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POSTURAL CONTROL SUPPORTS VISUAL PERCEPTUAL BUT NOT
COGNITIVE PERFORMANCE

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Abstract

The purpose of the present thesis was to investigate the relation between upright posture and perceptual performance. Some researchers have argued that the integration of multisensory perceptual stimulation, which is required for postural control, may draw on central processing capacity. From this perspective, performing cognitively demanding tasks should negatively influence postural control (i.e., induce higher levels of postural sway). This is because of competition for processing resources between the cognitive task and maintaining balance. An alternative theoretical view suggests that postural sway may be functionally related to performance on perceptual supra-postural tasks, independent of the effects of cognition. Three experiments were conducted in which the variability in postural sway was analyzed in the context of supra-postural goal variation. Experiment 1 focused on postural sway in response to performing a visually demanding signal detection task versus a mental arithmetic condition. The two tasks were equated in terms of overall subjective mental workload. Experiment 2 compared sway during performance of easy and hard mental arithmetic tasks. Experiment 3 controlled for a possible confound of vocalizing arithmetic responses in Experiment 1. There was significantly less sway when performing visual signal detection (relative to sway during mental arithmetic), but no significant differences in sway between the easy and hard arithmetic conditions. The results support the idea that postural sway is organized with reference to constraints imposed by the perceptual demands of supra-postural tasks, but not with reference to non-perceptual cognitive demand. Human factors design implications were discussed with respect to virtual reality and virtual environments.

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Postural control supports visual perceptual but not cognitive performance**Chapter I****Introduction**

The ability to achieve and maintain upright bipedal stance is an essential prerequisite for a wide range of behaviors that differentiate humans from most other animals. For example, upright, bipedal stance permits bipedal walking and running. Perhaps more important, upright stance frees the hands from the need to control body posture, permitting them to take on new roles in manipulation and exploration; some researchers have argued that the emergence of manual capabilities was a major driver in the evolution of human intelligence (Wilson, 1998). The extraordinary dexterity and utility of the hands is dependent upon the prior evolution of stable, upright, bipedal stance. However, the benefits of upright stance extend beyond the executive functions of the hand. In addition to freeing the hands, upright stance raises the sensory platform (the head) to its maximum height above the ground (aside from climbing trees, etc.). This extends the range and acuity of vision and hearing, and permits these senses to support more demanding perceptual tasks (e.g., Tobias, 1982). This relation between upright posture and perceptual performance is the subject of the present thesis.

Knowledge about the physical environment may be acquired through the senses and, as a direct consequence, may inform goal-oriented actions of an animal within its environment. Postural control is greatly influenced by the perceptual systems, including vision. For instance, Pagulayan, Hayes, and Stoffregen (2001) required standing subjects

to perform “hard” and “easy” visual signal detection tasks, and found that body sway was reduced during performance of the hard task. The tasks used by Pagulayan et al. varied in terms of oculomotor demand, and also in terms of cognitive demand. Hence, body sway might have been influenced by changes in oculomotor demand (as hypothesized by Pagulayan et al.), or by changes in cognitive demand. The latter effect would have no obvious functional basis; it is not clear why reduced sway would facilitate purely cognitive activity. A functional integration of postural control and supra-postural performance would predict that task-specific effects on body sway should be stronger for tasks that varied perceptual demand, and weaker or absent for tasks that varied only cognitive demand. The present study was conducted to evaluate this hypothesis.

Postural control as an independent function

Typically, the perceptual control of body sway is regarded as a task that is carried out independent of whatever else the person may be doing. This approach is embodied in the concept of *quiet stance*. The concept of quiet stance assumes that the participant’s main goal is the maintenance of postural stability, and that sensory inputs such as optical flow are used primarily for the control of stance. In research inspired by the concept of quiet stance, participants often are instructed to “look straight ahead and stand as still as possible” (Lee & Lishman, 1975, p. 90; cf. Andersen & Dyre, 1989, p. 455), or to “look at the center of the stimulus and stand relaxed” (Dijkstra, Schöner, & Gielen, 1994, p. 481). Typically, there is no experimentally controlled variation in supra-postural activity; that is, the participants are not asked to do anything other than maintain posture while

attending to the perturbing stimulus (e.g., Dijkstra et al., 1994a,b; Stoffregen, 1985; Van Asten, Gielen, & Denier van der Gon, 1988). Data analysis and interpretation are concerned solely with relations between sensory stimulation and postural control actions.

Posture as a competitor for central resources

If postural control is a task that is independent of, but simultaneous with, other tasks, then it might be possible for the control of stance to interfere with the performance of other tasks, and vice versa. This idea is popular among many posture researchers. For example, postural control may be regarded as a task that utilizes central cognitive resources. Researchers have argued that the integration of multisensory perceptual stimulation, which is required for postural control, may draw on central processing capacity (e.g., Hunter & Hoffman, 2001; Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1993, 1996; Marsh & Geel, 2000; Maylor & Wing, 1996; Simoneau, Teasdale, Bourdin, Bard, Fleury, & Nougier, 1999; Teasdale, Bard, LaRue, & Fleury, 1993). In these studies it is assumed (often implicitly) that postural control and perceptual or cognitive tasks are functionally independent. That is, aside from their possible competition for central resources, there is no functional relation between postural control and other mental activity.

Marsh and Geel (2000) measured supra-postural task performance in order to assess the attentional demands of postural control tasks. Participants performed a verbal reaction time task under both seated and standing conditions. Marsh and Geel argued that increasing the difficulty of the posture task (e.g., standing as opposed to sitting)

would require increased attentional resources that would, in turn, result in longer verbal reaction times. They theorized that fewer attentional resources would be available to complete the reaction time task when more attention was required to maintain balance, as compared to less demanding postural tasks (e.g., sitting). In line with their predictions, they found that reaction time did increase from a sitting to standing posture. Marsh and Geel interpreted this finding as indicating that participants required more cognitive resources to maintain standing posture as compared to sitting.

Teasdale et al. (1993) also used a reaction time task; they employed a handheld switch that recorded participants' response to an auditory tone presented through earphones. They studied elderly participants (mean age = 71) and younger participants (mean age = 25). Each participant stood barefoot on a force platform, (an instrument that records postural motion based on pressure readings taken underneath the platform; the global measure of postural sway that is recorded is termed the center of pressure [COP]). Participants were instructed to maintain an upright stable posture while fixating a stationary point 3m in front of them. They performed the reaction time task in each of four experimental conditions; (1) standing on the force platform (normal surface) with eyes open, or (2) eyes closed, and (3) standing on a foam surface placed on the force platform with eyes open, or (4) eyes closed. Two, 20-second trials while standing on the normal surface with eyes open were used to obtain the mean position and range of sway for each participant. The mean COP position was calculated, as well as COP position at the extreme ends of the range of sway. They divided each participant's average amount of sway into 2 areas, a central area and an eccentric area. The central area represented sway that fell within 80% of the mean COP position and its extreme range (i.e., the

position farthest from the mean), while the eccentric area was COP position that occurred past 130% of the mean and extreme range of COP values for each participant.

The auditory tone was presented randomly while participants were in either an eccentric or central range of their sway. COP position was monitored on-line, by means of an oscilloscope attached to the force platform. The authors argued that if postural adjustments require cognitive processing, then auditory reaction time should be greater for the eccentric than the central COP positions. That is, from an information-processing perspective, an eccentric position (the less stable position of the COP) requires a corrective response to be selected, programmed, and executed (Teasdale et al., 1993). Because the reaction time task occurs simultaneously with processing necessary to correct unstable balance in the eccentric position, the two tasks will compete for resources, leading to slower auditory reaction time. As predicted, participants had longer reaction times to the auditory stimulus when their center of foot pressure (COP) was in an eccentric position; however, this was true only for the elderly group, and only while standing on the foam surface. Teasdale et al. interpreted these results as evidence supporting the hypothesis that central processes are an important determinant of postural control.

Other researchers have found similar results suggesting a role for cognition in posture. Lajoie et al. (1993) used a verbal reaction time task while participants were either sitting, standing, or walking, and found increasing reaction time from the former to the latter condition. They suggested that attentional demands of a postural task increase with increasing balance requirements. Kerr et al. (1985) suggested that cognitive spatial processing may rely on neural mechanisms shared by the postural control system.

Participants performed a balance task (heel-to-toe tandem Romberg stance) while engaging in either a spatial or non-spatial memory task, as devised by Brooks (1967). The spatial memory task requires remembering number-word pairs by mentally placing the numbers in an imaginary 4 x 4 matrix. The instructions for mentally constructing this matrix were delivered over headphones in a series of 8 sentences that lasted for a total of 12 seconds. For example, the first sentence was “In the starting square put a 1” (Kerr et al., 1985); subsequent sentences instructed the participant to place the next number to the left or right of, or above or below the previous number. At the end of the trial, participants were required to repeat the instructions. The non-spatial memory task was similar; however, the words indicating placement of the subsequent numbers were replaced with the words quick, slow, good, and bad. Results revealed that performance on the spatial memory task was disrupted during heel-to-toe stance, but that this same stance produced no decrease in performance of the non-spatial memory task. There were no significant differences between sway for the two memory conditions.

