Journal of Motor Behavior, 2007, Vol. 39, No. 2, 126–138

Postural Stabilization of Perceptual But Not Cognitive Performance

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ABSTRACT. In 2 experiments, the authors independently varied the degree of cognitive and perceptual difficulty of suprapostural tasks. Participants were 23 students in Experiment 1 and 15 in Experiment 2. Increases in perceptual difficulty tended to be correlated with decreases in the variability of postural sway, consistent with the hypothesized functional integration of postural control with suprapostural tasks. Sway variability was not influenced by changes in the cognitive difficulty of tasks when perceptual difficulty was held constant, contrary to predictions derived from the perspective that postural and suprapostural activities compete for a limited pool of central processing resources. The results underscore the need for researchers to differentiate between suprapostural tasks that require perceptual contact with the environment and those that do not.

Key words: perception, posture, stance, visual performance

Stance is maintained not for its own sake but for the sake of other behaviors that are afforded during stance. Stance typically co-occurs with other, nonpostural activities, such as reading and walking. To avoid falling, an individual must maintain the center of mass over the base of support (the feet, in stance). That criterion differs qualitatively from the performance criteria for most nonpostural tasks (e.g., reading rate or comprehension, walking speed). What is the relationship between those simultaneous activities? Are they independent entities carried out by separate systems? Or, can they be controlled in a unified manner, that is, integrated so as to optimize overall performance?

Competition for Central Resources?

One view is that postural control and simultaneous suprapostural activities compete for a limited-capacity pool of central processing resources (for a review, see Woollacott & Shumway-Cook, 2002). Several investigators (e.g., Lajoie, Teasdale, Bard, & Fleury, 1993, 1996; Marsh & Geel, 2000; Maylor, Allison, & Wing, 2001; Maylor & Wing, 1996; Teasdale, Bard, LaRue, & Fleury, 1993) have suggested that control of stance and control of locomotion require some level of higher cognitive processing, despite their highly practiced nature. In this work, researchers focused on the possibility that cognitive demand is inherent in postural control. Cognitive demand stemming from postural control has been assumed to conflict with cognitive demand associated with other tasks.

In studies pursuing that interpretation, investigators have tended to use the dual-task paradigm (Abernethy, 1988), treating posture as one task and some nonpostural activity as another, separate task. For example, Lajoie et al. (1993, 1996) treated postural control as the primary task and auditory reaction time (i.e., spoken responses to an auditory tone) as the secondary task. Marsh and Geel (2000) also adopted the dual-task method, arguing that posture is the primary task and verbal or acoustic reaction time is the secondary task. Woollacott and Shumway-Cook (2002) reviewed numerous other examples.

Anomalous Findings

In several cases, investigators who attempted to demonstrate competition of postural control for central resources obtained results that were inconsistent with their hypotheses. In many instances, they dismissed the inconsistent findings as resulting from artifacts or poor design. Experimenters have generally not considered the possibility that the results may undermine the validity of their theoretical view of relations between postural control and cognition.

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Marsh and Geel (2000) argued that a more difficult postural task would demand greater central processing resources, and they predicted a consequent decrement in otherwise unrelated suprapostural task performance. Older (mean age = 72 years) and younger (mean age = 26 years) women executed a verbal reaction time task while standing on the floor or on a nonrigid surface. They listened for a tone presented through an earphone as they stood on a foam or hard surface and with their eyes either open or closed. Verbal reaction time was recorded as the time needed to vocalize the word *ha* after hearing a tone in the earphone. Contrary to the authors' predictions, the variation in support surface (i.e., presumptive variation in the difficulty of postural control) did not affect performance on the verbal reaction time task.

Hunter and Hoffman (2001) asked participants to add a series of 10 numbers that were presented sequentially. The numbers either were projected into circles (moving or stationary) presented on a screen or were heard through speakers. When the numbers were presented acoustically, they were synchronized to blank visual targets. Hunter and Hoffman predicted significant postural sway differences between the auditory and the visual presentations of the adding task. That prediction was not confirmed: There was no effect of presentation modality on postural sway. They also predicted that the adding task would cause increased postural sway compared with that during stationary fixation without the adding task. That prediction also was not confirmed. In fact, the opposite occurred: Sway was significantly reduced in conditions involving the adding task.

Dault, Geurts, Mulder, and Duysens (2001), Maki and McIlroy (1996), Maylor and Wing (1996), and Yardley, Gardner, Leadbetter, and Lavie (1999) reported similar findings. In those studies, the authors predicted that postural motion would increase during performance of a cognitive task. In each case, that prediction was not confirmed in one or more conditions, and in some cases the prediction was directly violated, that is, sway during an explicit suprapostural task was significantly reduced compared with that without an explicit suprapostural task. In most cases, the authors interpreted the absence of confirmation or the violation of their predictions in terms of design weaknesses (such as cognitive tasks that were not sufficiently demanding) or artifacts. The unexpected results obtained in those studies may have resulted from specific artifacts. However, the fact that similar results have occurred repeatedly in different studies in which different tasks and methods were used in different laboratories makes it unlikely that each result was caused by a separate artifact. Consistent with that view, Woollacott and Shumway-Cook (2002, p. 4) concluded that effects of competition between postural and suprapostural activities for central processing resources "appear to be small." An alternative interpretation of the repeated anomalies is that, in at least some cases, there may be functional integration between postural control and simultaneous suprapostural tasks. Such a position was hinted at by Maylor et al. (2001, p. 336) and by Hunter and Hoffman (2001, p. 46), who suggested, "a secondary task may, in effect, constrain the amount of acceptable postural sway." Those suggestions are consistent with our view of relations between postural control and the performance of suprapostural tasks, which we discuss next.

Functional Integration

Competition between postural and nonpostural activities for a limited pool of central cognitive resources is not the only possible interpretation of relations between postural and nonpostural activity. A very different view has been developed from the ecological approach to perception and action (Gibson, 1979/1986; McGinnis & Newell, 1984; Riccio & Stoffregen, 1988). In that alternative view, no assumptions are made concerning the capacity of mentation; instead, advocates of that view concentrate on how perception and action are organized so that animals achieve their behavioral goals. We do not assume that the control of stance is a task distinct from suprapostural performance or that the control of posture is primary to suprapostural performance. We do not assume that suprapostural and postural control impose competing demands on some central resource. Rather, we make an a priori argument that stance can be modulated in ways that facilitate the performance of some suprapostural tasks. In the case of tasks that involve deliberate movement, the functional integration of postural and suprapostural performances is well documented (e.g., Bardy, 2003; Gurfinkel, Kots, Paltsev, & Feldman, 1971; Slijper & Latash, 2000). However, postural control can also be integrated with suprapostural activities that involve little or no deliberate movement. The functional integration of stance with suprapostural activity extends to suprapostural activities that do not involve deliberate movement of the head, limbs, or body, such as looking (Stoffregen, Bardy, Bonnet, Hove, & Oullier, in press; Stoffregen, Bardy, Bonnet, & Pagulayan, 2006; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999).

