks paradigms have been less consistent. Studies showed either a decrease (Andersson et al., 2002; Hunter & Hoffman, 2001; Maylor et al., 2001; Maylor & Wing, 1996; Riley, Baker, Schmit, 2003; Swan, Otani, Loubert, Sheffert, & Dunbar, 2004; Vuillerme, Nougier, & Teasdale, 2000) or an increase in postural sway (Dault et al., 2001a; Pellechia, 2003; Shumway-Cook et al., 1997; Shumway-Cook & Woollacott 2000). Still other studies have found non-conclusive results (Kerr et al., 1985), or a decrease for some measures of postural sway and an increase for others (Dault, Yardley, & Frank, 2003). Similarly, decrements in postural sway in response to increasing difficulty of the cognitive task have been found in some studies (Riley et al., 2003), but not in others (Dault et al., 2001a). The effects on postural control of the performance of a cognitive task also seem to depend on the characteristics of the secondary cognitive task. For instance, some studies have observed increases in postural sway during the performance of auditory and visual reaction-time tasks (Redfern et al., 2001;Teasdale et al., 1993; Teasdale & Simoneau, 2001; Yardley et al., 2001), while others documented decreased sway in response to the same type of task (Vuillerme et al., 2000).

Due to the importance of visual information for the maintenance of balance, several studies focused on comparing changes in the pattern of postural sway while performing visual/spatial and verbal tasks. Shumway-Cook et al. (1997) found that elderly individuals swayed more during the performance of a sentence-completion (verbal) task than during performance of a judgment-of-line-orientation (visual) task. These results suggest that visuo-spatial cognition does not seem to strongly affect postural control despite the supposed visuo-spatial demands associated with maintaining body orientation in space. However, the results are inconclusive since, as discussed below, methodological inconsistencies make it difficult to interpret many of the existing studies on the relation between postural control and cognition.

Several studies have addressed the interaction between specific memory processes and postural sway. Both decrements (Maylor et al., 2001; Maylor & Wing, 1996) and increases (Dault et al., 2001a) in postural sway have been observed in response to verbal and visuo-spatial working memory tasks, and at least one study found a decrease in sway for some measures and an increase for others (Dault et al., 2003). Studies comparing verbal and visual working memory tasks have not yielded consistent results. Some studies found changes in sway predominantly for the verbal task (Shumway-Cook et al., 1997), others found changes in response to the visuo-spatial task (Maylor & Wing, 1996), and other studies found no differences between the tasks (Dault et al., 2001a). While typically these studies focused on either encoding or rehearsal memory processes, one study comparing the effects on postural sway of encoding and rehearsal found that differences between those processes depended on whether participants were performing verbal or visuo-spatial tasks (Maylor et al., 2001).

Problems and inconsistencies in previous findings

At least three potential reasons for the inconsistency of results of previous studies can be identified: (a) methodological problems with the implementation of dual-task designs; (b) use of dependent measures of postural sway that are insufficient or uninformative, and (c) problems introduced by inconsistencies in the secondary cognitive tasks selected.

Problems with dual-task methodology. Postural sway is affected by the introduction of articulatory or overt motor responses to the secondary cognitive task (Dault et al., 2001a; Yardley et al., 2001). In some studies the secondary task explicitly required the participant to produce verbal responses (Dault et al., 2001a; Marsh & Geel, 2000; Shumway-Cook et al., 1997), while in other studies participants were required to produce motor responses such as pressing a hand-held switch (Teasdale et al., 2001; Vuillerme et al., 2000). If verbal or manual responses are required for trials in dual-task conditions, but not in single-task control conditions (involving only postural control), then that confound renders it impossible to identify effects of the cognitive task, per se. Furthermore, the instructions given to the participants about the dual-task situation also affect performance of the posture task (see Mitra & Frazier, 2004, for a review of this argument). Previous studies differ in the emphasis given to the posture task; participants are in some studies instructed to stand normally or relaxed (Andersson et al, 2002; Dault et al., 2003; Hunter & Hoffman, 2001; Marsh & Geel, 2000; Riley et al., 2003; Vuillerme et al., 2000), while in other studies specific instructions to minimize sway are given (Dault et al., 2001a; Mitra, 2003; Pellecchia, 2003).

Problems with quantifying postural sway. Second, a major difficulty in interpreting dual-task findings is the use of different statistical parameters for the description of postural sway. Postural sway is a very difficult signal to quantify and interpret. The postural control system is a high-dimensional system that is usually measured as a two-dimensional (anterior-posterior, or AP, and medio-lateral, or ML) spatiotemporal signal. It is expected that parameters calculated from the postural sway signal faithfully represent the activity of the postural control system. However, due to the complexity of the information packed in the postural sway signal, its interpretation is complex and may vary according to the statistical parameters chosen to quantify it (Riley, 2001). There are two primary means of quantifying postural sway. The first is to employ statistical parameters that represent postural sway while averaging over or ignoring changes in sway over time. Raymakers, Samson, and Verhaar (2003) evaluated the usefulness of the most commonly employed statistical parameters of postural sway. They found that mean velocity of displacement (which is equivalent to COP path length, a measure used in the present study) and range of displacement of the COP were more informative and had higher discrimination power than more commonly used standardized displacement parameters (such as COP standard deviations, which were also employed in the present study).

However, it has been argued that those kinds of statistical descriptors can be sometimes inappropriate or insufficient to describe postural sway (Riley, 2001). Among other reasons, statistical descriptors tacitly assume that COP variability expresses the influence of random factors, which is not the case for postural sway (see Riley, Balasubramaniam. & Turvey, 1999; Riley & Turvey, 2002). Furthermore, summary measures such as mean values provide insufficient information about the online evolution of postural sway. Some studies have employed spectral analysis to capture the time-dependent responses of the COP to cognitive demand (e.g., Dault et al., 2003). That technique is inappropriate, however, because it assumes stationarity of the signal, which is not the case for postural sway (Carroll & Freedman, 1993; Riley et al., 1999). Methods based on the principles of nonlinear dynamics and stochastic processes and that explicitly assume non-stationarity—such as Recurrence Quantification Analysis (RQA) and Detrended Fluctuation Analysis (DFA) —may offer a better alternative (Riley, Baker, Schmit, & Weaver, in press).

Inconsistencies in cognitive tasks. Finally, a further source of inconsistency in results regards the characteristics of the cognitive tasks employed in previous studies (e.g., verbal vs. visual/spatial) and whether they actually engage the memory processes they were intended to target. The selection of adequate working memory tasks, in particular, is complex. The commonly used paradigms in the memory literature introduce methodological problems such as those described previously (they require motor or vocal responses). Some studies on postural-cognition dual-tasking have employed Brooks' (1967) spatial and non-spatial memory tasks (e.g. LaJoie et al., 1996; Shumway-Cook et al., 1997). While this task does not require articulatory or motor responses, it still presents problems. The task was designed to measure visuo-spatial but not visual memory processes, and fails to single out the visual and verbal components of working memory—both the spatial and the verbal tasks involve verbal memory factors. In addition, the task involves the translation of verbal instructions into spatial content, which involves the participation of executive processes.

Beyond those problems with that specific task, the secondary task that is used places limitations on the implementation of the postural task. The length of postural sway data collection varies across studies, ranging from 12 s to 60 s, depending on constraints imposed by the secondary task. Differences in trial length further complicate the interpretation of results across experiments since some postural sway measures (such as path length) are dependent on the length of the postural sway time series.

Theoretical accounts

Different explanations have been offered for the relation between postural control and cognition. One explanation is the “posture first” principle, which states that when there is competition between two tasks, the maintenance of postural stability becomes the priority over cognitive performance (Andersson et al., 2002; Shumway-Cook, 1997). The principle predicts that when balance conditions are difficult enough posture will be prioritized and cognitive performance will therefore decrease. This prediction has been confirmed by empirical evidence (Kerr et al., 1985). However, the converse of the posture first principle does not necessarily hold. If the maintenance of stability is the priority, the performance of concurrent cognitive tasks should not affect postural stability, but the empirical evidence does not support that prediction.