The studies reviewed above are representative of a body of research that has been interpreted as supporting the hypothesis that the task of controlling posture competes for a pool of central cognitive resources with other, concurrent, non-postural tasks.

Functional integration of posture and perception

The preceding review indicates that a substantial body of contemporary research is based on –and appears to confirm– the assumption that the control of upright stance is a perceptual-motor task that has little or no functional relation with other, simultaneous

perceptual-motor tasks, aside from possible competition among tasks for limited central cognitive resources. In this section, I present an alternative view of relations between postural control and other perceptual-motor tasks. This view is based on the assumption that there may be functional relations between body motion and the perceptual systems that guide our interactions with the environment (e.g., Bernstein, 1996; Reed, 1988; Riccio & Stoffregen, 1988). Vision, for instance, may directly influence body sway such that controlled changes in body sway could be used to facilitate performance of visual tasks (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999). For example, tasks that require precise control of the oculomotor system, such as reading, would be facilitated by reductions in body sway. Conversely, when visual performance does not require precise oculomotor control, there might be no functional advantage to a reduction of sway.

Lee and Lishman (1975) placed standing subjects in a large hall and measured their spontaneous (unperturbed) sway as they fixated objects at different distances. When fixating a distant wall, anterior-posterior (AP) sway amplitude was large. When fixating an object directly in front of them, sway amplitude decreased. Lee and Lishman interpreted this distance effect in terms of a detection threshold; in the “near” condition, the optic flow that results from body sway is more pronounced and, therefore, presumably more detectable. An alternative interpretation of the distance effect is that different degrees of visual stabilization are required for fixation at different distances. That is, the amount of visual instability that can be tolerated depends on how far away one is looking. Thus, the influence of distance on posture might be a function of what the person was looking at, rather than being a function of the detectability of optical flow.

When looking at a distant object there is nothing to be gained by minimizing sway, regardless of the presence or absence of nearby objects that are not fixated. This hypothesis was evaluated by adding a condition to the experiment of Lee and Lishman (1975).

Stoffregen et al. (1999) instructed subjects to ignore a nearby object while fixating a distant target. The magnitude of optical flow generated by body sway was greater for the nearby object than for the distant target, but this larger amplitude flow was irrelevant to the fixation task. As predicted, in this condition body sway was greater than during fixation of the nearby target. This finding suggests a reinterpretation of effects of distance on unperturbed sway reported by Lee and Lishman (1975). More broadly, the influence of fixation distance raises questions about the assumption that postural control is organized independent of supra-postural activities. Stoffregen et al. (1999) have suggested that sway was modulated in the service of visual performance, that is, influenced by the content of the visual task, rather than by the optical consequences of sway.

Stoffregen et al. (1999) operationalized variations in looking task in terms of variations in the distance of fixated targets. Thus, in their work the possible influence of visual task cannot be distinguished from any influence of distance-related variations in optics, in motion sensitivity, and so on. Distance-based constraints can be separated from task-based constraints by placing all targets at the same distance. For targets at a given distance, variations in postural sway that are associated with different looking tasks could not be attributed to distance-related variables.

Stoffregen et al. (2000) varied visual task parameters for visual targets that did not differ in distance from the eyes. Sway was measured while participants performed one of two visual tasks. One group looked at a blank target. For a second group a target at the same distance was covered with text, and participants were asked to search the text, counting instances of a designated target letter. This defined a supra-postural task that was independent of distance-related optical effects. As predicted, during visual search the variability of AP sway (mean = 0.533 cm) was significantly lower than during simple fixation (mean = 0.757 cm). Because the two tasks were performed at the same target distances, depth-related variations in sensitivity to visual motion cannot explain the results. The task-specific reduction in sway would tend to facilitate the precise oculomotor control needed for reading, and so Stoffregen et al. (2000) argued that the task effect on posture was functional: rather than simply competing for a central resource pool, postural control may be integrated with certain types of supra-postural tasks.

Anomalous findings

In several cases, studies that have attempted to demonstrate competition of postural control for central resources have produced results that were not consistent with the experimenters' hypotheses. In many of these cases, the results were more compatible with the functional view advocated by Riccio and Stoffregen (1988). Some of these findings are reviewed here. In each case, the inconsistent findings had been dismissed as resulting from artifacts. In none of the cases reviewed here did the experimenters

consider the possibility that the results might undermine the validity of their theoretical view of relations between postural control and cognition.

Marsh and Geel (2000) argued that a more difficult postural task would demand greater central processing resources, and predicted a consequent decrement in otherwise unrelated supra-postural task performance. Older (mean age = 72) and younger (mean age = 26) women executed a verbal reaction time task while standing on the floor or on a non-rigid surface. Participants listened for a tone that was presented through an earphone as they either stood with their eyes open or closed on a foam or hard surface. Verbal reaction time was recorded as the time it took to vocalize “ha” after hearing a tone in the earphone. Performance on the verbal reaction time task was not, contrary to predictions, affected by the variation in support surface (i.e., the presumptive difference in the difficulty of postural control). In attempting to explain this outcome, Marsh and Geel noted that their sample of older individuals were screened for factors that may have led to slower reaction times (over and above those due to age). Therefore, even though the older women were slower than the younger, they may have lacked decrements in cognitive performance that would lead to increased reaction times under the difficult stance condition. The authors also postulated that their cognitive task may not have been complex enough to elicit anticipated results. In sum, Marsh and Geel did not consider the possibility that performing verbal response time to an auditory stimulus may not compete with the postural system for resource allocation.

In research conducted by Maylor and Wing (1996), two groups of participants (an older group, mean age = 77, and a younger group, mean age = 57) were presented with five different cognitive tasks. The researchers predicted that performing the cognitive

tasks would lead to increased body sway compared to standing while only maintaining balance, and the elderly group would suffer the largest increased sway. However, they found that standing while performing a cognitive task (repeating a series of 3 numbers in the reverse order from how they were given) induced less sway than standing while fixating a stationary target. The older group, on average, swayed more than the younger group during all of the cognitive conditions, but the difference in body sway between the two age groups was statistically significant for only two of the five tasks. In explaining the fact that their predictions had been confirmed in only two of five conditions, Maylor and Wing suggested that the data may have been influenced artifactually, by a phenomenon termed “slow drift”. “Slow drift” describes the tendency of participants to shift their body weight forward (or backward) during the trials, presumably as a result of fixating the stationary visual target or attending to the experimenter standing behind them. Shifting their weight in such a manner could have artifactually increased body sway, leading to the finding of less sway during the cognitive trials. Maylor and Wing also suggested that slow drift might be caused by participants’ attending to the sound of a metronome placed behind them during 2 conditions, for example, if participants leaned towards the metronome over the course of the trials. As with Marsh and Geel (2000), Maylor and Wing did not consider the possibility that the results might disconfirm their *a priori* hypotheses.

Hunter and Hoffman (2001) had participants move their eyes (i.e., track a moving target) or simply fixate a stationary target. The cognitive task consisted of a series of ten numbers that were to be sequentially added. The numbers either were projected into circles (moving or stationary) presented on a screen, or were presented auditorily through

speakers. When the numbers were presented auditorily, they were synchronized to blank visual targets. In addition, there was a “no cognition” condition in which participants stood as still as possible while fixating on a blank stationary target. Hunter and Hoffman predicted significant postural sway differences between the auditory and the visual presentation of the cognitive task. This prediction was not confirmed: There was no effect of modality of presentation of the cognitive task on postural sway. They also predicted that performing a secondary cognitive task would show increased postural sway relative to the no cognition condition. This prediction also was not confirmed. In fact, the opposite occurred: Sway was reduced in conditions involving a secondary cognitive task. In each case, the results were interpreted in terms of design artifacts. The absence of a modality effect was attributed to cognitive tasks that may have been insufficiently demanding to cause interference with postural control. The finding that sway was greater without any cognitive task (rather than less) was interpreted as an effect of “concentration”: Hunter and Hoffman suggested that the lack of a cognitive task may have produced an increased concentration on balance which could, in turn, have led to increased muscle tension. The resulting increase in overall rigidity of the body might have amplified body sway. Hunter and Hoffman explored several post-hoc explanations of this kind for their unpredicted finding, but did not consider the possibility that their a priori hypotheses might have been incorrect.

The unexpected results obtained in the studies discussed above could have resulted from specific artifacts. However, the fact that similar results have occurred consistently in different studies using different methods, in different laboratories, makes it extremely unlikely that each result was caused by a separate artifact. A more

parsimonious interpretation is that the repeated anomalies reveal that, in at least some cases, there may be functional integration between postural control and simultaneous supra-postural tasks. In fact, many of the findings that were surprising to the experimenters could have been predicted on the basis of the functional integration view that motivates the present thesis. Each of the findings reviewed in this section is compatible with the approach and findings of Riccio and Stoffregen (1988), and Stoffregen et al. (1999, 2000).

Limitations of previous research

Previous research on relations between postural control and cognition has been characterized by limitations that make it difficult to evaluate the hypothesis that posture is modulated to facilitate perceptual performance, and is not modulated relative to purely cognitive factors. These limitations are reviewed in this section. The present research was designed, in part, to overcome these limitations.