We do not claim that posture is always and only subservient to suprapostural demand. Rather, they are integrated on the basis of the demands made by each task. (a) Maintenance of upright stance can be sacrificed entirely (e.g., when an outfielder falls down in attempting to catch a fly ball). (b) Conversely, suprapostural performance can be sacrificed to the maintenance of stance (e.g., if you are bumped while reading, then you are likely to stop reading until balance is restored). In our research, we have focused on the former, more controversial situation.

Cognitive Versus Perceptual Tasks

We base our interpretation of the existing literature relating postural control to the performance of suprapostural tasks on the distinction between cognition and perception. For us, the distinction between cognition and perception is simple: In some tasks, performance depends on the maintenance of some type of perceptual contact with the environment: That perceptual contact is achieved and maintained through active adjustments of perceptual systems (e.g., eye and head movements that are used to optimize vision). In this article, we refer to those as *perceptual tasks*. In other suprapostural tasks, performance does not depend on such contact; we refer to those as *cognitive tasks*. From our perspective, reading is an example of a perceptual task because reading is successful only when the reader is able to control gaze so as to see the text clearly. A memory rehearsal task (e.g., mentally rehearsing a set of words or numbers) would be an example of a cognitive task because the performance of such tasks does not depend on the precision with which gaze is controlled.

Stoffregen et al. (2000) compared sway during different suprapostural tasks. In the inspection task, participants were asked to keep their gaze on a sheet of blank paper. In the search task, participants searched a block of text for target letters. The variability of sway was significantly reduced during the search task compared with that during the inspection task. The search and inspection tasks differed in several ways. The search task presumably required greater cognitive effort than did the inspection task because performers had to read letters, shift their attention between letters, and compare letters with internal information about the target letter. However, the two tasks also differed in terms of perceptual-motor demand. The inspection task made modest demands on control of the visual system. Because there was no fixation point, gaze could be moving or stationary and could wander over a large area (the entire sheet of paper). In that task, body sway would tend to have little negative effect on visual performance. The search task required a sequence of fixations (in reading individual letters) and eye movements (in shifting gaze between letters). The maintenance of visual contact with the text could be negatively affected by body sway. To be sure, most activities involve both perceptual-motor and cognitive demands, and it can be difficult to distinguish between those in an a priori manner. In this article, we make no strong claims about whether perception and cognition are fundamentally distinct. Our distinction is simply between tasks that depend on perceptual contact with the environment (i.e., tasks whose performance requires active adjustments of perceptual systems relative to aspects of the environment) and those that do not.[1] We take it for granted that the control of posture depends on perceptual contact with the environment: To be controlled, postural motion must be detected.

Here, we contrast two possibilities. First, changes in posture may be keyed to differences in cognitive demand between suprapostural tasks. Second, postural changes may be keyed to differences between tasks in oculomotor demand. The former would not have any obvious functional benefit as long as sway was not so great as to threaten a fall. The latter would have a clear functional value in terms of the optimization of visual performance. We attempted to (a) vary nonperceptual cognitive demand while maintaining a fixed level of oculomotor demand and (b) vary oculomotor demand while maintaining a fixed level of cognitive demand. We predicted that postural motion would be influenced by variations in oculomotor demand when cognitive demand was held constant. We further predicted that variations in postural motion would be independent of variations in cognitive demand when oculomotor demand was held constant.

Independent Measurement of Mental Effort

In research implicating the role of cognition in postural control, participants have performed a variety of cognitive tasks. They often perform different kinds of cognitive tasks (e.g., random digit generation or backward digit recall) that are presumed to require different amounts of processing or processing from different areas in the brain. For instance, Maylor et al. (2001) and Maylor and Wing (1996) used several different cognitive tasks that were believed to involve different components of working memory. Maylor et al. assumed that those tasks were of equal cognitive difficulty, but they provided no evidence in support of that assumption. The data on task performance are not sufficient to enable one to determine the relative difficulty level of tasks because task performance is influenced by properties of the participants (e.g., how hard they try on each task) as well as by the inherent level of task difficulty. In addition, performance may be affected by the difficulty of the postural control task (e. g., standing on a nonrigid surface). Measures of task performance should therefore be accompanied by separate, independent measures of effort. That consideration is important when one makes predictions concerning the relation between cognitive task performance and body sway. For example, Maylor et al. used two cognitive tasks that they judged, a priori, to be equally difficult, but the data revealed significant differences in the level of performance of the tasks. Maylor et al. did not use an independent measure of mental or cognitive effort, and so it is not possible, on the basis of their data, to determine whether the tasks that they used actually were equally difficult. The problem is not unique to the study of Maylor et al. (for additional examples, see Woollacott & Shumway-Cook, 2002). In the present study, we addressed that issue by taking measurements of mental workload (using validated rating scales) that were independent of both task performance and body sway. Those measurements permitted us to assess postural performance (a) during cognitive tasks that were equal in terms of mental workload and (b) during tasks that differed in that respect.

EXPERIMENT 1

In separate conditions, participants executed two suprapostural tasks, one in which performance depended on precise scrutiny of visual stimuli and one in which it did not. We hypothesized that body sway would be reduced during performance of the visually demanding task but not during the task for which precise control of the oculomotor system was not needed. The visually demanding task was to detect subtle, critical signals in a visual display. The task with low visual demand was mental arithmetic (sequential subtraction by 3).

We hypothesized that in Experiment 1, variability of postural sway would be reduced during visual signal detection compared with that during mental arithmetic. We expected on the basis of a pilot study (which we discuss later) that the mental-arithmetic and signal-detection tasks would have equivalent levels of subjective mental workload.

Our hypotheses (and, consequently, our analyses) are related to the variability of postural motion. In part, we chose that measure so that we could compare the current study with our previous studies relating postural control to suprapostural tasks in which we focused on positional variability as a general index of the amount of postural motion. We focused on postural kinematics (i.e., body motion) rather than on kinetics (e.g., forces applied to the surface of support) or on muscle activity (e.g., electromyography) because, of those three types of data, only kinematics has a direct influence on the stability of the visual system relative to the environment (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Riccio & Stoffregen, 1988).

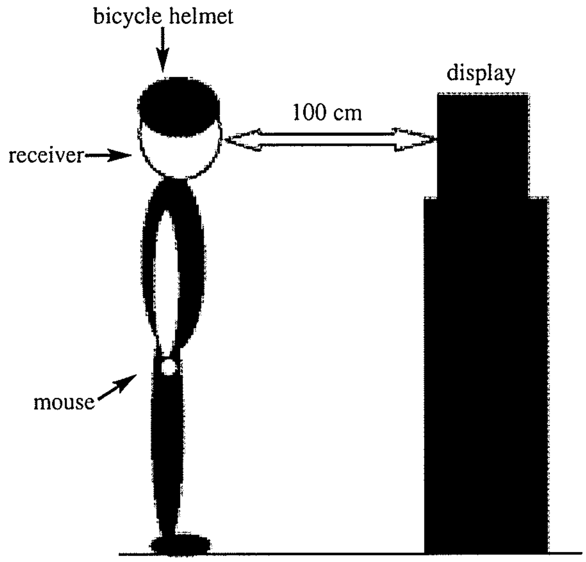

FIGURE 1. Experimental setup, Experiment 1.