An alternative family of models has attempted to explain results by referring to the workings of broader cognitive mechanisms. In these models, postural control changes are often conceived as resulting from fluctuations in the distribution of attentional resources. It has been suggested that the inability to allocate sufficient attention to postural control under dual-task conditions is the contributing factor to alterations in balance (Shumway-Cook & Woollacott, 2000). Similarly, the general capacity limitation hypothesis explains these alterations as resulting from the overload of the cognitive system (Dault, Geurts, Mulder, & Duysens, 2001b; Redfern et al., 2004). According to this view the postural control system normally operates autonomously from the direct influence of higher-order cognitive functions, and its task is to minimize sway in order to maintain postural stability. Increases in postural sway occur when demands exceed the capacity of the postural control system’s coping strategies. As a consequence of the failure to autonomously control posture, higher-order cognitive mechanisms intervene. Impairments in cognitive task performance then arise from either the relocation of resources from the secondary task to the primary postural task or from general cognitive overload. These models predict a decline in postural stability, without regard to the specific nature of the cognitive task. However, this prediction has been disconfirmed by evidence that shows apparent improvements in postural stability when the difficulty of the memory task exceeds the participant’s memory span (Andersson et al., 2002; Riley et al., 2003; Riley et al., in press) and is also contradicted by the limited evidence that suggests the postural response depends on the exact type of the cognitive activity (e.g., verbal vs. visuo-spatial tasks; see Maylor & Wing 1996, Maylor et al., 2001).

In the models just described, changes in postural sway respond to a general, adaptive CNS mechanism that distributes resources according to task demands. This conceptualization of the nature of the postural control system supports the assumption that postural control, as a ”lower” sensory-motor function, can be functionally separated from the system involved in ”higher” cognitive functioning. In that respect, the interaction between the postural control system and the cognitive system is accounted for by more general mechanisms (e.g., attention). The functional role of the postural control system in these models is the automatic activation of strategies intended to minimize postural sway. A contrasting view of the postural control system stresses the goal-directed nature of postural sway (Riccio, 1993; Riccio & Stoffregen, 1988). According to this approach, the postural control system detects, regulates, and generates sway according to a variety of intrinsic and extrinsic demands—the automatic reduction of postural sway is not the only goal of postural control. In this respect postural sway is not only an adaptive behavior, but also an active, goal-directed behavior involving exploration of the environment. This approach emphasizes that the ability to control posture largely depends on the tasks one is engaged in while maintaining balance (Balasubramaniam & Wing, 2002). The nature of the supra-postural task performed under dual-task conditions is, from this perspective, expected to influence the regulatory mechanisms activated by the postural control system.

Following this approach, Mitra and Frazier (2004; see also Mitra, 2003) proposed the adaptive-resource sharing model. This model stresses that the primary functions of the postural control system are to stabilize balance and facilitate supra-postural task performance. In the absence of threats to stability postural control has a facilitatory function for the performance of supra-postural tasks. Facilitation occurs either through increases or decreases in postural sway, depending on the nature of the task. This hypothesis excludes common interpretations of decrements in sway as indicating improved stability, and increases as indicating impaired stability. This framework predicts a facilitation effect (reduced sway) under relatively easy posture conditions but only if cognitive demand is low. However, the model makes no exact predictions for sway changes in response to varying difficulty levels, type of cognitive task, or type of cognitive processes. Moreover, Riley and Saunders (2005) partially disconfirmed this model—they failed to replicate the results of Mitra and Frazier using adequate dual-task methodologies that eliminated a confound present in Mitra and Frazier’s study.

Despite the inadequacy of the predictions of this particular model, goal-directed conceptualizations of the postural control system offer a more flexible framework for the study of the interactions between the postural control and cognitive systems. In that respect, a better understanding of the relation between the two systems should start by considering the characteristics of the cognitive task performed and the nature of postural adjustments in response to the cognitive task. More importantly, the online evolution of postural sway should be studied in reference to changing constraints posed by dual-task performance.

The present experiment: Overview and predictions

This project is intended as a first step in providing a comprehensive account of what it means for cognition and postural control to interact, and an account of the nature of those interactions. In order to address these broad goals, the experiment was designed to study the effects of well-defined cognitive tasks and to avoid methodological confounds observed in several previous studies. The specific purpose was to determine how postural control is affected by cognitive tasks that differed along three dimensions: (1) the type of information the participant is presented with (verbal vs. visual), (2) the distinct working memory components believed to be primarily responsible for the information processing (phonological loop, visuo-spatial sketchpad and central executive; see Baddeley, 1986), and (3) the type of processing to which the information is primarily subjected (encoding and rehearsal).

There are several reasons for choosing to investigate links between postural control and WM, rather than between postural control and other cognitive processes. Among those reasons, WM models allow for the operationalization of distinct cognitive tasks, which can be easily implemented in experimental settings and can be adapted to meet the practical constraints of postural control research. Furthermore, WM is understood to involve different cognitive structures and processes for different types of information (visual vs. verbal) and for different stages of processing (encoding vs. rehearsal). Two types of WM components have been proposed: Storage and central executive functions (see Baddeley, 1986, for a review). The two storage systems within the Baddeley model—the phonological loop (PL) and the visuo-spatial sketchpad (VSSP)—are primarily responsible for the temporary storage of verbal and visual information, respectively. The PL temporarily stores acoustic or speech-based information that fades away spontaneously within 2-3 s unless refreshed by rehearsal (Baddeley, 1996). The VSSP is a more complex system composed of two highly interacting subsystems, which store visual and spatial information (Baddeley, 1996). The most important, and least understood, aspect of WM is the central executive (CE), the primary function of which is the unitary control of working memory. The CE is responsible for the selection, initiation, and termination of processing routines (e.g., encoding, storing, and retrieving) (Baddeley, 1986, 1990, 1992, 1996). According to this model presenting the participant with a particular type of information (verbal or visuo-spatial) will result in the selective engagement of the respective storage system. In addition, if the function of the storage systems is disrupted by the introduction of verbal or visuo-spatial interference, the CE will become involved in cognitive performance.

A set of WM tasks was specifically developed for this project in order to avoid confounds introduced in previous studies. The tasks independently target the processing of visual and verbal information during encoding and rehearsal, and allow for continuous measurement of posture sway for 50 s. The WM tasks were performed while standing to result in concurrent WM performance and postural control. In order to avoid confounds due to task difficulty, the difficulty of both visual and verbal tasks was fitted to each participant's working memory spans. For the task, participants were asked to first encode visually presented information, which consisted of either a string of letters and numbers (verbal encoding) or Japanese anagrams (visual encoding) for 20 s, then to rehearse that information during a subsequent 30 s period, and finally, after rehearsal and after postural data collection ceased, to identify the serial position of a randomly selected item in the string (see Figures 1). During rehearsal participants were exposed to one of three interference conditions: no interference, verbal interference, and visual interference. The purpose of introducing interference was to affect the processing of the PL and VSSP, which provokes the activation of the CE (Christoff, 1999). Verbal articulation—both sub-vocal and auditory—interferes with PL functioning, and the presentation of visual and spatial information interferes with VSSP functioning. In both cases of congruent interference an activation of the CE is expected to result.