Research implicating the role of cognition in postural control often presents participants with some cognitive tasks to perform either with or without varying stance conditions (e.g., easy and hard balance tasks). Often the cognitive tasks utilized in these experiments that manipulate cognitive difficulty vary in terms of task requirement. For instance, participants perform different kinds of cognitive tasks (e.g., random digit generation or backward digit recall) that are presumed to engage either different amounts of processing, or processing from different areas in the brain. For instance, Maylor and Wing (1996) used five different cognitive tasks that involved at least one component of

working memory. However, these cognitive tasks were not chosen based upon any empirically evaluated difficulty or workload rating; therefore, it is unclear how to interpret their effects on postural sway. Two tasks that employ the same component of working memory can either be equally difficult or differentially so, which is an important consideration when predicting the relation between cognitive task performance and body sway. In the present experiments, I addressed this issue by utilizing a measure of mental workload to rate the demand of the cognitive tasks. This subjective rating procedure allowed me to compare postural performance both for cognitive tasks equated in terms of mental workload, and for those that differed.

The tasks used by Stoffregen et al. (2000) varied in terms of both oculomotor demand (fixation vs. eye movements), and of cognitive demand. This means that in their study, body sway might have been influenced by changes in oculomotor demand, or by changes in cognitive demand. The latter effect would have no clear functional basis; I hypothesize that there is no functional benefit of reducing body sway on purely cognitive activity. However, that hypothesis was not tested by Stoffregen et al. (2000).

Motivation for the present study

The majority of research investigating postural implications of concurrent cognitive task performance has been conducted from a theoretical framework that does not place much emphasis on the perception-action relationship between an organism and its environment. Cognitively involved tasks are manipulated under the assumption that variation in cognitive difficulty will differentially affect postural performance (e.g.,

Hunter & Hoffman, 2001; Teasdale, et al., 1993). The present research approaches the question from an alternative point of view, that people engage in supra-postural behavior, and that variations in supra-postural goals will produce changes in the variability of postural sway (Riccio & Stoffregen, 1988; Stoffregen et al., 1998). If posture is controlled as a consequence of the perception and action requirements of an organism interacting with its environment, then cognitive task difficulty *per se* should not influence body sway. The following experiments were conducted in order to address that hypothesis. Support for the hypothesis would imply that postural sway is functionally related to interactions with the environment, and variations in sway are not determined by the cognitive mental processing characteristics of tasks.

Predictions

The main goal of my research was to separate visual demand and cognitive demand, and to determine their respective relationships to postural sway. I hypothesized that postural sway should be less variable when a reduction in sway would facilitate performance on supra-postural tasks. The nature of the supra-postural task is important; performance of strictly cognitive tasks (e.g., mental arithmetic) is not facilitated by small reductions in postural sway. However, if a task requires precise visual fixation (e.g., visual signal detection as in Experiment 1), then reducing body sway would reduce the amount of movement in the visual scene, thereby enabling precise fixation and improving visual performance.

Experiment 1 was designed to assess whether postural control can be modulated in a goal-directed manner to aid visual performance. Body sway was measured during performance of two supra-postural tasks, one of which imposed perceptual demand. The two task conditions were 1) visual signal detection and 2) mental arithmetic; the two tasks were equated for subjective mental workload. I hypothesized that postural sway would be reduced during visual signal detection (to facilitate visual performance), but not during mental arithmetic.

Experiment 2 was designed to evaluate the same general issue as Experiment 1, using a complementary design. Standing participants carried out supra-postural tasks that varied in subjective mental workload, but which had a fixed level of perceptual demand. Two arithmetic tasks, vocalized iterative subtraction by three (*hard mental arithmetic*) and vocalized sequential addition by two (*easy mental arithmetic*), were used. Visual demand was held constant across both conditions, and participants gave ratings of the subjective mental workload of each arithmetic task. I predicted that the tasks would differ in subjective mental workload, and that this difference would be independent of any variation in body sway.

Experiment 3 controlled for a potential confound in Experiment 1, and will be discussed below.

Chapter II

General Method

Participants

Undergraduate students from the University of Cincinnati received course credit for participating in this research. All participants were screened 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). Each individual participated in only one experiment.

Apparatus

Postural sway was recorded using a 6-df magnetic tracking system (Flock of Birds, Ascension Technologies, Inc, Burlington, VT) sampled at 25hz. The position data were stored on a computer for later analysis. In order to record body position, a sensor was taped to the back of the participants' neck at approximately the seventh cervical vertebra. Participants wore a bicycle helmet to protect their head in case of a fall.

Experimental displays were presented using a 17-inch Apple Studio Display monitor driven by a Macintosh G3. The laboratory setup was the same for all three experiments and is depicted in figure 1.

Figure 1. Laboratory set up for Experiments 1, 2, & 3.

Visual displays were generated using *PsyScope*, a standard experimental control application (Cohen, MacWhinney, Flatt, & Provost, 1993). Displays are described separately for each experiment below. *PsyScope* was also used to collect data on suprapostural task performance in Experiment 1.

Assessment of Subjective Mental Workload

In order to investigate the relation between postural sway and supra-postural tasks, it was necessary to equate the level of difficulty of the supra-postural tasks. Mental arithmetic and visual signal detection are qualitatively different tasks, so in order to compare their effects on postural sway the tasks needed to be equated on some measure. Mental workload was chosen as a viable means for equating these tasks. Mental workload refers to the amount of mental work or effort necessary to perform a task (Proctor, 1994).

There is no universally accepted definition of mental workload (Nygren, 1991), and for this reason there are numerous rating scales available that purport 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 operators as a consequence of achieving a given level of performance. Factors both internal (e.g., feeling rushed) and external to the operator (e.g., environmental conditions) contribute to the subjective experience of workload. In the present study, I adopted Hart and Staveland's (1988) definition of workload, as well as their measurement instrument for assessing it.

Subjective mental workload was assessed using the NASA Task Load Index, or NASA-TLX (Hart & Staveland, 1988). The NASA-TLX is a widely used instrument for assessing subjective mental workload, and it provides a reliable index of overall workload (Warm, Dember, & Hancock, 1996). It is a multi-dimensional rating procedure that yields an overall workload score based upon 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 upon the nature of the task being rated.

A computerized version of the NASA-TLX was administered to the participants in Experiments 1 and 2. Participants read an instruction sheet (see Appendix) that described the two parts of the evaluation, the *rating scale* and the *source-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 in order to clarify its meaning and illustrate how the rating scale pertained to it.

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

The weighted subscales were designed to contribute to an understanding of how the rated workload for a particular task breaks down into its component measures (Hart & Staveland, 1988). However, my goal was not to identify how performance varied with regard to particular subscale loading characteristics, and no predictions were made

regarding subscale differences between conditions. For this 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 due to psychometric limitations of the weighting process. However, Hart and Staveland (1988) have argued that the weighted combination of factors provides a sensitive indicator of overall workload between different tasks. For these reasons, I used only the Overall Workload rating to represent evaluated workload for each of the tasks. The Overall Workload rating from the NASA-TLX was taken as the measure of subjective mental workload for each condition in Experiments 1 and 2.

Procedure

Participants were instructed to stand facing the computer monitor, with their toes on a line on the floor that was 100 cm from the monitor, and were asked to keep their feet pressed tightly together. Participants were told to maintain this foot position for the duration of each trial, but between trials they were free to move around. Display height was adjusted (by tilting the monitor on its stand) so that the top of the screen was approximately level with the participant's eye height. Participants were asked to stand with their arms in any one of three possible positions: (a) arms dropped by their side, (b) arms held in front or behind them, or (c) with their hands in their front pockets. They were instructed to choose their preferred arm placement and to maintain it during all trials of Experiments 2 and 3. Experiment 1 was more restrictive as participants held a computer mouse for half of the trials and were asked to keep both arms by their sides.

They were informed 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), a mandatory break was implemented midway through each experiment, in which participants sat in a chair for approximately five minutes.

In Experiments 1 and 2, the NASA-TLX was administered to the participants after each condition block. The instrument was administered on a desktop computer, which stored participants' responses for later analysis. Participants were shown how the computer rating scale worked and they were asked to let the experimenter 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), the experimenter instructed the participants to answer the items pertaining only to the condition most recently completed.

Design and data analysis

Postural data. For all three experiments the dependent variable was the standard deviation of torso position, examined separately in the anterior-posterior (AP) and mediolateral (ML) axes. Descriptive and inferential statistics were conducted on the mean, across participants, of this variable. The data were evaluated using paired *t*-tests, which were conducted separately for AP and ML.

Arithmetic task data. The tape-recorded responses to the arithmetic task were transcribed and evaluated in terms of rate of response per minute as well as the number of errors made. The arithmetic task consisted of either iteratively subtracting 3 from a three

digit-number or sequentially adding 2 to a 3-digit number. An error was operationalized as any deviation from the desired pattern of responding for the iterative addition and subtraction tasks.

Subjective Mental Workload. In Experiments 1 and 2, the Overall Workload rating from the NASA-TLX was taken as the measure of subjective mental workload for each condition.