Method

Participants

Twenty-three undergraduate students from the University of Cincinnati received course credit for participating. Nine participated in a pilot study and 14 in the main experiment. We screened participants for any history of disease or malfunction of the vestibular system, postural instability, recurrent dizziness, or falls. Participants had either normal or corrected-to-normal vision (glasses or contacts). Participants in the main experiment (7 men and 7 women) ranged in age from 18 to 25 years and in height from 157 to 183 cm. The University of Minnesota Institutional Review Board approved our experimental protocol, and our human experimental procedures were consistent with the Declaration of Helsinki.

Apparatus

We recorded postural motion by using a 6-degrees-of-freedom Flock of Birds magnetic tracking system (Ascension Technologies, Inc., Burlington, VT) that sampled at 25 Hz. We stored the position data on a computer for later analysis. To record body position, we taped a sensor between the participants' shoulder blades at approximately the level of the seventh cervical vertebra. Participants wore a bicycle helmet to protect their head in case of a fall.

Signal-detection display. We presented experimental displays by using a 17-in. Apple Studio display monitor driven by a Macintosh G3. The laboratory setup is depicted in Figure 1. The displays for the signal-detection task were pairs of vertical lines presented on the computer monitor (Figure 2). Each pair consisted of two lines separated horizontally by 1.55° of visual angle. One pair constituted the *neutral event*, and the other pair constituted the *critical signal.* The neutral events consisted of lines that were equal in height (1.95° of vertical visual angle). In critical signals, the lines differed in height; the left line had a vertical extent of 1.95°, and the right line had a vertical extent of 2.12° (Figure 2). We generated the signal-detection targets and sequencing by using PsyScope, a standard experimental control application (Cohen, MacWhinney, Flatt, & Provost, 1993). We also used PsyScope to collect data on suprapostural task performance.

Luminance of the display background was 108.44 cd/m^2. The luminance of the target color was 77.44 cd/m^2, resulting in a contrast ratio of approximately 1:1. Because of the small size (thickness) of the target lines, the actual luminance of the targets was 104.84 cd/m^2. We determined luminance with an LS-100 luminance meter (Minolta Camera Co., Osaka, Japan).

Assessment of subjective mental workload. To investigate the relationship between postural sway and suprapostural tasks, we had to equate the level of difficulty of the suprapostural tasks. We used mental workload for that purpose. *Mental workload* refers to the amount of mental work or effort used to perform a task (Proctor, 1994). There is no universally accepted definition of mental workload (Nygren, 1991), and for that reason there are numerous rating scales available that are purported to measure different aspects of workload. Hart and Staveland (1988) have taken a human-centered approach to defining workload; it is a construct that represents the costs incurred by the human operator as a consequence of achieving a given level of performance. Factors both internal (e.g., feeling rushed) and external (e.g., environmental conditions) to the operator contribute to the subjective experience of workload. We adopted Hart and Staveland's definition of workload, as well as their measurement instrument for assessing it.

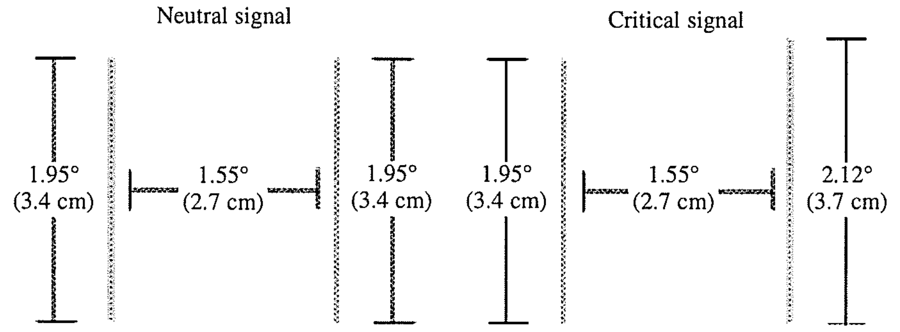

FIGURE 2. Signal detection targets used in Experiment 1.

We used the National Aeronautics and Space Administration Task Load Index (NASA-TLX; Hart & Staveland, 1988) to assess subjective mental workload. The NASA-TLX is a widely used instrument, and it provides a reliable index of overall workload (Warm, Dember, & Hancock, 1996). It is a multidimensional rating procedure that yields an overall workload score based on a weighted average of six subscales. The subscales Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration contribute differentially to an Overall Workload score depending on the nature of the task being rated.

Participants read an instruction sheet that described the two parts of the evaluation, the rating scale, and the sources-of-workload evaluation. The rating scale consisted of six questions related to each of the six subscales. The participants were to assign a value between 0 and 100 (in increments of 5) that corresponded to their assessment of how each subscale contributed to their mental workload. The rating scales had bipolar descriptors representing either extreme of the continuum (*high/low*, *good/poor*). As part of the instructions, participants made reference to a sheet of paper containing the definition of each subscale term.

The sources-of-workload evaluation is a weighting procedure that enables one to assess each subscale's relative contribution to the rater's subjective experiences of overall mental workload. We presented two subscale titles (e.g., Effort vs. Mental Demand) together and asked the participants to indicate which of the two factors contributed more to mental workload. There were a total of 15 paired comparisons representing all possible combinations of subscales.

The weighted subscales were designed so that they can contribute to an understanding of how the rated workload for a particular task breaks down into its component measures (Hart & Staveland, 1988). However, our goal was not to identify how performance varied with regard to particular subscale loading characteristics, and we made no predictions regarding subscale differences between conditions. For that reason, the primary variable of interest was a global measure of workload. Nygren (1991) cautioned that differences in the weighted subscale scores may not be entirely diagnostic because of psychometric limitations of the weighting process. Hart and Staveland argued, however, that the weighted combination of factors provides a sensitive indicator of overall workload between different tasks. For those reasons, we used only the Overall Workload rating to represent subjective workload for each of the tasks.

To assess the subjective workload associated with the signal-detection and mental-arithmetic tasks, we conducted a pilot study. Nine participants executed the signal-detection and mental-subtraction tasks while standing; each participant completed three trials with each task. Across those participants, the mean Overall Workload scores were 55.8 for the signal-detection task and 67.4 for the mental-subtraction task. The mean workload scores did not differ significantly, $t(8) = -1.214$, $p > .05$. We took that finding as evidence that the suprapostural tasks were appropriately matched in terms of task difficulty (i.e., mental workload).

Procedure

We instructed participants to stand facing the computer monitor, with their toes on a line on the floor that was 100 cm from the monitor, and we asked them to keep their feet pressed tightly together. We told participants to maintain that foot position for the duration of each trial but that they were free to move around between trials. We adjusted display height (by tilting the monitor on its stand) so that the top of the screen was approximately level with the participant's eye height. Participants held a computer mouse for half of the trials, and we asked them to keep both arms by their sides. We informed them that stance should be relaxed and normal. To minimize the possibility of fatigue or other adverse side effects of prolonged stance (e.g., Smart, Pagulayan, & Stoffregen, 1998), we implemented a mandatory break midway through the procedure. During the break, participants sat in a chair for approximately 5 min.

Each participant performed six trials (three trials per condition), each of which lasted 60 s. Trials were blocked by condition, and the order of conditions was counterbalanced across participants. The two experimental conditions consisted of a visual signal-detection task and a mental-subtraction task.