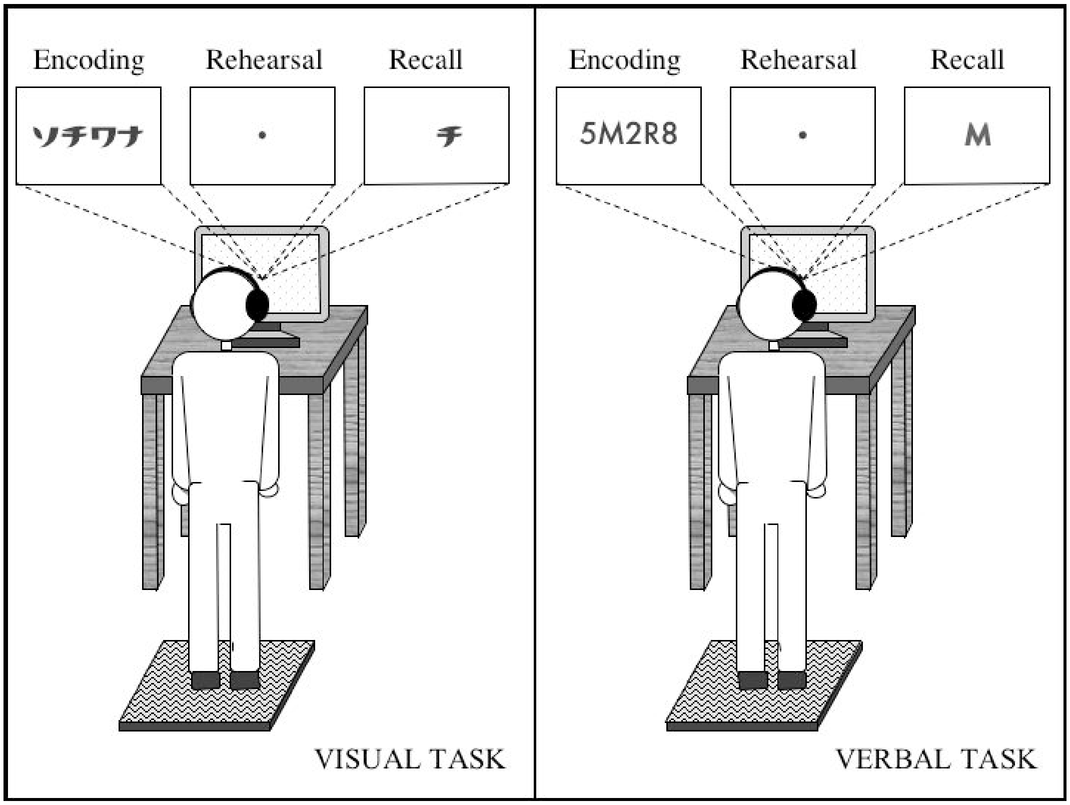

Figure 1. Experimental setting.

Predictions

Based on previous research (Andersson et al., 2002; Mitra & Frazier, 2004; Riley et al., 2003; Riley et al., in press), an overall reduction in postural sway variability during cognitive conditions (relative to the no-task control condition) was predicted. The primary memory process involved in the two experimental phases (encoding and rehearsal) was expected to differentially affect postural sway. A change in the pattern of postural sway during the encoding of cognitive information (relative to the no-task control condition during encoding) would indicate the involvement of CE functioning in postural control. Based on the assumption that the CE, and not the PL and VSSP, is primarily engaged during encoding, no differences were predicted for the encoding of visual versus verbal information.

During the rehearsal phase it was expected that postural sway variability would be differentially affected by the type of WM task (visual/spatial vs. verbal), indicating the involvement of specific WM components. Since postural control presumably involves visual/spatial demands, the visuo-spatial task was expected to produce a greater reduction in postural sway variability than the verbal task. Such a pattern of results during rehearsal would indicate that cognitive effects on postural control are due to the shared activity of specific verbal and visual WM components (LP and VSSP) other than central executive processes (CE). Such results would also suggest that specific cognitive (or neural) mechanisms are shared by the cognitive task and postural control. If that effect is accompanied by congruent interference effects (i.e., verbal interference during the verbal task, visual interference during the visual/spatial task) it would suggest involvement of the CE. Incongruent interference, or any interference effect in the absence of a cognitive task effect, would suggest an overall influence of amount of cognitive load rather than a specific postural response to specific types of cognitive activity.

CHAPTER II

General Method

Participants

Twenty-three undergraduate students (10 females, 13 males; mean age= 19.78 yrs, range = 18 to 25 yrs) from the University of Cincinnati received course credit for participation in this study. Participants' heights ranged from 1.53 to 1.83 m (mean height = 1.70 m) and weights ranged from 45.5 to 82.0 kg (mean weight = 65.88 kg). No participant had a medical history of diseases or recent injuries that would affect balance, impaired vision, knowledge of Japanese or similar iconic languages, or knowledge of the science-fiction language Klingon (Klingon sounds and Japanese symbols were used to create the verbal and visual interference stimuli, respectively).

Apparatus

Postural sway was measured using an AccuSway$^{\text{Plus}}$ portable force platform with *Balance Clinic* software (Advanced Medical Technologies, Inc., Waterton, MA) running on a PC. Data were sampled at 50 Hz. Cognitive stimuli were presented visually using Microsoft *PowerPoint* on a 36.8 cm × 25.4 cm LCD monitor (resolution 1024 × 768 pixels), positioned at eye height in front of the participant, 50 cm from the front edge of the force platform. Material was displayed on the monitor using 88-point font, subtending 0.9° of vertical visual angle. Auditory material for verbal interference was presented using headphones at a constant volume.

Procedure

Experimental procedures were approved by the University of Cincinnati Institutional Review Board, and participants signed an informed consent form prior to participation in the experiment. Each participant was tested individually in a laboratory setting. Dual-task trials consisted of the simultaneous performance of a postural and a WM task. The postural task requirements remained constant throughout the experiment. Three WM tasks (no task, verbal task, and visual task) and three levels of WM interference (no interference, verbal interference, and visual interference) were factorially combined to result in nine conditions. Three trials per condition were performed, resulting in 27 total trials. The order of presentation of trials was fully randomized. The experiment took about 50 minutes to an hour to complete. A short break was given at the middle of the experiment, after trial 14.

Memory Span Assessment. Before the beginning of the experiment visual and verbal memory tests were given to each participant in order to establish visual and verbal WM spans. The test was specially developed for the experiment, based on the Digit Memory Test (Turner & Risdale, 2002). The tests consisted of the successive presentation of strings of either random letters and numbers (verbal test) or Japanese symbols (visual test); the material used for the test resembled the actual material used for the experimental trials (see Figure 2). On each successive presentation the length of the string was increased. The material was presented for 10 s. Immediately afterwards, participants were asked to recall the serial position of a randomly selected item in the string. Two trials were completed for each string length. WM span was established as the longest string length for which a correct answer was given on both trials (mean verbal span = 7.04 items; mean visual span = 6.0 items). The length of the spans determined the number of units to be encoded and maintained in WM during the experimental trials.

Posture Task. Each experimental trial consisted of 50 s of posture data collection. On each trial, participants stood barefoot on the force plate with their feet separated shoulder-width. The position of the feet was measured and marked at the beginning of the experiment and remained constant for the duration of the experiment. Participants were instructed to stand relaxed, breath normally and let their arms hang naturally to the side. Participants stood with their eyes open.

Secondary Task. Each 50 s trial consisted of a 20 s encoding phase, followed by a 30 s rehearsal phase, and finally the recall task (see Figure 2). Postural data collection ceased after the rehearsal phase. The encoding phase consisted of the presentation of a string of either letters and numbers (verbal task) or Japanese symbols (visual task) displayed against a white background for 20 s. The number of units of information presented matched the participant's memory span for each task condition.

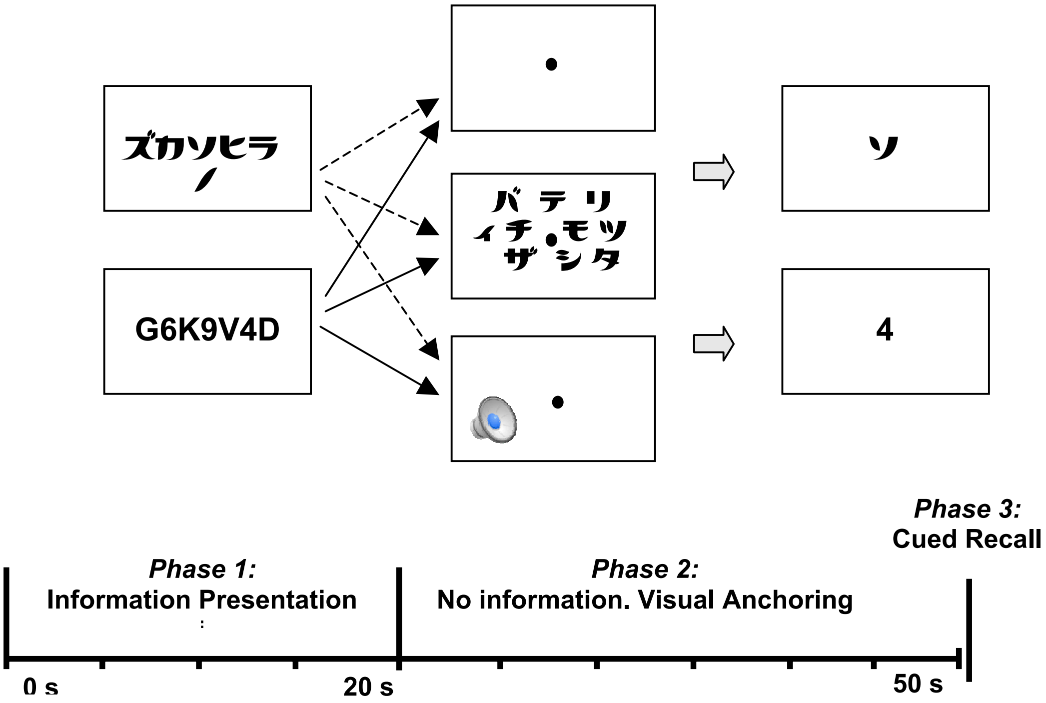

Figure 2. Secondary task procedure.

