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Abstract

It has been proposed that postural movements can be controlled so as to facilitate visual performance. Tasks that require more precise visual fixations should result in a decrease in postural sway variability. Three experiments were conducted that focused on (1) differences in postural behavior when tracking a moving versus stationary target, and (2) differences in postural behavior under constraints on visual performance theoretically unrelated to eye movements in a target detection task. In the first two experiments, sway variability was reduced when tracking a moving target relative to a stationary one. In the third experiment, sway variability was reduced when performing a more difficult target detection task, but only towards the latter part of the experiment. It seems that the functional relation between body sway and task demands developed over trials. Overall results suggest that postural behavior can be used to facilitate the achievement of other tasks. Results also suggest potential postural learning for more complex tasks to achieve adequate visual performance. Implications for the design of human-machine systems were discussed.
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Chapter I

INTRODUCTION

A large portion of vision research focuses on eye movements or on the physiology of the eye. This research has yielded important findings, and while it is obvious that vision is critically influenced by the sensitivity and motion of the eyes, it is less widely appreciated that in normal life, vision is also strongly influenced by other parts of the body, such as head movements. For behavioral scientists, the importance of studying perception and behavior in the context of a particular environment has been well established. In fact, many researchers have acknowledged the symbiotic relationship between an organism and its actions in an environment to the extent of arguing that perception and behavior cannot be understood without taking the perception-action interplay into account (e.g., Gibson, 1979/1986; Hancock & Chignell, 1995; Harris & Jenkin, 1998; Reed, 1996). In the case of vision, Gibson (1966) argued that our ability to see is strongly influenced by movements of the entire body, and that this influence is both functional and routine. Simple examples include walking around an object so as to be able to view it from multiple perspectives, and leaning toward an object, so as to be able to see it “up close.” Gibson offered an expanded definition of the visual system based on the notion that movements of the head and body influence the information that is available to the eyes. And yet, there has been very little research on the use of body
motion to facilitate vision. The present study addresses this topic in the context of postural sway.

*Action is organized around behavioral goals*

Action may be controlled, in part, to facilitate visual performance. From this perspective, the task of a behavioral scientist should be to determine the lawful nature of the integration of action with vision. On what basis does the person select among the range of available options for the control of action? Similarly, what drives the selection of perceptual information that is used for the control of behavior? One factor is behavioral goals. To the extent that behavior is goal directed, then in order to understand perception and behavior, behavioral goals must be taken into account. Behavioral goals impose constraints on the organization of action (Riccio & Stoffregen, 1988). At a general level, this notion contrasts with the hypothesis that behavior is organized with respect to constraints imposed by the nervous system, such as processing strategies, memory limitations, or physical dynamics of the body (cf. Turvey, Fitch, & Tuller, 1982). Of course, these two types of constraints need not be mutually exclusive. However, research on motor control has placed relatively little emphasis on ways in which action is constrained by behavioral goals.

Several lines of research suggest that the organization of perception and action is modulated to facilitate goal achievement (e.g. Fitch, Tuller, & Turvey, 1982; Fouque, Bardy, Stoffregen, & Bootsma, 1999; Latash, 1996; Riccio & Stoffregen, 1988). Young children show adaptive variations in postural control on differing surfaces of support.
Research in multi-segment postural control has shown that particular modes of coordination emerge dynamically under varying task conditions (Bardy, Marin, Stoffregen, & Bootsma, 1999; Marin, Bardy, Baumberger, Flückiger, & Stoffregen, 1999). Analyses of the spatial and temporal structure of postural sway have been shown to differ adaptively when people perform different postural goals (Balasubramaniam, Riley, & Turvey, 2000; Riley, Mitra, Stoffregen, & Turvey, 1997). Although these studies suggest that goals can organize behavior, the emphasis remains on postural control and not visual performance. Research on visual performance suggests that action is organized via goal constraints. For example, target identification tasks are influenced by behavioral goals rather than simply by the physical properties of the stimulus (Maruff, Danckert, Camplin, & Currie, 1999). Moreover, a review of the literature on the readability of text on computer screens suggests that superior visual performance depends on what the reader’s goal is (Mills & Weldon, 1987). However, studies such as those have not considered the possibility that postural movements may have a facilitory effect on visual performance.