For the signal-detection task, we presented participants with the stimuli described earlier (Figure 2). Each stimulus appeared for 200 ms, with 800 ms between stimuli. In each trial, we presented 20 critical signals and 40 neutral events, although participants were not aware of how many critical signals and neutral events to expect. For each trial, the experimental control software randomized the sequencing of neutral events and critical signals.

Participants held a computer mouse in their preferred hand while keeping both arms comfortably at their sides for the signal-detection task, and we told them to press the mouse button as quickly as possible after seeing each critical signal. The computer recorded the correct identification of critical signals (hits, i.e., button presses that occurred before the appearance of the next stimulus) and the number of false alarms (i.e., button presses more than 800 ms after the presentation of a critical signal). Participants did not receive feedback about their performance at any time.

We evaluated signal-detection performance in terms of signal-detection theory (Green & Swets, 1966). For each participant, we calculated d' (an index of perceptual sensitivity) by combining hits and false alarms across the trials in each condition. According to Craig (1984), tasks with d' values greater than 3.5 can be described as very easy, whereas tasks with d' values between 2.5 and 3.5 can be considered moderately easy. Values below 2.5 indicate moderate to very difficult tasks. The performance criterion for inclusion in the study was $d' < 3.0$. We replaced participants who did not meet that criterion to achieve the targeted sample size of 12.

The second condition consisted of a mental-arithmetic task. At the beginning of each trial, the experimenter stated a three-digit number that was randomly chosen from a set of three preselected numbers. Participants were asked sequentially to subtract 3 from that number and to state the result, and to do so iteratively at a steady quick pace for the duration of the trial. The starting number was different for each trial. While they performed the arithmetic task, we told them to keep their gaze on the computer monitor, which was turned off in that condition. A microphone placed beside the monitor recorded arithmetic performance on audiocassette for later analysis.

We administered the NASA-TLX to the participants after each condition block. The instrument was administered on a desktop computer that stored participants' responses for later analysis. We showed participants how the computer rating scale worked and asked them to let us know if they wanted clarification of the written instructions. Because the NASA-TLX was administered twice to each participant (after each block of trials per condition), we instructed the participants to answer the items pertaining only to the condition most recently completed.

Results

Signal-Detection Performance

Two participants did not meet the signal-detection criterion, so we did not include their data in the analyses. Therefore, we conducted data analysis on the remaining 12 participants. The mean value of d' across participants was 1.54 for the signal-detection task. Thus, for the sample used in this study, we considered that task moderately difficult (Craig, 1984).

Mental-Arithmetic Performance

We transcribed and evaluated the tape-recorded responses to the arithmetic task in terms of rate of response per minute as well as number of errors made. We operationalized an error as any deviation from the desired pattern of responding for the iterative subtraction task. We evaluated participants' performance on the mental-arithmetic task in terms of (a) the number of responses per 1-min trial (response rate) and (b) the percentage of correct responses per trial. We averaged each measure to provide mean values across trials. Across participants, the mean accuracy was 87%, with a mean response rate of 27 per trial.

Subjective Workload

We took the Overall Workload rating from the NASA-TLX as the measure of subjective mental workload for each condition. The mean Overall Workload scores for the detection and arithmetic conditions were 59.3 and 60.1, respectively. Those means did not differ, $t(11) = -0.114$, $p > .05$.

Postural Sway

The dependent variables were the standard deviation of torso position in the anteroposterior (AP) and mediolateral (ML) axes. We computed statistics on the mean, across participants, of those variables. The data are summarized in Figures 3 and 4. As predicted, the mean standard deviation of body position was reduced in the signal-detection condition compared with that in the arithmetic condition. Sway variability was significantly lower in the AP axis, $t(11) = 1.988$, $p < .05$. We estimated effect size by using Cohen's *d*. Cohen (1977) suggested that values around .20 can be considered small, values around .50 can be considered medium, and values above .80 can be considered large. The effect size for the mean AP standard deviation was $d = .71$, indicating an effect of medium size. In the ML axis, there was no task effect on sway, $t(11) = 0.913$, $p > .05$.

Discussion

In Experiment 1, standing participants performed two suprapostural tasks: visual signal detection and mental arithmetic. We predicted that the variability of body sway would be reduced during signal detection compared with that during mental arithmetic. That prediction was confirmed despite the fact that the two tasks did not differ in subjective mental workload. We conclude that the condition effect was related not to the cognitive difficulty of the suprapostural tasks but, rather, to the fact that the signal-detection task required perceptual contact with the environment (i.e., with the visible targets); whereas the mental-arithmetic task did not. By our chosen criterion, performance in the signal-detection task was good. Thus, our effects cannot be interpreted in terms of the sacrifice of cognitive performance to the demands of postural control (e.g., Riley, Baker, & Schmit, 2003).

EXPERIMENT 2

In Experiment 1, we found variations in postural sway across conditions despite the fact that the subjective mental workload of the suprapostural tasks was constant across conditions. The suprapostural tasks differed in the level of oculomotor demand (one required more precise control of gaze than the other did) but did not differ in overall subjective mental workload. In Experiment 2, we sought the reverse effect. We varied the level of subjective mental workload across suprapostural tasks that did not differ in the level of oculomotor demand. Our hypothesis was that the variation in subjective mental workload would be independent of any variations in postural sway because there was no variation in oculomotor demand.

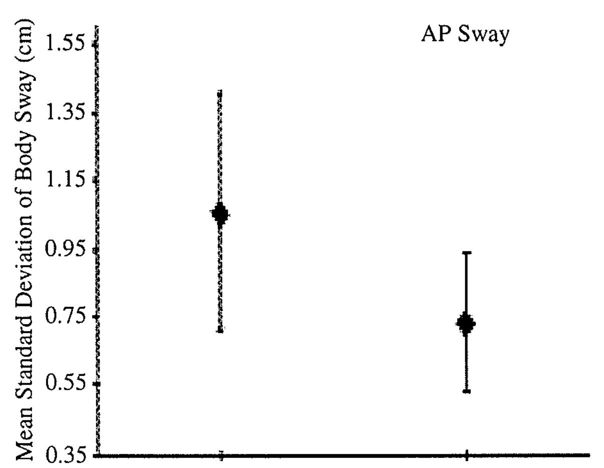

FIGURE 3. Mean standard deviation of body position in the anteroposterior (AP) axis as a function of task condition, Experiment 1. Error bars represent the 95% confidence interval.

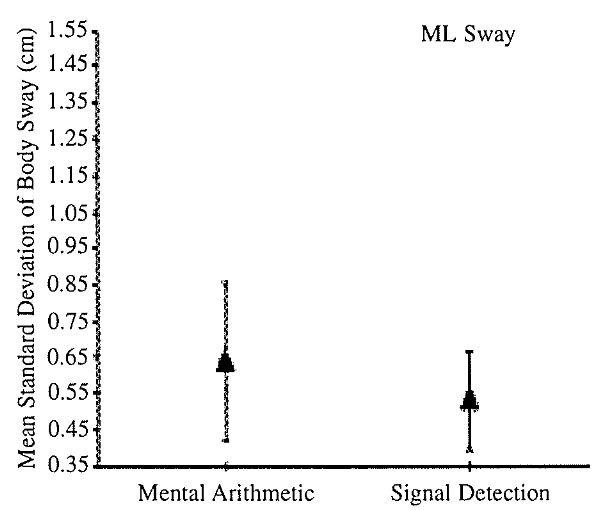

FIGURE 4. Mean standard deviation of body position in the mediolateral (ML) axis as a function of task condition, Experiment 1. Error bars represent the 95% confidence interval.