Chapter III

Experiment 1: Signal Detection and Mental Arithmetic

In separate conditions, participants executed different supra-postural tasks, one for which performance depended upon fine control of the oculomotor system, and one for which performance did not. I hypothesized that body sway would be reduced during performance of the oculomotor task (to facilitate visual performance), but not for the cognitive task, for which precise control of the oculomotor system was not needed. Using the NASA-TLX, overall workload scores were obtained for a mental arithmetic task (subtraction by 3) and for the hard visual signal detection task used by Pagulayan (2000), which is known to be visually demanding. A pilot study was conducted to determine whether the subjective workload of the subtraction task was an appropriate match to Pagulayan's (2000) signal detection task. In this pilot study, nine participants executed the signal detection and mental subtraction tasks, with each participant completing 3 trials with each task. Across these participants, the mean overall workload score for the signal detection task was 55.8, and 67.4 for the mental subtraction task. The mean workload scores did not differ statistically ($t_{(8)} = -1.214, p > .05$). This was taken as evidence that the supra-postural tasks were appropriately matched in terms of task difficulty (i.e., mental workload).

In Experiment 1, I hypothesized that variability of postural sway would be reduced more during visual signal detection, than during mental arithmetic. The predicted result would contrast with the findings of earlier research that has found a relation between postural stability and cognitive demands (Lajoie et al., 1993; Teasdale et

al., 1993). Increasing cognitive demand (attention) has been hypothesized to lead to less stable control of posture due to the depletion of central processing capacity (Hunter & Hoffman, 2001). A dual task methodology is often employed to evaluate the attentional demands necessary for maintaining stable postural control. Implicit in this methodology are the assumptions that (1) there is a limited central processing capacity; (2) performing a task depletes some of the available resources; (3) when two tasks share the same processing resources there may be a performance decrement on one or both tasks (Lajoie et al., 1993).

The importance of vision to postural control is well documented (e.g., Paulus, Straube, Krafczyk, & Brandt, 1989; Stoffregen et al., 2000; Warren, Kay, & Yilmaz, 1996). Hunter and Hoffman (2001) have predicted that a visual task (e.g., signal detection) combined with a cognitive task (e.g., sustained attention) may have a greater negative effect on postural stability than a cognitive task alone (e.g., mental arithmetic). The addition of a visual task to a cognitive task might interfere with the quality and/or quantity of visual information that is available specifically for postural control, or it might interfere with processing the visual information necessary for postural control (Hunter & Hoffman, 2001). Thus, the central processing hypothesis would predict that Pagulayan's (2000) hard visual signal detection task (which involves both visual performance and sustained visual attention) should induce a greater degree of postural instability than a mental subtraction task that does not share the same degree of visual attention. Thus, the prediction that sway will be differentially influenced by supra-postural tasks that do not differ in mental workload contrasts directly with the position of Hunter and Hoffman.

Method

Participants

Participants (6 males and 6 females) ranged in age from 18 to 25 years (mean = 21, median = 20, mode = 20), and in height from 157 to 183 cm (mean = 169 cm). Five participants had corrected vision (glasses or contacts). Originally there were 14 participants; however, two of them did not meet the signal detection criteria set by Pagulayan (2000), so their data were not included in the analyses. Therefore, data analysis was conducted on the remaining 12 participants.

Signal Detection Display

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).

Figure 2. Hard detection targets from Experiment 1.

Luminance of the display background was 108.44 cd/m² for all conditions. The luminance of the target color was 77.44 cd/m², resulting in a contrast ratio of approximately 1:1. Due to the small size (thickness) of the target lines the actual luminance of the targets was 104.84 cd/m². Luminance was determined using a luminance meter (LS-100, Minolta Camera Co., Ltd., Japan).

Procedure

Each participant performed six trials (three trials per condition), each of which lasted 60 seconds. Trial order was randomized within the counterbalanced condition blocks. The two experimental conditions consisted of a visual signal detection task and a mental subtraction task.

For the signal detection task, participants were presented with a pair of identical vertical lines on the monitor. Each pair appeared for 200 ms, with 800ms between stimuli. At various points during the sequence of stimuli, one bar appeared which differed (minimally) in height; this was defined as the *critical signal*. Twenty critical signals and forty neutral events were presented per trial, although participants were not aware of how many critical signals and neutral events to expect. Presentation order of the targets was randomized by the experimental control software.

Participants held a computer mouse in their preferred hand while keeping both arms comfortably dropped at their sides and were told to indicate the presence of a critical signal by pressing the mouse button as quickly as possible after seeing the critical signal. The correct identification of critical signals (hits) and the number of button presses during the presentation of the neutral events (false alarms) was recorded by the computer. Participants did not receive any feedback about their performance at any time during the trials.

Visual task performance was evaluated in terms of signal detection theory (Green & Swets, 1966). For each participant, d' (an index of perceptual sensitivity) was calculated 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, while 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. Following Pagulayan (2000), the performance criterion for inclusion in the study was $d' < 3.0$. Participants who did not meet these criteria were replaced 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 3-digit number that was randomly chosen from a set of three pre-selected numbers. Participants were asked to sequentially subtract 3 from this number, and to do so continuously at a steady quick pace for the duration of the trial. The starting number was different for each trial. While performing the arithmetic task, they were told to keep their gaze on the computer monitor, which was turned off in this condition. A microphone was placed beside the monitor in order to record arithmetic performance on audio cassette for later analysis. Participants completed the NASA-TLX after the detection condition and again after the arithmetic condition.

Results

Mental arithmetic performance. Participants' performance on the mental arithmetic task was evaluated in terms of the number of responses per one-minute trial (response rate), and the percent of correct responses per trial. Each measure was averaged to provide mean values across trials. Across participants, the mean accuracy was 87%, with a mean response rate of 27 responses per trial.

Signal detection performance. The mean value of d' across groups was 1.54 for the signal detection task. Thus, for the sample used in this study, this task can be considered "moderately difficult" (Craig, 1984). Two participants (approximately 9% of the original sample) did not meet the performance criterion and were replaced.

Postural sway. The data are summarized in table 1 and figures 3 and 4. As anticipated, the mean standard deviation of body position was reduced in the signal

detection condition, relative to the arithmetic condition. Sway variability was significantly lower in the AP axis ($t_{(11)} = 1.988, p < .05$). The effect size for the AP mean standard deviation was $d_{AP} = 0.57^1$. There was not a significant condition effect for sway in the ML axis ($t_{(11)} = 0.913, p > .05$).

	Signal detection		Mental arithmetic	
	Mean(cm)	SD(cm)	Mean(cm)	SD(cm)
Body sway AP	0.74	0.32	1.05	0.55
Body sway ML	0.53	0.21	0.64	0.34

Table 1. Postural data for Experiment 1. SD = standard deviation.

Figure 3. Graph of mean standard deviation of body position in the anterior-posterior (AP) axis as a function of task condition. Error bars represent the 95% confidence interval. Experiment 1.

¹ I estimated effect size using Cohen's d . Cohen (1977) recommends that values around 0.2 can be considered small, values around 0.5 can be considered medium, and values above 0.8 can be considered as indicating large effects.

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

Subjective mental workload. NASA-TLX ratings for the signal detection and mental arithmetic conditions did not differ statistically. The mean Overall Workload score for the hard detection and hard arithmetic conditions are 59.3 and 60.1, respectively ($t_{(11)} = -0.114, p > .05$).

Discussion

In Experiment 1, standing participants performed two supra-postural tasks: Visual signal detection and mental arithmetic. I predicted that body sway would be less during signal detection than during mental arithmetic. In addition, this effect was expected to be independent of the subjective mental workload associated with the tasks. During performance of a visually-demanding signal detection task, body sway was reduced, relative to sway during performance of a subtraction task that had low visual demand,

confirming my first prediction. In addition, the rated difficulty of the two tasks did not differ. This means that the significant condition effect in body sway was independent of subjective mental workload and, accordingly, my second prediction was confirmed.

These results are similar to some reported by other researchers interested in the effects of cognition on postural control. Maylor and Wing (1996) found that counting backwards by three did not interfere with postural control, as they had expected it would. An important difference between the mainstream view and the theoretical position that I am supporting is that the present results are considered as being anomalous from their perspective, but are anticipated *a priori* from my theoretical framework. For example, Kerr et al. (1985) found that young adults swayed less during performance of a memory task than when there was no explicit supra-postural cognitive task. This result was not predicted by Kerr et al. They interpreted the finding as an artifact of an order effect; in their study this was plausible because there was an order by condition interaction.

Similarly, Maylor and Wing (1996) found that sway was reduced for young adults in dual-task conditions (standing while performing a cognitive task) compared to balance-alone conditions. Maylor and Wing attributed this result to design factors of their experiment. They found that the participants' weight generally shifted forward during trials (what they call "slow-drift"), and suggested this effect was caused in part by either the presence of the experimenter behind the participant, or from the participant attending to the sound of a metronome. Neither Kerr et al. (1985) nor Maylor and Wing considered the possibility that their statistically significant results might reflect a theoretically interesting effect.