In discussing the functional role of body movement in vision, Gibson (1966) concentrated on gross movements, such as walking, and on movements that result from deliberate, conscious control. One example might be walking around a piece of sculpture, so as to be able to see all sides of it. Such movements certainly influence vision, and are often instituted and organized to facilitate vision. However, the functional influence of body motion on vision may not be limited to gross movements. It has been proposed that spontaneous postural movements (the small-amplitude body motions that occur in the absence of externally imposed perturbations) may be controlled so as to
facilitate the performance of other behaviors that are engaged in during stance (e.g., Harris & Jenkin, 1998; Latash, 1996; Reed, 1988; Riley et al., 1997; Riley, Stoffregen, Grocki, & Turvey, 1999). The movements in question tend to be very subtle. Of particular relevance to the current research are studies indicating that the organization of postural sway can be influenced, in a functional manner, by the demands of visual tasks (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999).

The primary goal for this dissertation is to examine the influence of different types of visual tasks on body sway. My hypothesis is that variations in the need for ocular stability will produce functional changes in the organization of body sway. That is, I propose that body sway will be controlled in different ways during the performance of different visual tasks, and that those variations in body sway will facilitate visual performance.

What follows in this chapter is a discussion of vision and potential constraints on visual performance. Based on Gibson’s broader view of the visual system (1966), I then relate visual performance to postural behavior and provide an overview of a general class of postural research. Then, I review some recent literature which suggests that posture may be controlled to facilitate higher order goals. In subsequent chapters, I describe three experiments that examine relations between body sway and visual performance. Two of these address the way body sway can be used to facilitate visual performance during eye movements. The third examines the utility of body sway in visual tasks that do not require eye movements. This latter experiment also includes a precise measure of visual task performance, thereby permitting the quantification of relations between visual
performance and body sway. The final chapter offers implications of this work for the paradigm of studying postural control in the context of behavioral goals, as well as implications of the experimental results for human factors issues.

Visual Performance and the Broader Visual System

Many types of visual performance require precise visual acuity, and so depend upon the fovea (Levy-Schoen, 1983). Acuity is highest in the central fovea with progressive degradation towards the periphery (Coren, Ward, & Enns, 1994). Generally, in order to differentiate fine details it is necessary to direct the fovea precisely on the object of regard, thus sacrificing visual acuity for objects in the periphery (Humphreys, 1996). In addition, the fovea (and the entire eye) must be held stable relative to the object of regard. The position and stability of the eye are influenced by the ocular muscles, but also by movements of the head and body. When demands on ocular stability are great, performance may be influenced by very small movements of the head and body, such as those that characterize postural sway. In the following sections, I will define various constraints on visual performance, and then discuss how body movements aid in achieving optimal visual performance.

Constraints on visual performance

Eccentricity. Research has amply demonstrated the importance of stabilizing an image on the fovea for optimal visual acuity. As the retinal image of a fixated target is
moved out towards the periphery, visual performance suffers (Donk, 1993; Findlay & Crawford, 1983; Kapoula, 1983; Nazir, 1993; Reilley, 1993; Wolfe, O’Neill, & Bennett, 1998). Thus, eccentricity, or retinal displacement of an object from the center of the retina, is a constraint on visual performance. Reilley (cf. Nazir, 1993) has shown that the spatial resolution of letters decreases as a function of eccentricity; increases in eccentricity led to decreases in the accuracy of letter identification. Donk (1993) performed a target detection study where participants were required to identify the capital letter ‘R’ among a group of distractor letters. Visual performance decreased with increasing eccentricity. The importance of foveation is of course, not limited to the perception of letters. For example, even one degree of eccentricity is enough to reduce the visual discrimination of four versus five dots to chance (Findlay & Crawford, 1983).