An additional motivation for Experiment 2 can be derived from the literature relating postural control to cognitive processing. On the basis of that literature, one might argue, the tasks in Experiment 1 were not appropriate for evaluation of the attentional resource hypothesis because the two suprapostural tasks placed different types of demands on central resources. The fact that rated subjective mental workload for the two tasks did not differ does not necessarily imply that the tasks drew on the same pool of processing resources. That is, the presumed central pool of resources may be dedicated (in whole or in part) to different sense modalities (e.g., visual resources or auditory resources) or to sensory and cognitive tasks. If that were true, then in Experiment 1 we may not have properly addressed theories of postural control that appeal to the concept of central cognitive resources. One can address that issue by using suprapostural tasks that necessarily draw on the same type of cognitive resources.

Mental-arithmetic tasks that vary only in the degree of difficulty should draw from the same pool of processing resources. As noted earlier, we predicted in our approach (e.g., Stoffregen et al., 2000; Stoffregen et al., 1999) that any variation in body sway across different mental-arithmetic tasks would be independent of differences in subjective mental workload between hard and easy mental arithmetic. A competing hypothesis is that harder arithmetic tasks draw more processing resources than do easier tasks. There would thus be a decrease in resources available to postural control, thus inducing greater sway variability.

In Experiment 2, participants executed easy and difficult mental-arithmetic tasks while standing. We predicted a difference in rated workload for the mental-arithmetic tasks that would be independent of any variation in body sway. In conjunction with the results of Experiment 1, confirmation of that prediction would provide support for the idea that postural sway is organized with reference to constraints imposed by perceptual-motor demands of suprapostural tasks, but not by nonperceptual cognitive demands.

Method

Participants

Fifteen undergraduate students from the University of Cincinnati (9 men, 6 women) received course credit for participating in Experiment 2. All participants were screened for any history of disease or malfunction of the vestibular system, postural instability, recurrent dizziness, or falls. Participants ranged in age from 18 to 27 years and in height from 152 to 191 cm. The University of Minnesota Institutional Review Board approved our experimental protocol, and our human experimental procedures were consistent with the Declaration of Helsinki.

Procedure

We presented the two experimental conditions, hard and easy mental arithmetic, in blocks of four trials. There were eight trials (four easy and four hard), each of 60-s duration. Eight participants had easy trials first, and 7 had hard trials first. The hard condition was the same one used in Experiment 1: Participants iteratively subtracted 3 from a three-digit number. In the easy task, the experimenter provided an even three-digit number, and participants were instructed to iteratively add 2. For both tasks, spoken responses were recorded on tape for later analysis. We administered the NASA-TLX after Trial 4 and again after Trial 8.

Participants were asked to look at a simple visual stimulus presented on the computer monitor. The stimulus consisted of a filled red circle (a dot) on a white background. The circle subtended approximately 1.15° of visual angle. The visual target appeared in the center of the display and remained there for the duration of the trial. In both conditions, we asked participants to maintain their gaze on the dot, but we did not stress that as an important goal and did not ask participants to treat the target as a fixation point.

Results

Subjective Mental Workload

The easy and hard tasks were rated as having Overall Workload scores of 38.6 and 61.4, respectively. The difference was significant, $t(14) = -4.080$, $p < .05$. The mean workload score for the hard task did not differ from the mean score for the mental-arithmetic task in Experiment 1 (60.1) between-participants *t* test, $t(23) = -0.298$, $p > .05$.

Mental-Arithmetic Performance

We evaluated participants' performance on the mental-arithmetic tasks in terms of (a) the percentage of correct responses per trial and (b) the response rate per trial. We averaged each measure to provide mean values across all trials. Across participants, the mean accuracy for the hard task was 91%, with a response rate of 28 responses/min (standard deviation = 6.2). For the easy task, the mean accuracy was 99% at 46 responses/min (standard deviation = 9.6). Across the two tasks, the means of both accuracy and response rate, $ts(14) = 1.941$ and 8.088, respectively, $ps < .05$, were significantly different, indicating that counting was more accurate and faster during the easy task. The performance measures were consistent with participants' judgments of the workload demands of the two tasks.

Postural Sway

Postural sway data are illustrated in Figures 5–6. Paired *t* tests indicated that there were no significant differences in sway between the easy and hard mental-arithmetic conditions in AP or in ML, $ts(14) = -0.512$ and 0.460, respectively, $ps > .05$.

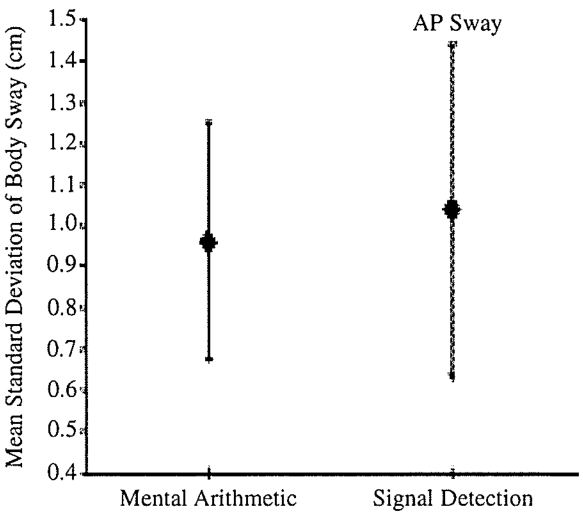

FIGURE 5. Mean variability of torso position in the anteroposterior (AP) axis as a function of task condition, Experiment 2. Error bars represent the 95% confidence interval.

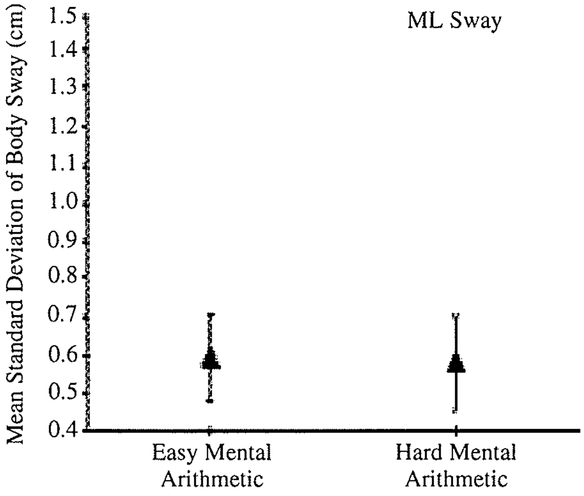

FIGURE 6. Mean variability of torso position in the mediolateral (ML) axis as a function of task condition, Experiment 2. Error bars represent the 95% confidence interval.