After the encoding phase the information vanished and a white screen showing a red dot in its center appeared for 30 s (rehearsal phase). Participants were instructed to keep their eyes fixed on the red dot and rehearse the material using their preferred strategy. Depending on the experimental condition, during this phase participants were exposed to either no interference, verbal interference, or visual interference. The visual interference material consisted of the presentation of Japanese symbols moving diagonally from the top and bottom corners of the screen (none of the same items employed as material to remember in the experimental trials was used as interference stimuli). The verbal interference consisted of a 30 s recording of a female voice repeating syllables in Klingon, which were selected because of their phonological differences with English and because of their unfamiliarity to participants.

Following the rehearsal phase, a screen showing either a symbol (for the visual task) or a letter or number (for the verbal task) appeared on the monitor. Participants were asked to provide the position in the string of the displayed item. The participant's responses and type of error (misidentifying the serial position or identifying a position that exceeded the string length) were recorded by the experimenter after each trial. In order to ensure dual-task performance for the verbal and visual tasks, only one out of three trials with an incorrect response per conditions was allowed. If the number of failed trials exceeded that value, failed trials were repeated at the end of the experiment. No feedback on performance was given during the testing section.

Data analyses and reduction

COP time series were computed based on the force platform recordings. COP data were subjected to software analyses in order to compute the primary dependent measures.

Data analysis and reduction routines were written in *Matlab*. First, a routine divided the COP time series for both the AP and ML directions into data windows that corresponded to the different phases of task performance (see Figure 3). The last two seconds of data of the encoding phase were excluded from the analyses. *Matlab* routines were used to calculate indices of postural sway variability including the standard deviation (SD) and local standard deviation (LSD; the within-trial average of SDs of non-overlapping 1 s data windows) of the AP (AP-SD) and ML (ML-SD) COP. LSD measures (AP-LSD and ML-LSD) provide a way of estimating time series variability occurring at a smaller time scale than is assessed by the overall SD. Path length, or the total distance traveled by the COP over the course of a trial, was also calculated.

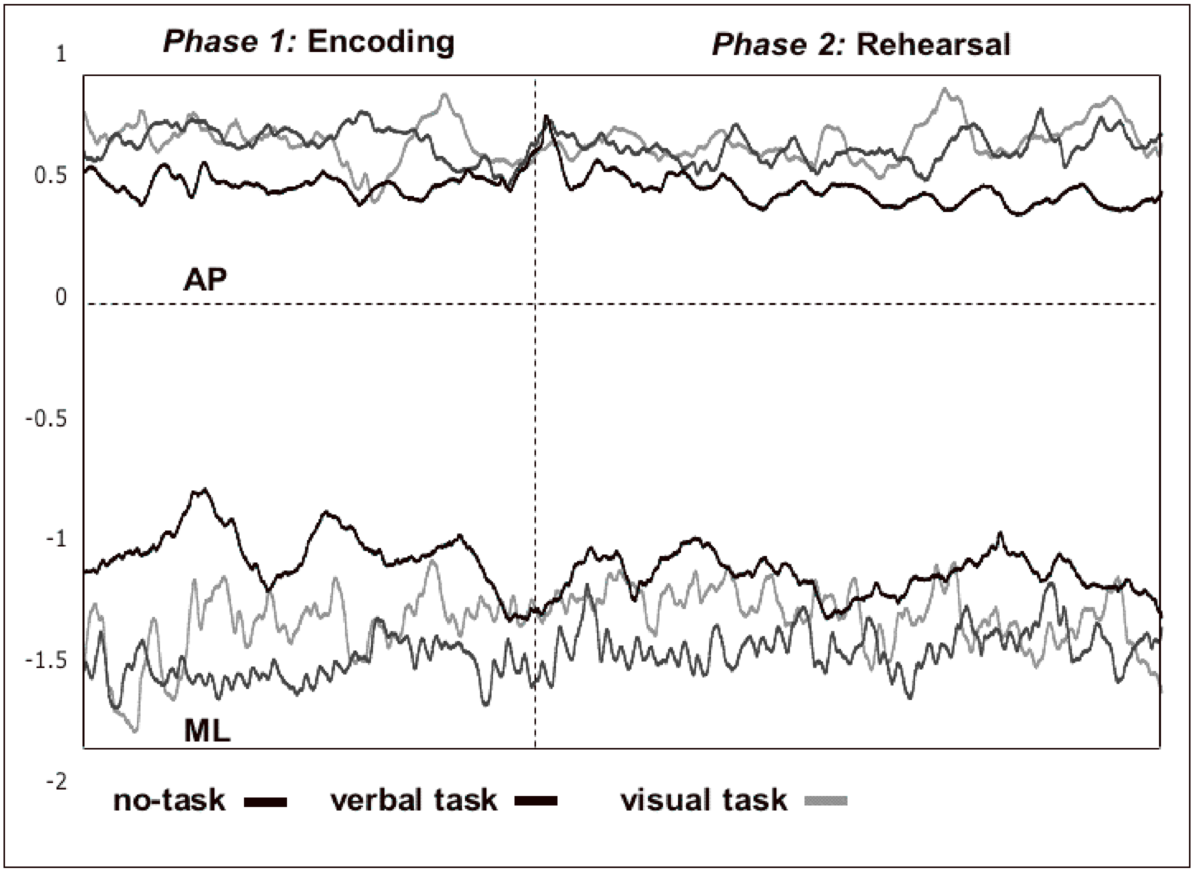

Figure 3. Examples of postural sway time series in each condition from one participant.

A *Matlab* routine was used to perform Detrended Fluctuation Analyses (DFA) on the COP time series for the encoding and rehearsal phases (Peng, Hausdorff, & Goldberger, 1999). DFA is a time series method used to study the complexity of posturographic signals by revealing the extent of long-range correlations in the COP time series. The analysis determines the manner in which postural sway variability scales with the size of the time window over which it is computed. Postural sway has been shown to exhibit fractal scaling (see, e.g., Collins & De Luca, 1993; Duarte & Zatsiorsky, 2001), which means that variability at one time scale is repeated (i.e., is correlated with) variability at other time scales (see Liebovitch & Shehadeh, 2005). DFA is a method for measuring fractal scaling. The COP time series (with *N* samples) is first integrated, and then the integrated time series is divided into boxes of equal length, n. Next, a least-squares line is fit in each box to the data (representing the trend for that box). The y-coordinate of the straight-line segments is denoted by $y_n(k)$. The integrated time series is then detrended by subtracting the local trend $y_n(k)$ in each box. Finally, the root-mean-square fluctuation of this integrated and detrended time series is calculated. This computation is repeated over different time scales (box sizes) to characterize the relation between [F(n)], the average fluctuation, and box size. In general, F(n) increases linearly as box size increases; a linear relation on a log-log plot (see Figure 5) indicates fractal scaling of the data. The slope of the line relating log F(n) to log n is used to quantify the fractal scaling relation, and is termed the scaling exponent. Values of the scaling exponents were averaged over trials in the same condition and submitted to statistical analysis. The scaling exponent also measures “memory” (autocorrelation) in the data.

White noise, which is uncorrelated, has a scaling exponent of 0.5. Departures from 0.5 (in either direction) indicate a departure from a random process.