*Luminance and contrast.* Visual performance is also influenced by properties of the object of regard. Among these are luminance and contrast ratio. *Luminance* is the amount of light reflected from a surface (Coren et al., 1994). *Contrast ratio* represents the luminance difference between light and dark regions of an image (Coren et al., 1994). In order to discriminate targets with low levels of luminance, or in situations where the target reflects very low levels of light, objects of fixation require more precise visual stabilization on the retina in order to perceive the target. A physiological explanation can be found in the retinal ganglion cells and the cells of the lateral geniculate nucleus (LGN), which are most sensitive to differences in luminance (Deubel, Findlay, Jacobs, & Brogan, 1988). These retinal ganglion cells mainly reside in the fovea, which specialize in low-contrast sensitivity. Thus, in order to perceive targets in these situations, the physiological components of the visual system responsible for perception are mainly
retinal ganglion cells and the LGN. Therefore, the object of fixation needs to be positioned on the fovea.

In terms of luminance and contrast ratio, the more difficult an object is to perceive, the longer the eye will remain fixed on it (Kapoula, 1983). The amount of fixation time can be controlled by presenting stimuli for limited periods of time. For stimuli that are presented for less than 300 ms, the probability of discriminating a detail can be increased by increasing the contrast ratio (Coren et al., 1994; Proctor & Van Zandt, 1994). However, this effect should exist for longer durations as well. Increasing contrast ratio should increase the probability of discriminating detail in most situations.

Luminance and contrast influence visual performance not only with stationary targets, but also in situations in which eye movements are required. Eye movements are less accurate and less efficient under conditions of low target luminance (0.3 cd/m²) but are more accurate and efficient with higher levels of target luminance (10-100 cd/m²) (Ditchburn, 1973). Deubel et al. (1988) even suggested that the computation of saccade distance is a direct function of target dissimilarity to its background structure, or contrast ratio. The greater the salience of the target is relative to its background, the more accurate oculomotor performance should be (Deubel et al., 1988; Kröse, 1987).

Contrast is a subject of much interest among designers of computer displays in operational settings. Higher contrast ratios between character and background produce better visual performance regardless of the colors used (Mills & Weldon, 1987). Radl (1980) concluded that luminance and contrast ratio were more important factors than color when reading letters. Similarly, Bouma (1980) found that the legibility of text on a computer screen is more dependent on contrast ratio than on color.
Because luminance and contrast ratio play such a large role in visual performance, the American National Standards Institute in conjunction with the Human Factors Society put forth a set of display guidelines to ensure ease of character recognition (Grandjean, 1987). Human factors design guidelines have also included recommendations relating to luminance and contrast ratio (Cushman & Crist; Grandjean, 1987a; Proctor & Van Zandt, 1994).

Eye movements. When discussing vision, it is not uncommon to use a classification based on eye movements. One classification is based on movement magnitude. For larger movements, the primary function is to bring the image of a target to the center of the fovea. Smaller movements are responsible for maintaining fixation in order to achieve precise levels of stabilization (Ditchburn, 1973). The eyes can and often do move independently of the body and head, and these movements give rise to their own optical flow as the retina moves relative to optical changes deriving from body movement.

Voluntary eye movements (both smooth pursuit movements and saccades) generally do not exceed 15° amplitude (Hallett, 1986). Eye rotation can exceed 15°, but when gaze is shifted beyond 15°, eye movements are typically supplemented by rotation of the head. This usually results in the total displacement of eye to be less than 15°.

Robinson and Zee (1981) suggested that rapid eye movements depend on what the head is doing. They broke down their descriptions into ones that incorporate head and eye movements together. Quick phase eye movements are rapid eye movements that move in the direction of head turns. Their purpose is to reorient the visual system in the field of view into the which the head turns. In other words, their purpose is to keep a
person looking in the direction his/her head turns. *Foveating saccades* place a specific image on the fovea during simultaneous head movements. This classification is useful because it takes body motions into account whereas previous descriptions did not.