Discussion

The experimental manipulation for Experiment 2 consisted of easy and hard spoken arithmetic tasks. Overall Workload scores for the two conditions were significantly different. Counting forward by 2 was judged to be easier than counting backward by 3 and was performed more accurately. In addition, the rate of responding was reduced in the hard task compared with the rate in the easy task. Despite the differences in task difficulty and performance, there were no condition-related variations in body sway in either AP or ML axes.

The results from Experiment 2 provided support for the hypothesis that the motor system does not modulate postural sway to facilitate performance in a strictly cognitive task for which the performer does not benefit from maintaining a specific physical relation with the environment. The hard mental-arithmetic task was rated as being more difficult than the easy task. If postural control suffers (or becomes more variable) as one or more central pools of processing resources are taxed, then the hard task should have induced a greater degree of postural sway (a decrement in the quality of control) than the easy task did. The results of Experiment 2 did not support that hypothesis.

During performance of the hard task, the mental workload scores were higher despite the fact that there were significantly fewer spoken responses. Taken together, both facts confirm that the higher workload in the hard task was related to mental arithmetic per se and not to the organization and execution of the spoken responses. That result confirms that our attempt to manipulate the central processing load was successful.

GENERAL DISCUSSION

In two experiments, we independently varied the level of perceptual-motor and cognitive demands in suprapostural tasks. Our general prediction was that variations in perceptual-motor demand, but not variations in nonperceptual cognitive demand, would modulate postural sway. That prediction was supported by the data. Overall, our results appear to contradict predictions that may be derived from the idea that postural and suprapostural tasks compete for a limited central pool of cognitive resources. The view that the motor system adaptively modulates postural control to facilitate the performance of suprapostural activities that require stabilization of perceptual performance relative to the surroundings more easily accounts for our results.

Postural Facilitation of Perceptual Performance

Sway was reduced during difficult suprapostural tasks compared with that during easy ones (Experiment 1). Sway was influenced by variations in visual demand (Experiment 1) but not by nonperceptual variations in cognitive demand (Experiment 2). Finally, the sway effects were functional; that is, sway was reduced when reduction would facilitate visual performance.

Yardley et al. (1999) found that sway was influenced by speech articulation but was not influenced by purely cognitive variations (hard vs. easy numerical tasks). They suggested that the latter observation may necessitate a reinterpretation of the finding in a corpus of studies that sway increases during performance of a cognitively demanding suprapostural task, because in many of those studies the suprapostural task included a speech component. Yardley et al. did not question the assumption that postural control competes with suprapostural tasks for a limited pool of central processing resources. In essence, their reinterpretation was methodological rather than conceptual.

Our results also suggest a reinterpretation of the literature, but on a different basis and with a different outcome. In most previous studies, researchers have not distinguished between cognitive and perceptual-motor demands in suprapostural tasks. They have instead tended to focus on distinctions between different types of cognitive tasks, such as verbal versus spatial tasks (e.g., Ehrenfried, Guerraz, Thilo, Yardley, & Gresty, 2003; Woollacott & Shumway-Cook, 2002). Our results suggest that the distinction between cognitive and perceptual-motor demands may be important in understanding previous research and in designing future research. In particular, our results (as well as the theory of Riccio & Stoffregen, 1988; Stoffregen et al, 1999) suggest a reinterpretation of previous studies in which postural sway has been reduced during performance of a suprapostural task compared with that in the absence of any explicit suprapostural task.

Tasks that have been interpreted by researchers as imposing cognitive demand often include some component of perceptual-motor demand. A relatively simple example concerns tasks that include visual targets or stimuli. In those tasks, performance may be influenced by the ability to maintain a steady gaze (for stationary targets) or by the ability to execute precise shifts in gaze (Stoffregen et al., in press; Stoffregen et al., 2006). Another example concerns verbal tasks. In many verbal memory tasks, items to be remembered are presented auditorally. Researchers have tended to focus on the cognitive demand imposed by verbal tasks, but there is also perceptual-motor demand. Listening to speech includes auditory perception. The ability to maintain auditory contact with the environment may be influenced by postural motion, just as postural motion influences the ability to maintain visual contact with the environment. That point was made by Maylor et al. (2001, p. 336), who suggested that people may reduce sway during auditory tasks "to enhance perception." Hence, the reduction in sway during suprapostural tasks that require listening (e.g., Maylor et al.) may reflect what we would call *postural stabilization of listening*.

In future studies of relations between postural control and suprapostural activity, it will be useful to distinguish not only between different levels of cognitive demand but also between cognitive and perceptual-motor demands. The results of the present study (consistent with previous work; Stoffregen et al., in press; Stoffregen et al., 2006; Stoffregen et al., 2000; Stoffregen et al., 1999) suggest that changes in posture may have a functional relationship with variations in the perceptual-motor demand of suprapostural tasks. It will also be useful to evaluate the generality of the present findings across variations in other factors that are known to influence postural control, for example, variations in the dynamics of the support surface. Smart, Mobley, Otten, Smith, and Amin (2004) repeated the study of Stoffregen et al. (1999) and included variations in the extent and rigidity of the support surface. As expected, they found that sway variability was greater during stance on short and nonrigid surfaces. Despite those increases, they also found that the variability of postural sway was significantly reduced during fixation of nearby targets (compared with sway during fixation of more distant targets), as originally reported by Stoffregen et al. (1999). On the basis of those findings, we predict that the effects observed in Experiment 1 of the present study would also be robust to variations in the extent or rigidity of the support surface.

Our main hypothesis is that the perceptual-motor system can modulate posture adaptively to support the performance of suprapostural tasks that depend on perceptual contact with the environment. We believe that the functional integration of postural control with suprapostural performance is a common feature of daily life (cf. Campos et al., 2000). However, we do not claim that that particular type of integration is the only way in which suprapostural activity can influence postural control. One obvious area of influence is suprapostural tasks that include movements of the limbs such as are required in manual manipulation tasks. Such movements alter the position of the body's overall center of mass and, for that reason, typically mandate postural adjustments. The adjustments can be either compensatory or anticipatory (e.g., Gurfinkel et al., 1971; Slijper & Latash, 2000). Adjustments of that type clearly are functional because they act to stabilize overall body posture and also to facilitate manual performance.

Does Quiet Stance Exist?

Our results and our theoretical position have implications for the concept of quiet stance, as that term is used in research on postural control. It is assumed that in quiet stance the maintenance of upright stance is the sole activity in which the individual is engaged (e.g., Woollacott & Shumway-Cook, 2002). The maintenance of perceptual contact with the environment (e.g., looking, listening, touching) is pervasive, however. For example, clear vision of an environmental object is logically distinct from upright stance, and the adjustments required to maintain clear vision may differ from those required to maintain stance. Thus, true quiet stance may be so rare as to be unrepresentative of normal postural control. In many studies, quiet stance is operationally defined as a situation in which there is not an explicit task beyond maintaining stance. In our view, an implicit assumption in such operational definitions is that postural control is influenced only by suprapostural tasks that are explicit. By contrast, we regard that notion as a testable hypothesis. For a detailed discussion, see Stoffregen et al. (1999).