The results of Experiment 1 are consistent with research demonstrating effects of supra-postural visual tasks on the control of body sway (e.g., Stoffregen et al., 2000; Stoffregen et al., 1999). In addition, Experiment 1 provides an important confirmation of the hypothesis that the relation between body sway and supra-postural tasks is functional. Experiment 1 establishes that body sway is not automatically reduced in the presence of any mentally-demanding supra-postural task. Rather, a reduction in body sway was observed only for supra-postural tasks for which performance could be facilitated by reduced sway. In Experiment 1, body sway was not controlled with respect to mental demand, *per se*. While this supports my hypothesis that changes in body sway are functionally related to the performance demands of supra-postural tasks, it leaves open at least one important issue. If body sway is modulated with respect to supra-postural tasks only when those tasks impose constraints on perception and/or action, then there should be no variation in body sway across tasks that vary mental workload while maintaining a constant level of visual demand. Experiment 2 was conducted to evaluate this hypothesis.

Debriefing participants from Experiment 1 revealed a possible problem with the design. Participants' reports suggested that looking at a blank monitor during mental arithmetic trials was not an appropriate means of maintaining low visual demand. Several participants reported being able to see their reflection in the monitor, and some indicated that they imposed their own task constraints independent of experimental instructions. Some people used their reflection as a basis for controlling their degree of movement. The purposes of asking participants to look at the blank monitor were (1) to establish a low level of visual demand during performance of the mental arithmetic task,

and (2) to maintain a level of visual demand that was consistent across participants. The post-experimental reports suggested that there might be an undesirable level of inter-individual variability in the degree of visual demand associated with looking at the blank monitor during the mental arithmetic task. For this reason, in Experiments 2 and 3 a more structured display was used.

Chapter IV

Experiment 2: Hard and Easy Mental Arithmetic

It has been proposed that postural movements can be controlled so as to facilitate visual performance (Stoffregen et al., 2000; Stoffregen et al., 1999). The present experiments address limitations in past research where visual demand has been confounded with cognitive demand. It is not the case that performance on all tasks can be facilitated by subtle changes in body sway. To be sure, postural control must be sufficiently robust to prevent falling, staggering, and so on. However, for certain kinds of tasks, small variations in body sway may be irrelevant to task performance, per se. This should be true of supra-postural tasks that do not impose significant constraints on perception or action systems. One example of this type of task could be those that require “thinking” that is not related to or dependent upon features of the surroundings (such as visual targets that might be fixated, or acoustic targets that might be localized). Mental arithmetic is an example of this type of supra-postural task. Mental arithmetic does not require the performer to maintain any particular type of perceptual contact with his or her surroundings. Because this is so, subtle changes in body sway might not influence mental arithmetic performance; this would be true regardless of the level of difficulty of mental arithmetic. Specifically, decreases in overall sway would not be expected to facilitate performance of more difficult mental arithmetic tasks.

In Experiment 1, variations in postural sway were shown not to depend on the subjective mental workload of supra-postural tasks. The supra-postural tasks differed in the level of visual demand (one was more visually demanding than the other), but did not

differ in overall subjective mental workload. In Experiment 2, I sought the reverse effect. I varied the level of subjective mental workload across supra-postural tasks that did not differ in the level of visual demand. My hypothesis was that, because there was no variation in visual demand, the variation in subjective mental workload would be independent of any variations in postural sway.

An additional motivation for Experiment 2 can be derived from the literature relating postural control to cognitive processing. Within this literature, it might be argued that the tasks in Experiment 1 were not appropriate for evaluation of the attentional resource hypothesis because the two supra-postural tasks placed different types of demand on central resources. The fact that rated subjective mental workload for the two tasks did not differ does not necessarily imply that they drew upon the same pool of attentional resources. That is, the presumed “central” pool of resources might be dedicated (in whole or in part) to different sense modalities (e.g., visual resources, auditory resources, etc.), or to “sensory” and “cognitive” tasks. If this were true, then Experiment 1 might not properly address theories of postural control that appeal to the concept of central cognitive resources. This issue can be addressed by using supra-postural tasks that necessarily draw upon the same type of cognitive resources.

Mental arithmetic tasks that vary only in the degree of difficulty should draw from the same pool of attentional resources. As noted above, any variation in body sway across different mental arithmetic tasks is predicted from the supra-postural task hypothesis (e.g., Stoffregen et al., 1999, 2000) to be independent of differences in subjective mental workload between hard and easy mental arithmetic. A competing hypothesis is that harder arithmetic tasks draw upon more attentional resources than

easier tasks. This would result in 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. I 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 this prediction would support the idea that postural sway is organized with reference to constraints imposed by perceptual demands of supra-postural tasks, but not by non-perceptual cognitive demands.

Method

Participants

Fifteen undergraduate students from the University of Cincinnati (9 males, 6 females) 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 (mean = 20.27, median = 19, modes = 18 and 19), and in height from 152 to 191 cm (mean = 171.13 cm). Eight participants had corrected vision (glasses or contacts).

Experimental Display

The experimental stimulus presented on the monitor consisted of a filled red circle 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 (see figure 5).

Figure 5. Visual target used in Experiments 2 and 3.

Procedure

The two experimental conditions, hard and easy mental arithmetic, were presented in blocks of 4 trials. There were 8 trials (4 easy and 4 hard), each of 60 seconds duration. Eight participants had easy trials first, and seven had hard trials first.

Participants were instructed to keep their eyes on the visual target while performing the mental arithmetic task. They were asked to maintain their gaze on the target, but this was not stressed as an important goal, and participants were not asked to treat the target as a fixation point. The hard condition was the same one used in Experiment 1; participants iteratively subtracted 3 from a 3-digit number. In the easy task, the experimenter provided an even 3-digit number and participants were instructed to iteratively add 2. The NASA-TLX was administered after trial four and again after trial eight.

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 ($t_{(14)} = -4.080, p < .01$). 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-subjects t -test: $t_{(23)} = -.298, p > .05$).

Mental arithmetic performance. Participants' performance on the mental arithmetic tasks was evaluated in terms of the percent of correct responses per trial, and response rate per trial. Each measure was averaged 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 per minute (standard deviation = 6.2). For the easy task, the mean accuracy was 99% at 46 responses per minute (standard deviation = 9.6). The means of both accuracy ($t_{(14)} = 1.941, p < .05$) and response rate ($t_{(14)} = 8.088, p < .01$) were

significantly different, indicating that participants counted more accurately and more rapidly during the easy task. The performance measures were consistent with participants' judgments of the workload demands of the two tasks. None of the participants reported any confusion regarding task requirements of the visual target that replaced the blank monitor from Experiment 1.

Postural sway. Postural sway data are illustrated in table 2 and figures 6 and 7. Paired *t*-tests indicated that there were no significant differences in sway between the easy and hard mental arithmetic conditions in AP ($t_{(14)} = -.512$, $p > .05$) or ML ($t_{(14)} = .460$, $p > .05$).

	Easy mental arithmetic		Hard mental arithmetic	
	Mean(cm)	SD(cm)	Mean(cm)	SD(cm)
Body sway AP	0.96	0.52	1.04	0.73
Body sway ML	0.59	0.20	0.58	0.23

Table 2. Postural data for Experiment 2. SD = standard deviation.

Figure 6. Graph of mean for body position in the AP axis as a function of task condition. Error bars represent the 95% confidence interval. Experiment 2.

Figure 7. Graph of mean for body position in the ML axis as a function of task condition. Error bars represent the 95% confidence interval. Experiment 2.

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, relative to 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 support the hypothesis that postural sway was not modulated to facilitate performance for a strictly cognitive task for which the individual did not benefit from maintaining a specific physical relation with the environment. The Hard math task was rated as being more difficult than the Easy math task. If postural control suffers (or becomes more variable) as one or more central pools of attentional resources are taxed, then the Hard task should have induced a greater degree of postural sway (a decrement in quality of control) than did the Easy task. The results of Experiment 2 do not support this hypothesis.

The results of Experiments 1 and 2 suggest that modulation of postural sway was done in a manner that was functionally related to the perceptual constraints imposed by supra-postural tasks. The participant's goals in Experiment 1 were to perform well on the signal detection and math (subtraction by three) tasks. Similarly, the goals of Experiment 2 concerned the adequate performance on the Hard (iterative subtraction by three) and Easy (iterative addition by two) math tasks. Visual performance in the signal detection

condition from Experiment 1 was the only task where reduction of postural sway offered potential benefits in terms of goal fulfillment. Reduction of sway could have aided target fixation by reducing the amount of lens accommodation required to precisely foveate the small targets.

Experiments 1 and 2 are suggestive of a relation between postural control and the facilitation of performance of tasks that require precise perception and/or action interactions with the environment. However, they cannot be taken as unambiguous evidence in favor of that hypothesis. This is because of a possible confound of talking on measured postural sway in Experiment 1. Experiment 3 was designed to address this confound.

Chapter V

Experiment 3: Spoken and Silent Mental Arithmetic

The results of Experiments 1 and 2 were consistent with the stated hypotheses, and with the general hypothesis that body sway can be subtly modulated in support of the perception-action demands of supra-postural tasks. However, there was a confound in Experiment 1. Experiment 1 consisted of two conditions, one which did not require vocalization and one which did. 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. In Experiment 1, this could have led to an artifactual increase in measured body sway. But this seems unlikely, given the results of Experiment 2, in which significant differences in response rate across conditions—and so, presumably, differences in talking-related movement—did not produce a significant difference in measured sway. Nevertheless, a direct test was desirable.