For a more ecologically valid classification framework, head and body movements should be included as well. For example, when viewing a moving object, it is more natural to follow it with a combination of head and eye movements than to track it with our heads fixed (Tomlinson & Robinson, 1981). Fixed head and body positions are constraints characteristic of laboratory situations, not those outside the laboratory.

*Relations between visual performance and postural sway*

Visual stabilization is one of the fundamental requirements for successful vision, but theory and research on eye movements have concentrated on seated, restrained persons who are not allowed to control their body posture. However, to optimize acuity, the visual system must integrate sources of information ranging from visual inputs from the fovea and the retinal periphery to the influence of head and body motions (Koenig & Dichgans, 1981). Body sway produces optical changes that are projected into the eye. Thus, in many ordinary situations the optical flow to which the visual system is exposed has multiple sources, including body sway.

Research in the field of vision has sometimes unintentionally produced results that suggest a functional relation between visual performance and postural sway. Barnes (1981) asked participants to visually track a sinusoidally moving target. During slow velocity movements (< 20°/second) and low frequencies (< 0.5 Hz), eye and head
movements were highly coupled with the target motion. As the frequency, velocity, and amplitude of displacement were increased, eye movements became more saccadic while the head movement continued to correlate highly with the target motion. Barnes concluded that eye movements were independent of head position even though they were both highly coupled with the target during slow velocity/low frequency movements. An alternative explanation could be based on the view that head movements facilitate visual stabilization.

As mentioned earlier, many studies suggesting that goals can organize behavior were established in the motor control literature with no explicit statements about visual performance. Similarly, it has been shown that visual performance studies which potentially support the organization of behavior by goals do not directly bring together the influence of body movements in the achievement of visual performance. In the next section I provide a theoretical motivation for the role of body sway in visual performance.

Posture and Supra-postural Tasks

This section briefly reviews current experimental practice in research on postural control and identifies an important assumption implicit in this practice. I will suggest that this assumption can and should be put to empirical test, and I will provide a theoretical basis for predicting the outcome of such tests. An alternative approach that focuses on behavioral goals other than upright stance will be presented.
The quiet stance paradigm

Research on stance commonly does not require participants to do anything other than maintain upright stance while attending to a perturbing stimulus (e.g., Dijkstra, Schöner, & Gielen, 1994; Stoffregen, 1985; Van Asten, Gielen, & Denier van der Gon, 1988). Some studies give participants no explicit task other than stance (e.g., Collins & De Luca, 1993; Yamada, 1995). None of those studies has directly manipulated behavioral goals. This approach to postural research is commonly referred to as the quiet stance paradigm.

The quiet stance paradigm presumes that the primary goal of postural control is the maintenance of postural stability, independent of the achievement of any other behavioral goals. Postural stability is commonly evaluated in terms of how close the center of mass ($C_M$) is relative to the base of support, in terms of biomechanical stability of the body (e.g., Collins & DeLuca, 1993; Yamada, 1995), or in terms of postural responses to a stimulus or perturbation (e.g., Dijkstra et al., 1994; Stoffregen, 1985). In at least one respect this approach is not representative of stance outside the laboratory (Stoffregen et al., 2000; Stoffregen et al., 1999). In daily life, posture is maintained across variations in the goals of behavior. Because the quiet stance paradigm does not include variations in behavioral goals, it cannot be used to evaluate the role of such variations in the organization of postural control. If a significant influence of behavioral goals on posture could be demonstrated, this would raise questions about the ability of the quiet stance paradigm to lead to a general understanding of posture.
**Facilitating supra-postural tasks**

Riccio and Stoffregen (1988) argued that stance is used as a means to achieving an end. From this viewpoint, postural control facilitates the achievement of *supra-postural* tasks (Riley et al., 1997; Stoffregen et al., 1999). Supra-postural tasks differ from the task of controlling posture in that they are defined and evaluated in qualitatively different terms. The success or failure of reading (for example) is not defined in terms of the position or motion of the body’s $C_M$, the minimization of global optical flow, and so on. These parameters of postural motion can influence performance on supra-postural tasks (e.g., excessive sway can degrade reading), but influences on supra-postural tasks are measured in different terms (e.g., reading rate or comprehension). Thus, supra-postural tasks differ qualitatively from postural control.