If quiet stance does not exist (that is, if there is always suprapostural activity), then there can be no baseline condition against which to compare stance during the performance of suprapostural tasks. Moreover, if quiet stance is so rare as to be unrepresentative of stance outside the laboratory, then there is little practical or theoretical value in comparing postural control during suprapostural activity with postural control during quiet stance. That explains why, in the present study, we did not attempt to compare sway during the experimental tasks with sway during a baseline condition in which there was no suprapostural activity: We believe that such a comparison is either impossible or meaningless.

Reduced Sway During Cognitive Tasks?

As just noted, we do not claim that the tasks involving perceptual contact with the environment are the only type of suprapostural tasks that will influence the control of stance. Our position is that perceptual performance provides a pervasive type of constraint on postural motion and that the influence of suprapostural perceptual-motor demand on posture is functional. That is, we claim that postural changes associated with the perceptual-motor demand of suprapostural tasks tend to facilitate the performance of those tasks. Researchers sometimes observed a reduction in postural motion during performance of suprapostural tasks that did not include any perceptual component. Riley et al. (2003) measured sway while participants mentally rehearsed digit strings of varying lengths. Sway data were collected only during mental rehearsal (i.e., not during the visual presentation of the digit strings), and participants rehearsed the task with their eyes closed, thus eliminating the need to stabilize the visual system relative to the surroundings. Riley et al. found that sway in the AP axis was reduced for the longest digit strings compared with that during stance with no rehearsal task. The generality of that study is limited by the facts that (a) participants eyes were closed during the rehearsal of digit strings and (b) participants stood on a nonrigid surface. Andersson, Hagman, Talianzadeh, Svedberg, and Larsen (2002) also observed an effect of a purely cognitive task on sway in a task in which participants standing on a force plate either did or did not count backward (silently). During counting, ML sway was reduced compared with that in the no-counting condition. However, eyes were closed in all conditions.

In the studies of Andersson et al. (2002) and Riley et al. (2003), participants' eyes were closed in all conditions. For that reason, the results bear an uncertain relationship to stance in general: People usually stand with their eyes open. That point was especially salient in a study by Swan, Otani, Loubert, Sheffert, and Dunbar (2004). They asked standing participants to perform the encoding phase of Brooks's (1967) spatial memory task. Older and younger adults were tested while they stood on a force platform that was stationary or was sway referenced. Significant decreases in sway (positional variability of the center of pressure) were observed during performance of the spatial and nonspatial versions of the Brooks task, but only for older adults and only when the eyes were closed and the platform was sway referenced. In all other conditions, sway during either version of the Brooks task did not differ from sway in the absence of an explicit suprapostural task. Contrasting effects were reported by Riley, Baker, Schmit, and Weaver (2005), who found a reduction in sway during performance of purely cognitive tasks (digit rehearsal) with eyes closed or open.

The studies of Andersson et al. (2002), Riley et al. (2003), Riley et al. (2005), and Swan et al. (2004) provide support for the hypothesis that postural motion may be reduced during performance of suprapostural tasks that do not depend on perceptual contact with the environment. Such an effect would not have clear functional significance (Riley et al., 2005), and therefore would not be predicted on the basis of the hypothesis that posture is functionally integrated with suprapostural activity so as to facilitate the performance of suprapostural tasks.

Mitra (2003, 2004) and Mitra and Frazier (2004) presented their adaptive resource-sharing model in an effort to account for the relationships among postural control, suprapostural task facilitation, and cognitive demand. A prediction of the adaptive resource-sharing model is that postural control can facilitate suprapostural perceptual tasks under relatively unchallenging balance conditions. If balance conditions become too challenging or if postural adjustments cannot facilitate the task, then, according to the model, suprapostural task facilitation may not occur. Another prediction in the model is that under some conditions, a hybrid sway pattern can occur, leading to performance tradeoffs between postural and suprapostural task performance. In the present study, participants stood on ordinary floors that were rigid, extensive, and inertially stationary. That is, the postural control tasks were not inherently challenging for our healthy adult participants. For that reason, the adaptive resource-sharing view does not appear to make predictions about our experiments that differ from our own.

Influence of Speech Articulation

The condition effect in Experiment 1 may have resulted from variation in oculomotor demand, as we hypothesized. However, it might also have resulted from the fact that in the mental-mathematics condition, participants spoke. Talking causes both jaw and head motion as well as an irregular pattern of breathing to accommodate speech. Thus, movements associated with talking could have contaminated motion of the torso-based sensor used to measure postural sway. That interference could have led to an artifactual increase in measured body sway. Talking may separately produce an actual increase in body sway. If either of those effects occurred, then measured sway would tend to be greater during the mental-arithmetic task, regardless of any other differences between it and the signal-detection task.

There is empirical support for the idea that body sway increases during speech. As noted earlier, Yardley et al. (1999) measured stance across variations in speech articulation. In the most direct comparison, participants stood while counting silently and while counting aloud. The total excursion (path length) of the center of pressure was significantly greater during spoken counting than during silent counting.

We did not deliberately address the role of speech articulation in the results of Experiment 1. The results of Experiment 2 are, however, directly relevant to that issue. In Experiment 2, there was a significant difference in the response rates for the hard and easy mental-arithmetic tasks. There was an average of 28 responses per trial in the hard task and an average of 46 in the easy task. The responses consisted of speech acts, and, consequently, there was significantly more speech in the easy condition than in the hard condition. Despite the variation in the quantity (and frequency) of speech, there were no condition effects on postural motion in either axis. We can conclude that variations in the quantity of speech articulation were not sufficient to influence measured body sway in the context of the present task. That conclusion is consistent with the results of Dault, Frank, and Allard (2001) and supports our argument that the significant effect of condition in Experiment 1 resulted from variations in oculomotor demand and not from the fact that participants spoke in only one condition.

Speech can influence measured sway, as Yardley et al. (1999) have shown. Our results suggest, however, that speech is not sufficient to influence sway. Overall, the ability of speech to influence sway is real, but it does not appear to be stronger than the influence of oculomotor demand. That distinction is important because speech has a biomechanical effect on the body that may mandate postural adjustments (cf. Gurfinkel et al., 1971), whereas variations in the oculomotor demand of suprapostural tasks do not.

Conclusion

Woollacott and Shumway-Cook (2002, p. 1) defined postural control as "the control of the body's position in space for the purposes of balance and orientation." Our research suggests that that definition may not fully capture the functional value of postural control. According to our theory, an important part of the purpose of postural control is to facilitate the performance of suprapostural tasks that make no biomechanical demands on the body's position or orientation. Our results indicate that postural control can be influenced by variations in oculomotor demand that are independent of variations in nonperceptual cognitive demand. In future research, it will be useful for researchers to distinguish between perceptual-motor demand and cognitive demand that is independent of perceptual-motor contact with the environment.

ACKNOWLEDGMENTS

Enactive Interfaces, a network of excellence (IST Contract No. 002114) of the Commission of the European Community and grants from the National Science Foundation (BCS-0236627 awarded to T. A. Stoffregen and CMS-0432992 awarded to M. Riley) supported preparation of this article. We are grateful to Joel Warm for instruction and consultation on the use of the NASA-TLX. We thank Gerry Matthews, whose comments inspired the study, and Valerie Neverman, who helped with data collection and analysis. Experiment 2 was conducted as part of Philip Hove's master's thesis. Portions of the data were reported at the XIth International Conference on Perception and Action, Storrs, CT, July 2001.