The purpose of Experiment 3 was to evaluate the possibility that measured body sway in the mental arithmetic condition of Experiment 1 might have been artifactually influenced by the fact that participants spoke the results of their iterative counting. In Experiment 3, I compared body motion during spoken and silent mental arithmetic.

Method

Participants

Eight undergraduate students from the University of Cincinnati (2 males, 6 females) received course credit for participating in Experiment 3. 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 21 years (mean = 19.38, median = 19, mode = 19), and in height from 154 to 170 cm (mean = 164.5 cm). One participant had corrected vision (glasses or contacts).

Procedure

Participants completed eight trials of the hard mental arithmetic task (iterative subtraction by 3 from a 3-digit number). On half of the trials participants were asked to conduct the iterative subtraction aloud, while on the other four trials they were asked to subtract silently. The starting three digit number and condition order were randomized. As in Experiments 1 and 2, a rest break was imposed after the fourth trial. The spoken condition was the same as the mental arithmetic condition in Experiment 1. To provide some metric for assessing performance in the silent counting condition, participants were asked to report at the end of each trial what number they had reached. Participants were instructed to provide their final number to help insure that they were indeed performing the task. While performance was not directly observable, participants were deemed

likely to comply with experimental instructions to perform mental subtraction if they believed they were being evaluated on this measure.

They were asked to conduct the iterative subtraction “at a quick, steady pace” in both conditions. To facilitate this request they were given a practice trial during which they performed vocalized backwards counting in order to gauge their rate of responding so that they could match it for the silent trials. The experimental display was the same as in Experiment 2. In Experiment 3, data on subjective mental workload were not collected.

Results

Mental arithmetic. Participants’ performance on the spoken mental arithmetic task was evaluated in terms of the percent of correct responses per trial and response rate per minute trial length. Each measure was averaged to provide mean values across all trials. Across participants, the mean accuracy was 91%, with a response rate of 28 responses per minute. As noted earlier, performance in the silent condition was not directly observable as participants provided only the last number they reached through silent iterative subtraction at the end of each trial.

Postural sway. The postural data are illustrated in table 3 and figures 8 and 9. Paired *t*-tests on mean standard deviation of body position were not statistically significant in the AP axis ($t_{(7)} = 1.276$, $p > .05$). However, significance was found in the ML axis ($t_{(7)} = 2.845$, $p < .05$) with an effect size of $d_{ML}=1.01$. ML sway was greater during performance of the vocalized task.

	Spoken mental arithmetic		Silent mental arithmetic	
	Mean(cm)	SD(cm)	Mean(cm)	SD(cm)
Body sway AP	0.82	0.27	0.72	0.27
Body sway ML	0.57	0.12	0.50	0.13

Table 3. Postural data for Experiment 3. SD = standard deviation.

Figure 8. Graph of means for body position in the AP axis as a function of task condition. Error bars represent the 95% confidence interval. Experiment 3.

Figure 9. Graph of means for body position in the ML axis as a function of task condition. Error bars represent the 95% confidence interval. Experiment 3.

Discussion

Experiment 3 was designed to determine whether the significant results from Experiment 1 were actual condition effects or were spurious, arising from the effects of speech on postural sway. In this experiment, mental arithmetic was performed either aloud or silently. During task performance, postural sway in the AP axis did not differ across the spoken and silent tasks. Thus, the significant difference in AP sway between the spoken mental arithmetic and visual signal detection tasks observed in Experiment 1 cannot be attributed to the fact that participants spoke during the mental arithmetic task and were silent during visual signal detection.

In Experiment 3, sway in the ML axis was significantly greater during spoken mental arithmetic relative to ML sway during silent mental arithmetic. This result indicates that speaking did have an effect on postural sway in the ML axis. However, the

effect in the ML axis may be independent of (and so unrelated to) body sway in the AP axis. There are two lines of evidence that support the possibility that AP and ML sway are independent. The first line of evidence is based on biomechanical measurements (Winter, Prince, Frank, Powell, & Zabjek, 1996; Winter, Prince, Stergiou, & Powell, 1993). Winter et al. (1993, 1996) noted that because of anatomical constraints, different muscle groups acting at different joints are responsible for the production of torques that result in body motion in the AP and ML directions. Postural motions in the AP direction result from activity about the ankle (i.e., plantar flexor and dorsiflexor activity), while postural motions in the ML direction result from activity about the hip (i.e., abductor and adductor activity). Winter et al. proposed that if motions in the different axes result from the activities of different muscle groups acting about different joints, then postural motions in the different axes may be independent of one another, to the extent that the muscle groups can be activated independently. Using biomechanical measurements taken simultaneously from two force platforms (one beneath each foot), Winter et al. (1996) found evidence to support the proposal that the muscle groups respectively responsible for AP and ML sway functioned independently of one another. Thus, they concluded that self-generated AP and ML body motions are independent of one another.

The second line of evidence is based on statistical time series analyses of AP and ML postural sway (Balasubramaniam et al., 2000; Balasubramaniam & Turvey, 2000; Rosenblum, Firsov, Kuuz, & Pompe, 1998). Of greatest relevance to the present study, a broad range of correlation measures (e.g., linear coherence, cross-average mutual information, and cross-general mutual information) revealed that AP and ML center of pressure data did not share any significant degree of spatio-temporal structure. That is,

the motions of the body in the AP and ML directions were statistically independent of one another.

The results of Winter et al. (1993, 1996), Rosenblum et al. (1998), and Balasubramaniam et al. (2000; see also Balasubramaniam & Turvey, 2000) lend strong support to the idea that AP and ML postural sway can be independent of one another. Thus, the results lend credibility to the interpretations of Experiments 1 and 3 stated above—the significant increase in body sway in the ML axis while talking in Experiment 3 is not relevant to the significant results of Experiment 1, which were in the AP axis. While statistically significant sway differences were observed in the ML axis for Experiment 3, there were no such differences in Experiment 1. In Experiment 1, sway in the ML axis did not differ across conditions. This may have been because the two visual tasks in this experiment were not identical, as they were in Experiment 3. In Experiment 3, both conditions involved fixating the same visual target (the stationary ball). However, in Experiment 1, the visual targets for the two conditions were not the same; participants performed the visual signal detection task for one condition and fixated on the blank computer monitor during the other. This may account for the absence of an ML sway effect in Experiment 1.

Chapter VI

General Discussion

The purpose in conducting these experiments was to explore the relationship between postural control and the performance of supra-postural tasks in which cognitive and perceptual demand were varied independently. The main goal of my research was to determine whether posture is influenced by cognitive activity, *per se*, or only by cognitive activity that relies on perceptual contact with the environment. I hypothesized that postural sway should be reduced during performance of supra-postural tasks having a perceptual component, but not during performance of supra-postural tasks that were entirely cognitive, having no perceptual component. In Experiment 1 I addressed this by varying visual (perceptual) demand across tasks that had been equated for cognitive demand (i.e., subjective mental workload). There were two task conditions: (1) visual signal detection; and (2) mental arithmetic. Postural sway was less in the AP axis for the signal detection condition, relative to sway during mental arithmetic. In Experiment 2, I varied cognitive demand while maintaining a constant level of perceptual demand, and found that variation in the subjective workload of mental arithmetic had no effect on postural sway. Experiment 3 was conducted to address a potential confound of speech on the measurement of postural sway during Experiment 1. The results suggest that speech did not compromise my measurements of body sway in the AP axis. My general conclusion is that my original hypothesis was supported. Several issues raised by my research are discussed below.

Postural support for perceptual coupling with the environment

Riccio and Stoffregen (1988) suggested that, in addition to maintaining balance, body sway might be controlled to support performance on supra-postural tasks. Few studies have attempted to evaluate this possibility. However, studies that were designed to evaluate it have yielded results supporting it (e.g., Riley, Mitra, Stoffregen, & Turvey, 1997; Riley, Stoffregen, Grocki, & Turvey, 1999; Stoffregen et al., 1999, 2000). In the Stoffregen et al. (1999, 2000) studies, however, variations in visual perceptual demand were confounded with variations in cognitive demand. The functional hypothesis presented by Riccio and Stoffregen implies that task-specific modulation of posture should not occur for supra-postural tasks that are “purely” cognitive, that is, for tasks that can be performed without perceptual contact with the environment. The main goal of my research was to isolate visual demand from cognitive demand and explore how these factors are related to changes in postural sway.

In some contemporary views of stance, postural control is conceptualized as requiring central processing resources (e.g. Lajoie, et al., 1993; Teasdale, et al., 1993; Kerr, et al., 1985). In this framework, the precision or accuracy of postural control should suffer (i.e., sway becomes more variable) when standing participants are required to engage in non-postural tasks that require cognitive processing. Put simply, postural control should be best (i.e., most accurate, or efficient), during “quiet stance”, that is, when stance is the only task. Increases in the cognitive demands of supra-postural tasks should produce either (1) degradation in the control of posture, (2) degradation in the performance of supra-postural tasks, or (3) both. This view has led to experiments in

which the kind or difficulty of cognitive tasks is manipulated and the resultant postural effects are observed under different stance conditions (e.g., Maylor & Wing, 1996).