One implication of the quiet stance paradigm is that minimization of postural sway is the primary goal. Although minimizing postural sway may facilitate many supra-postural tasks, this strategy is in conflict with other types of supra-postural tasks that require movement such as jogging, dancing, or chasing a ball (Stoffregen et al., 2000; Stoffregen et al., 1999).

In some of the research which suggests that posture may be modulated adaptively to facilitate supra-postural tasks (e.g., Bardy et al., 1999; Marin et al., 1999; Riley et al., 1997), movement of the $C_M$ is required to perform the supra-postural task successfully. Because of this, no clear statements about the effect of supra-postural goals may be made due to the possibility that the previous effects found were influenced by the dynamics of the $C_M$, and not by supra-postural tasks (Stoffregen et al., 1999).
In order to test more accurately the hypothesis that posture modulates the achievement of supra-postural goals, it is necessary to study supra-postural tasks that do not require displacement of the $C_M$. One class of tasks that meet this requirement is visual performance tasks that do not require movements of the head. Postural control may be organized so as to facilitate visual performance in such tasks. As mentioned earlier, constraints on visual performance may revolve around the degree of stabilization or precision necessary to achieve a given task that does not necessarily require a change in $C_M$ movements.

**Facilitating visual fixation**

Lee and Lishman (1975) demonstrated the relation between vision and posture in an experiment that combined quiet stance, spontaneous sway, and optical flow. Participants were placed in a large lecture hall and told to fixate objects at different distances—a target on the far wall, or on a coat stand placed about 45 cm in front of them. The coat stand was removed when participants looked at the far wall. Lee and Lishman measured the amplitude of participants’ spontaneous (unperturbed) body sway and found that sway amplitude was lower when participants fixated the near than the far object.

At least two interpretations of these results can be made. The first interpretation, and often the standard one (Balasubramaniam et al., 2000), is based on the implicit assumption derived from the quiet stance paradigm. Postural motion can be detected visually from the optical flow that results from sway. When fixating the near object, the visual change in optical flow is more evident due to the projective geometry of the
surroundings, leading to a decrease in postural sway amplitude (Lee & Lishman, 1975). That is, close objects should produce greater optical change relative to far objects. This effect has been widely replicated, in each case with the same interpretation (e.g. Bles, Kapteyn, Brandt, & Arnold, 1980; Dijkstra, Gielen, & Melis, 1992; Paulus, Straube, Krafszyk, & Brandt, 1989).

An alternative interpretation of the effect reported by Lee & Lishman (1975) is that postural behavior facilitates the achievement of supra-postural tasks. From this perspective, postural sway amplitude is decreased when fixating the near object because only a particular degree of visual stabilization is required in order to successfully see the object (Stoffregen et al., 1999). For reasons of projective geometry, as noted above, fixation of the far object requires less visual stabilization, thereby permitting more sway. This interpretation assumes that in organizing action, people attempt to maximize energy efficiency (Diedrich & Warren, 1995; Riccio & Stoffregen, 1988). In other words, people will tend to select control strategies that achieve task performance in the most energy-efficient manner.

To evaluate this interpretation, Stoffregen et al. (1999) added a new condition to the Lee and Lishman (1975) study. Participants fixated nearby (Object-Near) and distant (No Object-Far) targets. In the new condition, participants fixated a distant object while ignoring the nearby object which remained in the field of view (Object-Far). The original interpretation of Lee and Lishman’s effect would predict that sway would be determined by the distance of the surroundings, and not by the distance at which participants were looking. That is, Lee and Lishman would predict that sway amplitude would be the same in the Object-Near and Object-Far conditions. The results of the Stoffregen et al. (1999)
study were not consistent with this prediction (see Figure 1). Sway amplitude in the Object-Far condition was not significantly different from the No Object-Far condition. However, sway in both of these conditions was significantly greater than in the near-fixation condition (Object-Near). Thus, sway amplitude was influenced by distance of fixation, and not by distance of the surroundings. The greater detectability of optical flow due to the presence of the near object did not seem to play a role in controlling postural sway.