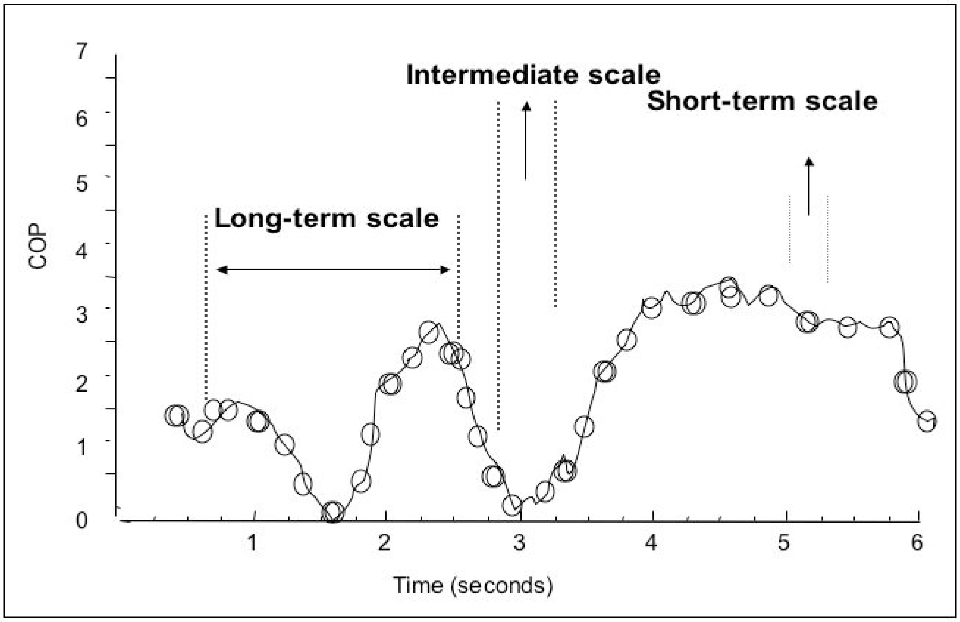

Figure 4. Schematic of procedure for detrended fluctuation analysis.

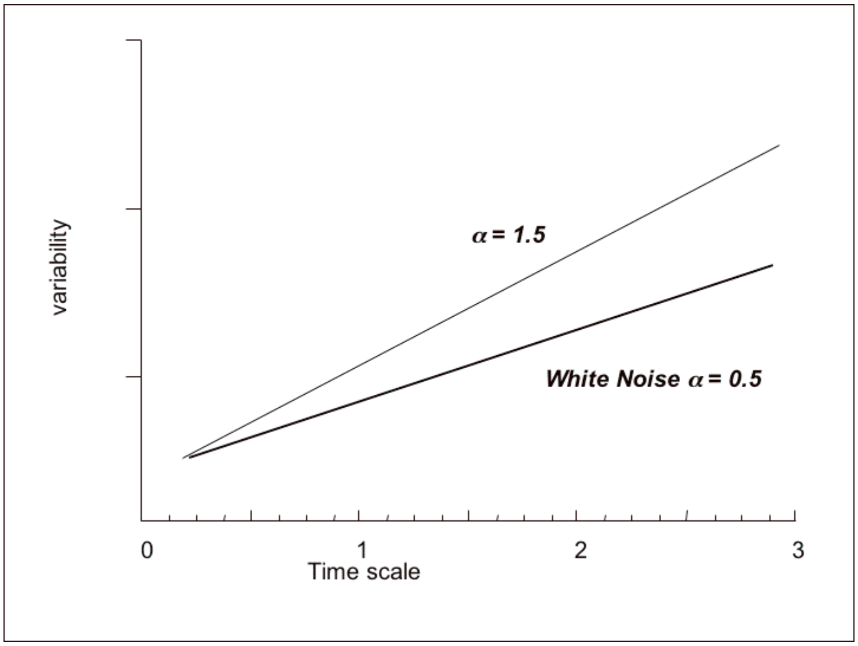

Figure 5. Scaling relations for fractional Brownian motion and white noise.

CHAPTER III

Results

Postural Stability Measures

Analysis of variance (ANOVA) was used to analyze the mean values of each dependent variable for each condition. One set of ANOVAs was conducted on the encoding phase data with task condition (no task, verbal task, and visual task) as the independent factor. A second set of ANOVAs was conducted on the rehearsal phase data with cognitive task (no-task, verbal task, and visual task) and interference (no interference, verbal interference, and visual interference) as independent factors. Finally, a third set of ANOVAs compared the encoding and rehearsal phases with cognitive task condition and memory process as independent factors (trials with interference were excluded). For that analysis difference scores were used—no-task mean values were subtracted from the mean values of each cognitive task condition for each dependent variable for each participant. Using difference scores that factored out the no-task control condition ensured that any difference between encoding and rehearsal reflected a difference due to cognitive factors, not simply due to the passage of time during the trial.

Encoding phase

Analyses of the encoding phase revealed significantly lower sway variability for no-task compared to verbal task for the ML-SD [$F(2,22) = 4.23$, $p < .05$, $\eta_p^2 = 0.16$] (see Figure 6). No other effects were significant during encoding.

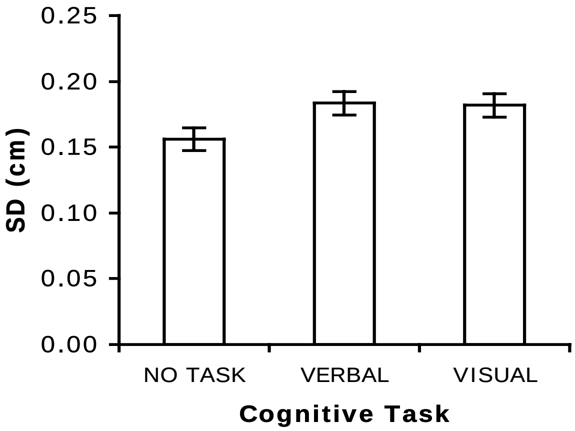

Figure 6. Mean values for ML-SD during encoding as a function of cognitive task.

Rehearsal phase

ANOVA on the ML-SD and AP-SD data revealed significant main effects of cognitive task, $F(2,22) = 20.90$, $p < .05$, $\eta_p^2 = 0.48$, and $F(2,22) = 12.42$, $p < .05$, $\eta_p^2 = 0.36$, respectively (see Figures 7 and 8). Post-hoc tests revealed that for both measures the verbal and visual tasks resulted in less sway variability than the no-task control condition (all $p < .05$), but the two cognitive conditions did not differ significantly from each other. Analysis of the LSD data for ML and AP postural sway revealed an effect of interference for ML-LSD, $F(2,22) = 3.41$, $p < .05$, $\eta_p^2 = 0.20$ (see Figure 9). Post-hoc tests revealed that verbal interference was associated with less sway variability than the no-interference condition ($p < .05$). No significant effects were found for either ML-LSD or P-length. No interactions were significant for any of the measures.

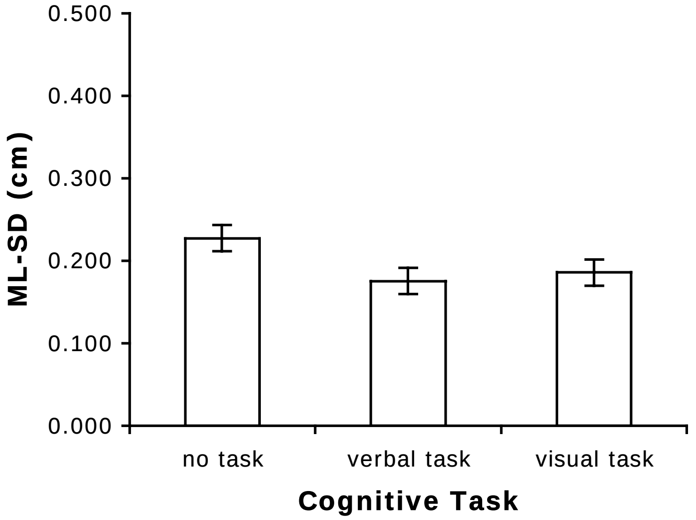

Figure 7. Mean values for ML-SD during rehearsal as a function of cognitive task and type of interference.