A variant of the above view is to manipulate the biomechanical difficulty of postural control and examine the resulting effects on the performance of supra-postural tasks. Increasing the biomechanical difficulty of stance should increase the demand for central resources imposed by postural control. Here, the assumption is that when balance is threatened, cognitive resources will be diverted to maintaining balance, at the expense of any other concurrent cognitive activity. In evaluating this hypothesis, researchers have manipulated characteristics of the surface of support. A foam surface reduces the stability of stance, if stability is defined in terms of the gross amount of sway (e.g., Marsh & Geel, 2000). Compared to stance on a hard surface, standing on foam generally is characterized by greater sway variability. The biomechanical difficulty of stance can also be increased by requiring participants to assume the Tandem Romberg stance (i.e., heel-to-toe; e.g., Kerr et al., 1985). Performance on a cognitive task (e.g., a reaction time task) has been shown to suffer as a consequence of standing on foam because more attentional resources are being used to maintain balance (Teasdale et al., 1993). These findings have been interpreted as indicating that in these unusual stances, fewer cognitive resources are available to perform the arithmetic task.

The view described above would appear to make clear predictions about Experiments 1 and 2 of the present study. In Experiment 1, in which perceptual demand was varied while cognitive demand was held constant, there should be no difference in body sway between the signal detection and mental arithmetic conditions. In Experiment 2, the more difficult (i.e., higher workload) arithmetic task should yield degraded postural

performance (because of the demanding nature of the arithmetic task, which would divert central resources away from postural control), while the easier mental arithmetic task should be associated with reduced sway (because more central resources would be available to be utilized in postural control).² The results of Experiments 1 and 2 did not support these predictions and, in fact, contradicted them. The data are not consistent with the idea that postural control engages in an antagonistic competition with supra-postural activities for a limited pool of central cognitive resources.

The data do support predictions derived from the idea that postural control is integrated with supra-postural activity in a functional manner. I predicted that sway would be reduced in a situation that involved a direct perception-action link with the environment, that is, when reduction in sway could facilitate perceptual performance. I have shown that cognitive demand alone does not necessitate postural adaptation, but that visual demand can. This is consistent with the general position articulated by Riccio and Stoffregen (1988; cf. Bernstein, 1996; Reed, 1988) and tested by Stoffregen et al. (1999, 2000). This same position can account for numerous findings in the studies of Hunter and Hoffman (2001), Marsh and Geel (2000), Maylor and Wing (1996) and others (e.g., Kerr et al., 1985), in which variations in the difficulty of postural control did not have a detrimental impact on the performance of supra-postural tasks (or vice versa). Thus, the functional integration view appears to account for a wider spectrum of empirical findings than does the central competition view.

² The mainstream theoretical perspective does not make clear predictions about the outcome of Experiment 3. The spoken mental arithmetic task of Experiment 3 might be expected to require greater central processing than the silent task, but only if it is assumed that speech requires greater cognitive activity than performing the same task silently. Since there is no direct statement about cognitive demand associated with speech per se, this prediction is conjectural.

Postural motion versus speech motion

Experiment 3 was conducted to address a possible artifact of speech motion on measured body sway in Experiment 1. Experiment 1 consisted of a signal detection task that did not involve speaking, and a spoken arithmetic subtraction task. As I predicted, postural sway was significantly less during the signal detection condition. I interpreted this result as indicating that postural sway is more tightly controlled to facilitate visual performance. However, this interpretation relied on an assumption that the act of talking (which involves jaw movements and a different breathing pattern as compared to breathing uninterrupted by speech) was not the cause of greater sway variability in the spoken arithmetic task. A control experiment was needed in order to clarify the potential effects of speech on sway.

Experiment 3 addressed this issue by comparing body sway during vocalized and silent mental arithmetic tasks. In Experiment 3, there were no significant postural effects between the two conditions in the AP axis. This is an important result, because the AP axis was the axis of significance in Experiment 1—the only differences in body motion between the cognitive and visual signal detection conditions seen in Experiment 1 was in the AP axis. Because no differences in AP body sway were seen in Experiment 3, the results of Experiment 1 can be interpreted in terms of stabilization demands imposed by the visual signal detection task. However, in Experiment 3 there was a significant difference in ML postural sway between silent and vocalized conditions. When talking, there was a greater amount of postural sway in the ML axis. This result does suggest that the act of vocalizing, in and of itself, can influence the degree of body sway, but because

the effect was in the ML axis rather than the AP axis, it does not imply that the results of Experiment 1 were artifactual.

My interpretation of the results of Experiment 3 is credible to the extent that body sway in the AP and ML axes can be considered to be independent of one another. If AP and ML sway are independent, then an effect in the ML axis in Experiment 3 has no bearing on the effect in the AP axis in Experiment 1. As noted earlier, the independence of sway in the AP and ML axes can be argued on both biomechanical (Winter et al., 1993, 1996) and empirical grounds (Balasubramaniam, Riley, & Turvey, 2000; Balasubramaniam & Turvey, 2000; Rosenblum et al., 1998). The work of Winter et al. (1993, 1996), Rosenblum et al. (1998), and Balasubramaniam et al. (2000) lend converging support to the idea that AP and ML postural sway are independent of one another. Thus, their results lend credibility to the interpretations of Experiments 1 and 3 stated above—the significant increase in body sway in the ML axis while talking in Experiment 3 is not relevant to the significant results of Experiment 1, which were in the AP axis.

Additional support for that interpretation comes from consideration of the results of Experiment 2, which are directly interpretable. In Experiment 2, there was no speech-related confound, as both conditions involved vocalization and performance on the same type of task (mental arithmetic). The two arithmetic tasks in Experiment 2 differed significantly in terms of rated overall workload, response rate, and accuracy of performance. The difference in response rate is of direct relevance to the present issue. Responding was significantly more rapid in the Easy mental arithmetic condition, which means that participants spoke more often in that condition. Thus, if speech-related

motion was measured as body sway, we might expect an increase in measured sway in the Easy condition of Experiment 2, yet there were no task—or condition—related differences in body sway, in either the AP or ML axis. Thus, in Experiment 2, measured body sway was not affected by concurrent speech, supporting my interpretation of the results of Experiments 1 and 3 about relations between speech and measured body sway.

Taken together, the three experiments can be most easily interpreted as showing that the act of speaking did not have an artifactual effect on measured body sway in Experiment 1. Therefore, the significant effect of supra-postural tasks on measured sway in Experiment 1 should be taken at face value. Postural control supports perceptual task performance because of the direct link to the perception and action requirements of the organism. Strictly cognitive task performance does not require an organism to maintain a specific perceptual relation to the environment; therefore, postural control should not affect the process of cognition.

Possible learning effects

A related interpretation of the results of Experiment 3 is suggested by the work of Pagulayan (2000). Pagulayan found that, across trials, participants changed their postural sway patterns, and that the changes tended to facilitate performance with respect to the supra-postural visual tasks (signal detection). Experiment 3 consisted of 4 trials per condition. It is possible that postural sway behaviour changed over trials as participants adapted to the task requirements. If so, it might have been appropriate to provide participants with a practice period prior to the experimental trials, in order to minimize

changes in postural sway that would be attributable to postural exploration and learning. A less desirable alternative would be to remove the first trial from each condition from the data analysis. That is, the first trial in each condition might be construed as a practice trial. This approach is less desirable because it would reduce the number of experimental trials included in data analysis. Ultimately, new research should be conducted that is deliberately designed to assess possible changes in postural control with experience at different supra-postural tasks.

In the present study, several participants indicated that they were apprehensive and self conscious about performing iterative spoken subtraction in the presence of an audience (the experimenters), especially when they were asked to speak loudly so the microphone would record their voice. Sometimes participants would engage in small extraneous movements, or “fidgeting”, while hesitantly speaking their arithmetic results. Familiarity with the task seemed to reduce anxiety, and participants often seemed more at ease during subsequent trials. Once participants were more comfortable with the demands of the task, they decreased their “fidgety” behaviour. Thus, the first trial of each condition might exhibit uncharacteristically increased body sway as a result of the small extraneous movements associated with being self conscious about task performance. Including data from trials in which participants are learning to cope with the demands of the arithmetic task (i.e., the first trial) may mask sway differences that are due to the experimental manipulations.

Implications for human factors design

Research on postural control that investigates the nature of the perception and action requirements of task performance can offer some important insights into the realm of virtual reality and virtual environments (VR/VE). A VR/VE may be represented by a wide array of simulation systems, such as a fixed or moving base driving or flight simulator. As well, it may consist of a system that immerses the user in a virtual world by means of a head mounted display (HMD) that incorporates such peripherals as 3-D audio and motion sensors that allow the user to interact with the computer-generated environment. There are many potential applications of this family of technologies for education, entertainment, and business. One example is the creation of teleoperation systems where human operators remotely control industrial processes or manipulate objects (e.g., Smets, 1995). Teleoperation allows people to manipulate or act on objects and systems that occur in an environment otherwise detrimental to human well-being (e.g., working with radioactive materials, or in extreme hot or cold temperatures). Collaborative Virtual Environments (CVE) represent an emerging extension of this technology, allowing multiple users from different geographical locations to meet and to work collaboratively in virtual, interactive, meeting rooms (Benford, Greenhalgh, Rodden, & Pycock, 2001). Potential uses involve collaborative design efforts where all parties can manipulate and interact with other people and objects in the virtual meeting space.