NOTES

1. The term *demand* has been closely associated with information processing, which is hypothesized to occur in the central nervous system. For example, demand typically is defined in terms of the use of hypothetical *central processing resources* (e.g., Abernethy, 1988). That association is so close that it may be difficult to recall that a task can be demanding in ways that may be independent of the use of central processing resources. For example, reading of text is more demanding than is looking at a blank target, in the sense that the former requires precise eye movements that are not required in the latter. With practice, many activities are believed to become automatic, that is, to have reduced demand on central processing resources. By contrast, the perceptual-motor demands of reading will always be greater than the demands involved in looking aimlessly at a blank target. The eye movements involved in reading may or may not draw on central processing resources, but if they are not sufficiently precise, then the ability to foveate the text and to minimize blur will be degraded, resulting in compromised reading.

REFERENCES

Abernethy, B. (1988). Dual-task methodology and motor skills research: Some applications and methodological constraints. *Journal of Human Movement Studies, 14,* 101–132.

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin, 58,* 135–139.

Bardy, B. G. (2003). Postural coordination dynamics in standing humans. In V. K. Jirsa & J. A. S. Kelso (Eds.), *Coordination dynamics: Issues and Trends* (Vol. 1, pp. 103–121). New York: Springer Verlag.

Bardy, B. G., Marin, L., Stoffregen, T. A., & Bootsma, R. J. (1999). Postural coordination modes considered as emergent phenomena. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1284–1301.

Brooks, L. R. (1967). The suppression of visualization by reading. *Quarterly Journal of Experimental Psychology: General, 125,* 289–299.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy, 1,* 149–219.

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences.* New York: Academic Press.

Cohen, J. D., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: A new graphic interactive environment for designing psychology experiments. *Behavioral Research Methods, Instruments, & Computers, 25,* 257–271.

Craig, A. (1984). Human engineering: The control of vigilance. In J. S. Warm (Ed.), *Sustained attention in human performance* (pp. 247–282). Chichester, NY: Wiley.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait & Posture, 14,* 110–116.

Dault, M. C., Geurts, A. C. H., Mulder, T. W., & Duysens, J. (2001). Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. *Gait & Posture, 14,* 248–255.

Ehrenfried, T., Guerraz, M., Thilo, K. V., Yardley, L., & Gresty, M. A. (2003). Posture and mental task performance when viewing a moving visual field. *Cognitive Brain Research, 17,* 140–153.

Gibson, J. J. (1986). *The ecological approach to visual perception.* Mahwah, NJ: Erlbaum. (Original work published 1979)

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics.* New York: Wiley.

Gurfinkel, V. S., Kots, Y. M., Paltsev, Y. I., & Feldman, A. G. (1971). The compensation of respiratory disturbances of the organization of interarticular interaction. In I. M. Gelfand, V. S. Gurfinkel, S. V. Fomin, & M. L. Tsetlin (Eds.), *Models of the structural-functional organization of certain biological systems* (pp. 382–395). Cambridge, MA: MIT Press.

Hart, S. G., & Staveland, L. (1988). Development of the NASA Task Load Index (TLX): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). Amsterdam: North-Holland.

Hunter, M. C., & Hoffman, M. A. (2001). Postural control: Visual and cognitive manipulations. *Gait & Posture, 13,* 41–48.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research, 97,* 139–144.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1996). Upright standing and gait: Are there changes in attentional requirements related to normal aging? *Experimental Aging Research, 22,* 185–198.

Maki, B. E., & McIlroy, W. E. (1996). Influence of arousal and attention on the control of postural sway. *Journal of Vestibular Research, 6,* 53–59.

Marsh, A. P., & Geel, S. E. (2000). The effect of age on the attentional demands of postural control. *Gait & Posture, 12,* 105–113.

Maylor, E. A., Allison, S., & Wing, A. M. (2001). Effects of spatial and nonspatial cognitive activity on postural control. *British Journal of Psychology, 92,* 319–338.

Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *Journal of Gerontology Series B: Psychological Sciences and Social Sciences, 51,* P143–P154.

McGinnis, P. M., & Newell, K. M. (1984). Topological dynamics: A framework for describing movement and its constraints. *Human Movement Science, 1,* 289–305.

Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science, 22,* 253–270.

Mitra, S. (2004). Adaptive utilization of optical variables during postural and suprapostural dual-task performance: Comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). *Journal of Experimental Psychology: Human Perception and Performance, 30,* 28–38.

Mitra, S., & Frazier, E. V. (2004). Effects of explicit sway-minimization on postural–suprapostural dual-task performance. *Human Movement Science, 23,* 1–20.

Nygren, T. E. (1991). Psychometric properties of subjective workload measurement techniques: Implications for their use in the assessment of perceived mental workload. *Human Factors, 33,* 17–33.

Proctor, R. W. (1994). Attention and the assessment of mental workload. In R. W. Proctor & T. Van Zandt (Eds.), *Human factors in simple and complex systems* (pp. 186–209). Boston: Allyn and Bacon.

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science, 7,* 265–300.

Riley, M. A., Baker, A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin, 62,* 191–195.

Riley, M. A., Baker, A. A., Schmit, J. M., & Weaver, E. (2005). Effects of visual and auditory short-term memory tasks on the spatiotemporal dynamics and variability of postural sway. *Journal of Motor Behavior, 37,* 311–324.

Slijper, H., & Latash, M. (2000). The effects of instability and additional hand support on anticipatory postural adjustments in leg, trunk, and arm muscles during standing. *Experimental Brain Research, 135,* 81–93.

Smart, L. J., Mobley, B. S., Otten, E. W., Smith, D. L., & Amin, M. R. (2004). Not just standing there: The use of postural coordination to aid visual tasks. *Human Movement Science, 22,* 769–780.

Smart, L. J., Pagulayan, R., & Stoffregen, T. A. (1998). Self-induced motion sickness in unperturbed stance. *Brain Research Bulletin, 47,* 449–457.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., Hove, P., & Oullier, O. (in press). Postural sway and the frequency of horizontal eye movements. *Motor Control.*

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., & Pagulayan, R. J. M. (2006). Postural stabilization of visually guided eye movements. *Ecological Psychology, 18,* 191–222.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science, 19,* 203–220.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception & Performance, 25,* 1641–1658.

Swan, L, Otani, H., Loubert, P. V., Sheffert, S. M., & Dunbar, G. L. (2004). Improving balance by performing a secondary cognitive task. *British Journal of Psychology, 95,* 31–40.

Teasdale, N., Bard, C., LaRue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research, 19,* 1–13.

Warm, J. S., Dember, W. N., & Hancock, P. A. (1996). Vigilance and workload in automated systems. In R. Parasuraman & M. Mouloula (Eds.), *Automation and human performance: Theory and applications* (pp. 183–200). Mahwah, NJ: Erlbaum.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait & Posture, 16,* 1–14.

Yardley, L., Gardner, M., Leadbetter, A., & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *NeuroReport, 10,* 1–5.

Submitted December 19, 2005
Revised March 9, 2006
Second revision June 29, 2006