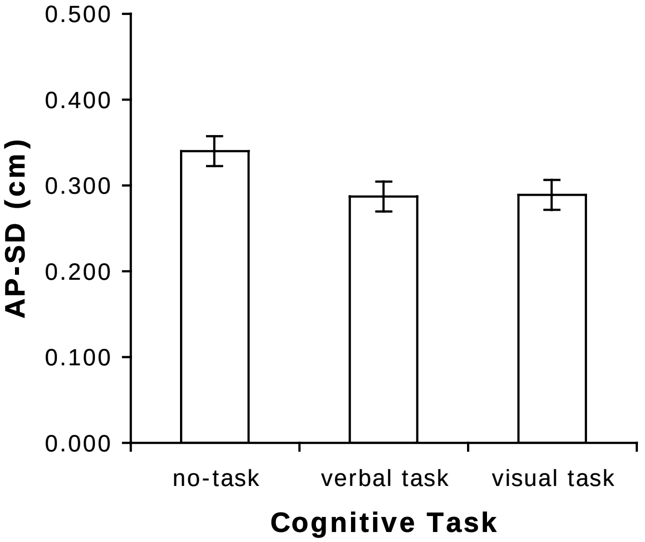

Figure 8. Mean values for AP-SD during rehearsal as a function of cognitive task and type of interference.

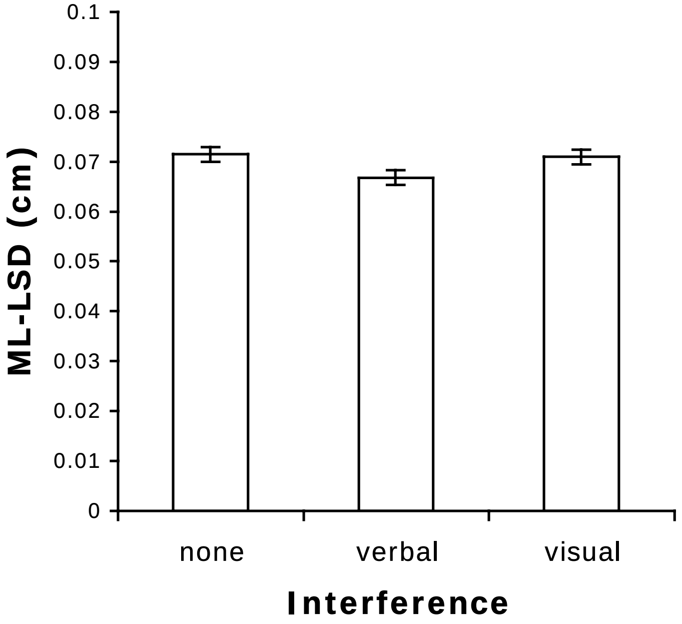

Figure 9. Mean values for ML-SD during rehearsal as a function of type of interference (averaged over cognitive task).

Encoding vs. rehearsal phases

ANOVAs comparing the encoding and rehearsal phases for AP-SD revealed a significant interaction between cognitive task and cognitive process, $F(1,22) = 9.81$, $p < .05$, $\eta_p^2 = 0.45$ (see Figure 10). A simple effects analysis revealed significantly less postural sway variability during encoding for the visual task compared to the verbal task [$F(1,22) = 8.44$, $p < .05$, $\eta_p^2 = 0.26$] and significantly less postural sway variability for the visual task during encoding than during rehearsal [$F(1,22) = 10.44$, $p < .05$, $\eta_p^2 = 0.35$]. No significant effects or interactions were found for the other postural stability measures.

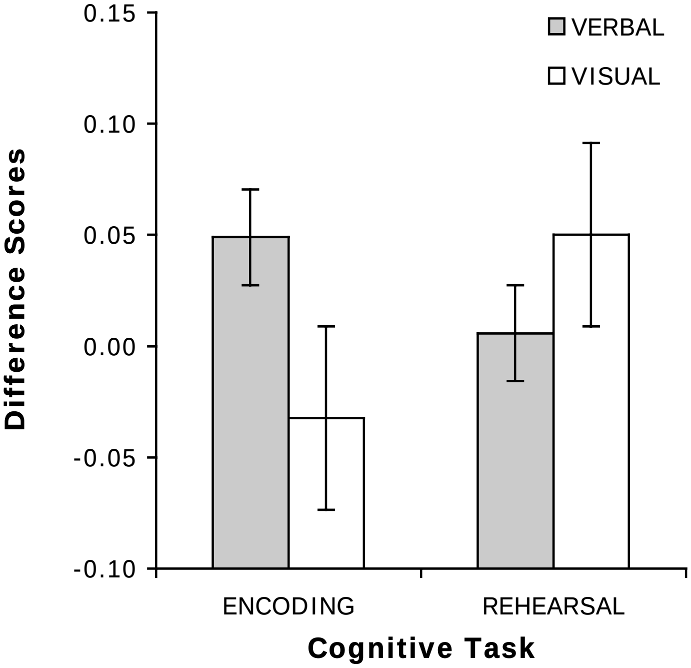

Figure 10. Mean difference values for AP-SD a function of cognitive task and cognitive process.

Detrended Fluctuation Analysis (DFA)

Analyses of the encoding phase revealed a significant effect of cognitive task in both the ML and AP directions, $F(2,22) = 3.33$, $p < .05$, $\eta_p^2 = 0.14$, and $F(2,22) = 9.81$, $p < .05$, $\eta_p^2 = 0.30$, respectively (see Figures 11 and 12). Post-hoc analyses showed that for ML sway scaling exponents obtained for the verbal and visual tasks were significantly smaller than those obtained for no-task. For AP sway the visual task yielded significantly smaller slope values than did the verbal-task and control conditions. Analyses performed on the rehearsal phase data and on the comparison between encoding and rehearsal phases differential values showed no significant effects.

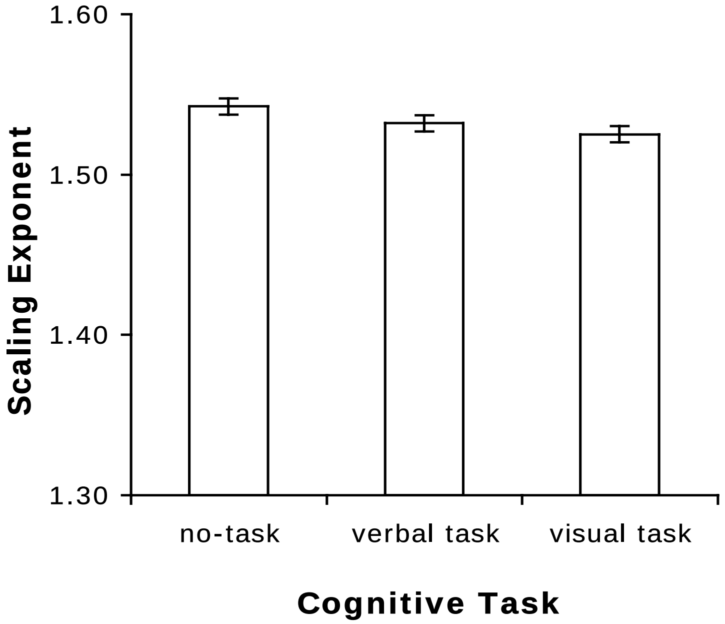

Figure 11. Mean values of DFA scaling exponents in the ML direction during encoding as a function of cognitive task.

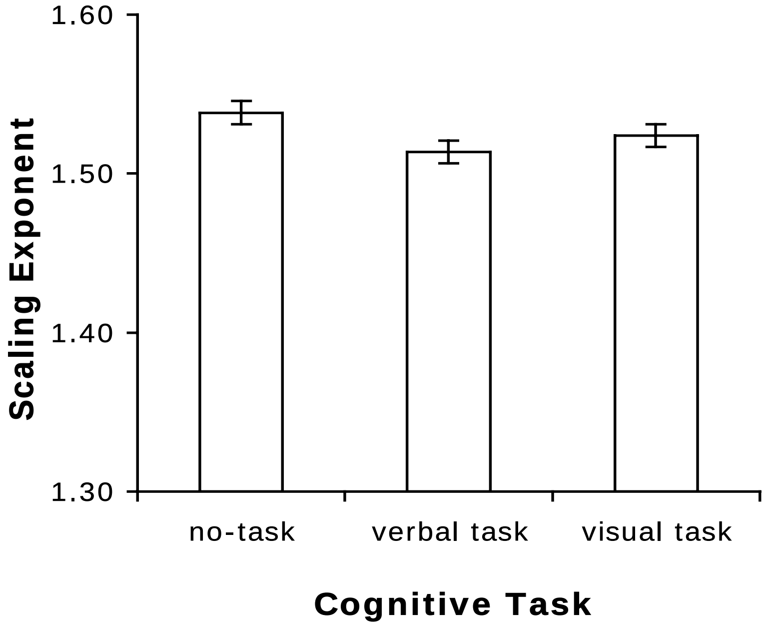

Figure 12. Mean values for DFA exponents in the ML direction during encoding as a function of cognitive task.