One major drawback of VR/VE technology is that some users of these systems experience a multitude of motion sickness-like symptoms during or after system use.

Termed “cybersickness”, the symptomology includes eye strain, headache, disorientation, nausea, and vomiting (LaVoila, 2000; Howarth, 1999). These symptoms range from inconvenient to potentially very dangerous for the user (e.g., if disorientation is experienced hours after leaving a simulator while driving a car). In order to realize the full potential of this technology, there needs to be a greater understanding of what causes cybersickness and how to control for it through design.

The competing theories attempting to address why and how some individuals experience cybersickness enjoy varying levels of support, but no one theory adequately predicts who will become sick and the severity of the symptoms (Cobb, 1998). However, the ecological theory of motion sickness (Riccio & Stoffregen, 1991) offers some insight into the potential causes of cybersickness and how informed design may help alleviate the problem. Riccio and Stoffregen (1991) have suggested that prolonged postural instability causes and precedes motion sickness (and cybersickness). Postural stability refers to the minimization of uncontrolled movements in the perception and action systems (Riccio & Stoffregen, 1991). For instance, wearing an HMD changes the normal relation between postural sway and vision. Sensors updating HMD display information identify where the head is pointing (so that people can look around the virtual environment to uncover information in much the same way as turning the head reveals a different part of the real visual scene), and the visual display is updated accordingly. My experiments have supported the hypothesis that postural control is regulated to facilitate performance on perceptually based supra-postural tasks, which suggests that HMD head tracking needs to incorporate subtle body sway changes in addition to simply monitoring the direction in which the head is pointing. The visual display should subtly change the

depth of focus of objects projected onto the screen in a similar manner to how AP sway changes the depth of focus for objects in the real world.

Body sway is naturally influenced by action in the environment. This relationship should be maintained when designing virtual systems in order to minimize postural instability that results from a mismatch between body sway and what is presented visually. Minimizing postural instability for the user of VR/VE systems may be achieved through designs that actively incorporate postural sway and change visual information accordingly. For instance, eyestrain commonly experienced while using head-mounted displays (HMD) may result from the operator's inability to stabilize the visual scene through body sway. The operator may be forced to over-use the eye as the sole method to accommodate fixation. HMDs decouple the human from the environment by removing the effect that postural sway has on the visual scene. Therefore, what may be needed is a system that re-introduces this human-environment coupling that is removed when a visual display is placed on the head of an operator.

Future directions

Several questions are raised by the present study. Additional research is needed to clarify the relationship between cognition, perception, and postural control. My results suggest that controlled changes in body sway, which are used to facilitate performance of visually-demanding supra-postural tasks, do not appear to be used in response to variations in the difficulty of purely cognitive supra-postural tasks. I achieved this result through a contrast between supra-postural tasks that did or did not involve visual demand.

Alternative, converging methods could be used to assess the generality of this effect. For example, it might be possible to vary the level of difficulty of a visual signal detection task without varying the precision of ocular control required for task performance.

An appropriate task might use as neutral events contrast gratings that subtended a large visual angle. The critical signal might be an otherwise identical grating having a different degree of contrast. An easy task could be constructed in which the contrast in the critical signal differed greatly from the contrast in the neutral event, and a hard task could be created in which the neutral and critical signals differed only slightly in contrast. Contrast sensitivity is roughly equal across a wide region of the retina (Legge & Kersten, 1987), and so precise control of ocular position would be unnecessary. With tasks of this kind, cognitive demand could be varied (i.e., via the hard and easy tasks), while maintaining a constant low level of ocular demand. The appropriate bar width and contrast levels could be determined based on information about the sensitivity of the retina at different eccentricities from the fovea.

If properly designed, the hard version of such a contrast-based signal detection task should require more concentration and mental effort than the easy version (and so, should result in higher subjective mental workload), but would not require or benefit from any increment in the precision with which the eyes were pointed or stabilized. Neutral and critical signals could be adjusted so that the rated workload for the contrast-based hard and easy tasks matched the workload for the hard and easy signal detection tasks used by Pagulayan (2000), respectively. Then, I would predict that there would be a significant difference in rated workload between the hard and easy contrast-based visual

tasks, and that any variation in postural motion across the contrast-based task conditions would be independent of this workload effect.

In the present study, I examined how task demands influenced body sway while maintaining the same stance throughout. Additional research is needed to address the reciprocal effects of difficulty of stance on cognitive task performance. For instance, mainstream researchers (e.g., Marsh & Geel, 2000) hypothesize that cognitive task performance is degraded as a consequence of increasing stance difficulty (e.g., standing on a hard surface versus a foam surface; standing heel-to-toe versus feet at shoulder width). This type of hypothesis may be addressed from my perspective. For instance, visual demand can be held constant across conditions where participants perform mental arithmetic while standing in differentially demanding ways. I would expect that cognitive task performance would be equal across standing conditions provided that perceptual (visual) demand is also held constant across conditions.

Conclusion

I manipulated both the perceptual and cognitive demand of several supra-postural tasks while observing body sway. In Experiment 1, I showed that postural sway was less during performance of a visually demanding task as compared to a purely cognitive task, with the tasks equated for overall subjective mental workload. Experiment 2 manipulated the difficulty of two purely cognitive tasks (with differentially rated subjective mental workload) and revealed that body sway was not significantly different in the two tasks. Finally, Experiment 3 served as a control for the effects of speech on postural sway.

Results were interpreted as supporting the findings of Experiment 1, that sway reduction was task-related rather than speech-related. The argument that postural sway increases as a function of cognitive demand, due to a reduction in attentional resources available for postural control, was not supported. The results provide support for the view that postural control is a goal-directed behaviour governed by the perception and action requirements of supra-postural tasks.

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Appendix

SUBJECT INSTRUCTIONS: RATING SCALES

We are not only interested in assessing your performance but also the experiences you had during the different task conditions. Right now we are going to describe the technique that will be used to examine your experiences. In the most general sense we are examining the "workload" you experienced. Workload is a difficult concept to define precisely, but a simple one to understand generally. The factors that influence your experience of workload may come from the task itself, your feelings about your own performance, how much effort you put in, or the stress and frustration you felt. The workload contributed by different task elements may change as you get more familiar with the task, perform easier or harder versions of it, or move from one task to another. Physical components of workload are relatively easy to conceptualize and evaluate. However, the mental components of workload may be more difficult to measure.

Since workload is something that is experienced individually by each person, there are no effective "rulers" that can be used to estimate the workload of different activities. One way to find out about workload is to ask people to describe the feelings they experienced. Because workload may be caused by many different factors, we would like you to evaluate several of them individually rather than lumping them into a single global evaluation of overall workload. This set of six rating scales was developed for you to use in evaluating your experiences during different tasks. Please read the descriptions of the scales carefully. If you have a question about any of the scales in the table, please ask me about it. It is extremely important that they be clear to you. You may keep descriptions with you for reference during the experiment.

After performing each of the tasks, you will be giving a sheet of rating scales. You will evaluate the task by putting an "X" on each of the six scales at the point which matches your experience. Each line has two endpoint descriptors that describe the scale. Note that "own performance" goes from "good" on the left to "bad" on the right. This order has been confusing for some people. Please consider your responses carefully in distinguishing among the different task conditions. Consider each scale individually. Your rating will play an important role in the evaluation being conducted, thus, your active participation is essential to the success of this experiment and is greatly appreciated by all of us.

Appendix (cont'd)**SUBJECT INSTRUCTIONS: SOURCES-OF-WORKLOAD EVALUATION**

Throughout this experiment the rating scales are used to assess your experiences in the different task conditions. Scales of this sort are extremely useful, but their utility suffers from the tendency people have to interpret them in individual ways. For, example, some people feel that mental or temporal demands are the essential aspects of workload regardless of the effort they expended on a given task or the level of performance they achieved. Others feel that if they performed well the workload must have been low and if they performed badly it must have been high. Yet others feel that effort or feelings of frustration are the most important factors in workload; and so on. The results of previous studies have already found every conceivable pattern of values. In addition, the factors that create levels of workload differ depending on the task. For example, some tasks might be difficult because they must be completed very quickly. Others may seem easy or hard because of the intensity of mental or physical effort required. Yet others feel difficult because they cannot be performed well, no matter how much effort is expended.

The evaluation you are about to perform is a technique that has been developed by NASA to assess the relative importance of six factors in determining how much workload you experience. The procedure is simple: You will be presented with a series of pairs of rating scale titles (for example, Effort vs. Mental Demands) and asked to choose with of the items was more important to your experience of workload in the task(s) that you just performed. Each pair of scale titles will appear on a separate card.

Circle the Scale Title that represents the more important contributor to workload for the specific task(s) you performed in this experiment.

After you have finished the entire series we will be able to use the pattern of your choices to create a weighted combinations of the ratings from that task into a summary workload score. Please consider your choices carefully and make them consistent with how you used the rating scales during the particular task you were asked to evaluate. Don't think that there is any *correct* pattern: we are only interested in your opinions.

If you have any questions, please ask them now. Otherwise, start whenever you are ready. Thank you for your participation.