Cognitive task performance

No inferential statistics were computed because the data did not meet ANOVA assumptions. For the verbal task a total of 19 errors were made; 26.32% of those occurred in the no-interference condition, 42.11% in the verbal interference condition, and 31.58% in the visual interference condition. For the visual task a total of 35 errors were made; 31.43% of those occurred in the no-interference condition, 31.43% in the verbal interference condition, and 37.14% in the visual interference condition (see Figure 13).

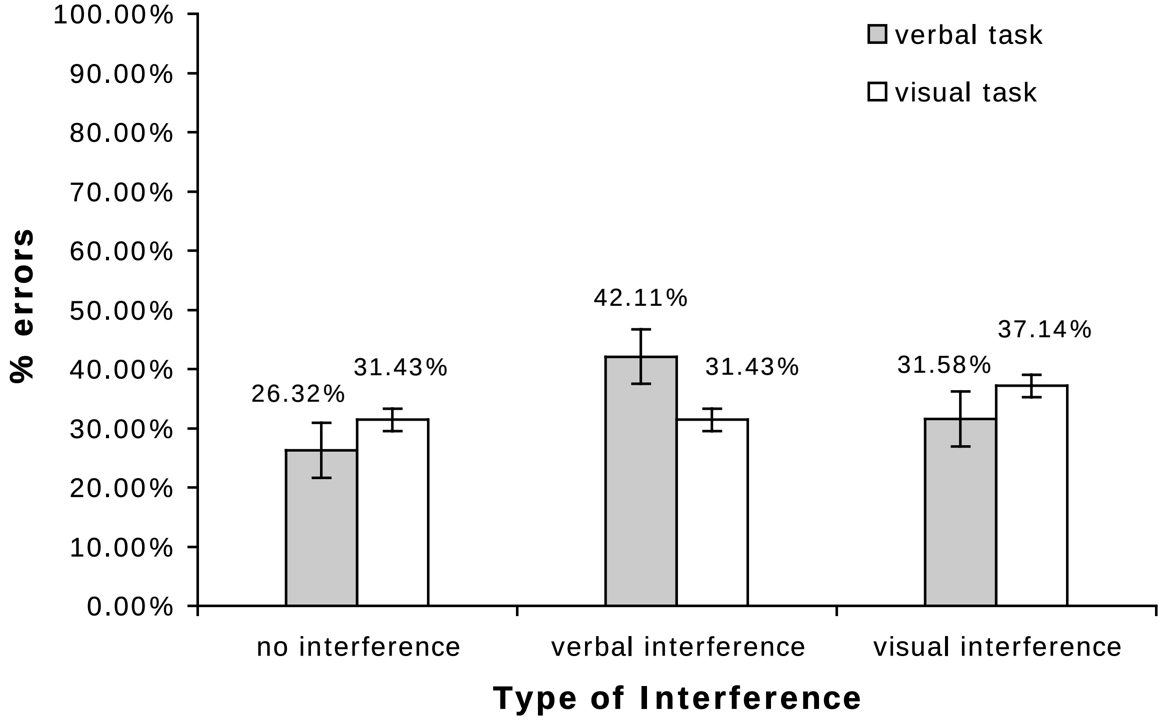

Figure 13. Cognitive task performance results expressed as percentage error for the verbal and the visual tasks as a function of type of interference.

CHAPTER IV

General Discussion

The general purpose of this project was to study the pattern of changes in postural sway during the performance of WM tasks. Inconsistent results concerning the effects on postural control of the performance of different types of secondary cognitive tasks have been documented in the literature. Some of those inconsistencies may be due to methodological problems (see discussion by Riley et al., 2003). The aim of the current project was to determine whether postural sway was distinctly affected by the specific type of cognitive task (verbal vs. visual) and cognitive process (encoding vs. rehearsal), and by specific types of interference (verbal vs. visual) during rehearsal. If postural control responds specifically to the types of cognitive task, process, and interference, it would suggest that postural control and those specific processes share specific mechanisms, processes, or structures. A failure to find differential effects on postural sway of the specific cognitive tasks and processes would suggest that postural control and cognitive activity interact at a more general level, such as by competing for limited attentional resources.

Based on previous research that employed a methodology similar to the present study (Andersson et al., 2002; Mitra & Frazier, 2004; Riley et al., 2003; Riley et al., in press) a general decrement in sway variability during the performance of cognitive tasks (relative to the no-task control condition) was predicted. Predictions about the distinct effect on postural sway of the performance of the verbal and the visual task were also evaluated. Based on previous research (Maylor & Wing, 1996; Maylor et al., 2001) a more pronounced effect on postural sway variability was expected for the visual than for the verbal task. The study also examined whether a distinct effect on postural sway of the encoding versus the rehearsal phases of the experiment would occur. Finally, the effects of interference during the rehearsal phase were examined to determine whether or not CE processes might have an effect on postural control.

The results of the current project provide some evidence that postural control might be sensitive to the type of the cognitive task performed and, hence, to the specific cognitive mechanisms or processes involved in performance of the cognitive tasks. However, a number of results of this study suggest instead that the interaction between postural control and cognitive activity may be due to more general factors. Thus, the question of whether postural control and cognition interact at a general level or share specific mechanisms and processes at present remains unclear. Regardless of the issue of general versus specific cognitive influences on postural control, the results of this study are inconsistent with traditional assumptions about the functional separation between sensory-motor and cognitive functions. The present results, along with other demonstrations of interactions between postural control and cognition (see review by Woollacott & Shumway-Cook, 2002), are not easily accounted for by current theoretical models of postural control or of the cognitive system(s). The results are instead consistent with an emerging view that postural control reflects the task-specific organization of neuromotor and cognitive elements.

Effects of cognitive process on postural sway

The results showed a general tendency for postural sway to decrease during the rehearsal of cognitive information (as predicted) and to increase during the encoding of cognitive information. The rehearsal results are consistent with previous studies (e.g., Riley et al., 2003; Riley et al., in press). The observed increase in sway variability for encoding is inconsistent with the results of those studies, and was not predicted, but is consistent with previous findings on the effects on postural sway of WM task performance. Maylor and Wing's (1996) study compared postural sway variability during the performance of different WM tasks. The authors found significantly more sway variability for the encoding versus the retrieval of information during the performance of Brook's spatial task, and significantly less sway variability during encoding for the same task compared to no-task condition. Nevertheless, the opposite pattern of results has also been reported. Swan et al. (2004) found that older (but not younger) adults exhibit a decrease in sway variability under difficult posture conditions during the encoding of Brook's (1967) spatial and non-spatial tasks relative to no-task condition (there was no difference between the spatial and non-spatial versions of the Brooks' task). An important difference between those studies and the current experiment is that in the current experiment the information was presented visually and not auditorily. The modality of information presentation imposes distinct sensory demands, which might explain at least partially the differences in results (cf. Riley et al., in press).

The DFA results suggest a difference in the composition and organization of postural synergies between no-task and cognitive task conditions during encoding. DFA slope values (i.e., fractal scaling exponents relating variability to the size of the time window over which variability was measured) close to 1.5 indicate the presence of brown noise or fractional Brownian motion in postural sway (cf. Collins & De Luca, 1993, 1994, 1995; Riley, Mitra, Balasubramaniam, & Turvey, 1998). Slope values were slightly lower during the performance of both verbal and visual cognitive tasks (relative to the no-task control condition) during the encoding phase, indicating a tendency for postural sway to show a less deterministic (i.e., more random) pattern during secondary task performance. That result confirms previous findings observed using recurrence quantification analysis to analyze postural sway during rehearsal performance (Riley et al., in press). The change in the temporal structure of postural sway revealed by DFA can be interpreted as a reorganization of the underlying postural control processes, which could be due to a structural change in the postural control system—a reorganization of the postural synergy (Riley & Turvey, 2002; cf. Newell & Slifkin, 1998; Riccio, 1993).

The DFA results additionally suggest that the organization of the postural synergy is not affected by whether the cognitive task is verbal or visual, or by the experience of interference during rehearsal. Since DFA effects were observed during encoding but not rehearsal, it could be argued that type of cognitive process does have an effect on the organization of the postural synergy. Consistent with that argument, analyses that directly compared the scaling exponents from the encoding and rehearsal phases failed to reveal a difference in the temporal structure of postural sway across experiment phases. The conclusion that only general features of cognitive performance affect the organization of the postural synergy must be qualified, however, since the absence of significant differences in DFA results for rehearsal could be due to a lack of sensitivity of the analysis to important properties of the time-series profile. Other analysis techniques (such as RQA, and analyses of the time-to-contact of the COP with the stability boundary) might capture more subtle changes (for instance, nonlinear autocorrelations, determinism, complexity and non-stationarity) in the spatiotemporal profile of postural sway.

Effects of verbal and visual cognitive tasks on postural sway variability

The encoding and rehearsal results suggest that the effects on postural sway variability are not specific to the type of cognitive task presented (verbal vs. visual). In principle, this finding could be taken in support of the capacity limitation hypothesis, i.e., postural sway is affected by the amount of cognitive load imposed by secondary task performance and not by the characteristics of the task (see Dault et al., 2001a). However, when comparing encoding and rehearsal the interaction between cognitive process and cognitive task suggests that postural sway might be sensitive to the characteristics of the cognitive task performed. For encoding, the difference between cognitive-task conditions and the no-task control condition was greater for the verbal than the visual task, whereas for rehearsal (considering only the no-interference trials) the difference was greater for the visual than for the verbal task. These results are generally not consistent with the findings of Maylor et al. (2001), who reported greater postural sway variability during encoding of visual information than during retrieval of verbal information during performance of Brooks' spatial memory task (however, since Maylor et al. compared encoding to retrieval, and the present study compared encoding to rehearsal, it is difficult to draw direct comparisons between the studies). They interpreted their results as indicating that the neural structures involved in the encoding of visual information and in processing visual (or visuo-spatial) information for postural control might interact.

Despite the appearance of a specific postural response to the particular demands of the cognitive task, some of the present findings may be explainable in light of a capacity limitation hypothesis. A difference in the encoding demands placed on the WM system by the two cognitive tasks might explain this pattern of results. A pilot study conducted to determine the preferred amount of time necessary for the encoding of the visual and the verbal materials indicated that participants required significantly less encoding time for the verbal compared to the visual task. The existence of differences in preferred encoding times between the verbal and the visual tasks suggests that the verbal encoding task was easier than the visual encoding task. The pattern of errors in cognitive performance (participants made almost twice as many errors for the visual than the verbal task) supports the hypothesis that the visual task was more cognitively demanding overall than the verbal task, despite efforts to tailor task difficulty to each participant's verbal and visual WM spans. These considerations suggest that the apparent specificity of postural responses to cognitive task and cognitive process might instead have been due to a difference in the difficulty of the cognitive tasks.

Effects of interference on cognitive performance and postural sway variability

The pattern of cognitive errors suggests that the interference manipulations successfully targeted the intended WM sub-components. However, the absence of interactions between cognitive task and type of interference for the postural sway measures lends additional support to the possibility that postural sway may not be sensitive to the characteristics of the cognitive task performed. There was a decrement in postural sway variability for verbal interference trials as compared to no-interference trials, but not for visual interference trials. Overall the inference results do not support the hypothesis that postural responses would be specific to the type of cognitive performance.

Instead of interacting with modality-specific WM subsystems the postural control system might be interacting with the CE. The CE has the role of distributing attentional resources between the WM sub-components. According to attentional explanations the results of this project may indicate that the postural control system interacts in general with the cognitive system, and particularly with cognitive structures involved in the distribution of attentional resources. However, any model predicated on limited attentional resources (or limited processing capacity) cannot account for the rehearsal phase data, since postural sway variability decreased (i.e., postural stability increased) under dual-task conditions.

Implications for the understanding of postural control

Competing explanations of the interaction between the postural control system and the cognitive system have been proposed. One class of explanations (Dault et al, 2001; Woollacott & Shumway-Cook, 2002) conceives of the system in charge of postural control as a cognitively insulated system that automatically functions to minimize postural sway in response to changing external demands. Decrements in postural sway variability are thus taken as evidence for enhanced postural control, and increments as signaling impoverished postural control. According to this view, interactions between postural control and cognitive performance are due to some sort of functional interaction between the postural control and cognitive systems. For instance, changes in postural sway variability are often explained as the result of a redistribution of limited attentional resources that are required by both postural control and cognitive performance, but not as changes in the internal functions and/or structural make-up of the postural control system. However, the details of the hypothetical interaction between postural control and the cognitive system, and what that interaction means for our understanding of the workings of the postural control system, remain largely undefined from within this framework. Moreover, since this approach assumes that attentional resources are required for the successful control of posture and that adding a secondary cognitive task draws those necessary resources away, this approach cannot account for apparent improvements in postural performance (i.e., reduced sway variability) during dual-task conditions.

Alternative models that emphasize the facilitatory and adaptive role of the postural control system (e.g., Riccio, 1993; Riccio & Stoffregen, 1988; Riley et al., in press; Riley & Turvey, 2002; Riley, 2005) propose that constraints arising biomechanical, environmental, and task-related factors will dictate the functional and structural make-up of the postural control system. According to this view, the postural control system is only as permanent as that set of constraints. In other words, as the constraints vary, so does the underlying organization of postural control—the postural control system is conceived as a "softly-assembled", task-specific organization of neuromotor degrees of freedom into a low-dimensional control structure (see also Kugler & Turvey, 1987; Turvey, 1990). This approach additionally proposes that changes in the underlying organization of postural control will be reflected in time-dependent patterns of postural sway, since the organization of the underlying control system determines the range of observable behavioral dynamics that the system is capable of exhibiting (cf. Saltzman & Munhall, 1989). This approach thus predicts that sensitivity of postural control to specific task demands will be evidenced by a change in the temporal profile of postural sway time series. In principle the approach can account for either increases or decreases in postural sway variability, since they claim that the goal of postural control is not necessarily to minimize postural sway, but rather that "the moving segments will be coordinated or structured to the continuously changing demands of the task" (Bertenthal, in press, p. 10). Postural control adjustments to meet task demands involve a change in the postural synergy, which in turn may lead to either increments or decrements in postural sway variability.

The DFA results provide some support for this approach. The temporal structure of postural sway changed during the encoding phase when performing a cognitive task compared to the no-task control condition. The results of Riley et al. (in press) are also consistent with the notion of task-specific assembly of postural synergies. Riley el al. also observed changes in the temporal structure of postural sway during cognitive performance compared to a no-task control condition. This approach has been applied mainly to the study of changes in postural synergies during the performance of supra-postural tasks, which usually involve overt, goal-directed movements that have to be coordinated with postural control. In those cases, it is more straightforward to clearly identify the mutual influence of postural and supra-postural tasks, which is required in order to make a priori predictions about the organization of postural control in light of supra-postural task constraints. A major challenge for future research on the relation between cognition and postural control will be to formulate the relation between postural control and cognition in such ways that specific predictions about the organization of postural synergies (and, hence, the temporal dynamics of postural sway) can be formulated.

Conclusions

It is well-established that cognitive activity affects the maintenance of upright stance. The nature of the interaction between postural control and cognition is unclear, however. This research provided some indications that postural control is sensitive to the specific characteristics of the cognitive task, but does not rule out the possibility of a more general interaction between postural control and cognitive activity. Additional research is clearly needed to address that issue. The present study suggests that the effects of cognitive activity on postural control, whether due to general or specific interactions between the two systems, may be explained by a change in the postural synergy during dual-task performance.

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