*The distance-task confound*

Stoffregen et al. (1999) showed that the control of body sway could be related to the distance of fixation, rather than to the detectability of optical flow created by sway. They concluded that this finding is incompatible with the two traditional assumptions: (1) that optical flow created by sway is always used to minimize sway, and (2) that postural control is organized solely around movements of the $C_M$. This is an important conclusion, and one that raises doubts about the utility of the quiet stance paradigm.

However, the findings of Stoffregen et al. (1999) do not unequivocally show that sway can be organized with respect to the goals of supra-postural behavior. They varied the constraints on ocular control without introducing any meaningful variation in the nature of the supra-postural looking task. As explained above, varying the distance of target objects varied the degree of ocular stability that was required for fixation. However, in all conditions, participants received essentially the same instructions, to stare intently at the designated object. The “task variation” consisted solely of a variation in
the distance of targets. Thus, the fixation-distance effect might have resulted from mechanistically controlled optimization of the visual system. A clear evaluation of the task-effect hypothesis would require that postural sway be organized around variations in the contents, as opposed to the ocular mechanics, of supra-postural tasks.

A second limitation of the Stoffregen et al. (1999) study is that it did not include any measure of visual performance. This was reasonable, given the simplicity of the looking task; it could be assumed that participants would successfully fixate the appropriate target. From an experimental perspective this was convenient; however, the argument that body sway varies with the difficulty of supra-postural tasks could be more precisely evaluated using tasks for which performance could be measured and quantified.

Variation in supra-postural visual tasks

The two problems discussed in the preceding section have been addressed in a recent study. Stoffregen et al. (2000) contrasted simple inspection with a visual search task. Each of these tasks could be performed at a given target distance, thus eliminating the distance-related optical effects employed in previous studies. In addition, there is a clear, qualitative difference in visual performance requirements between simple inspection and visual search. Finally, the visual search task that was used (counting target letters embedded in a block of text) permitted a quantitative measure of search performance. Stoffregen et al. (2000) combined a variation in target distance with a variation in visual task. In the Inspection task, participants were asked to maintain their gaze on a blank target. In the Search task, participants were asked to count instances of
target letters that were embedded in blocks of text. Search performance was measured in terms of the percentage of targets detected. As predicted, variability in postural sway was less when participants fixated the a near target. In addition, sway variability was reduced when they performed the visual search task as opposed to fixating a featureless target.

What can be concluded from the Stoffregen et al. (2000) results? For one, the ecological validity of the experiment was increased due to the representativeness of their supra-postural tasks, and given the high level of task performance, the results suggest that there were real differences in task demand in terms of visual stabilization. Counting letters in a block of text required more precise visual stabilization than fixating a featureless target, which was facilitated by a decrease in postural sway. Postural behavior was modulated to adapt to the changes in visual stabilization requirements. One can also conclude that postural behavior was adaptively organized due to the dynamic changes in supra-postural tasks imposed within the study. Not only did postural behavior change to accommodate differing visual stabilization requirements, it did so in an adaptive manner.

The distance confound was also addressed. If previous results were due to distance rather than a task effect, the observed reduction in sway amplitude would not have appeared across near and far distances. Since both supra-postural tasks (visual search and blank inspection) were presented equally at a near and far distance, it is possible to rule out a competing explanation based on fixation distance. The visual environment did not change across trials and the near and far targets were always in the field of view.
One question raised by the Stoffregen et al. (2000) study revolves around the different types of constraints that influence postural behavior. Postural sway was reduced during the Search task. The issue is whether the supra-postural task effect is attributable to the eye movement requirements for achieving visual performance, or to the content aspect of behaviors such as scanning the text or counting letters. It is possible that eye movements might constrain sway independently of other constraints.

Oblak, Gregoric, and Gyergyek (1985) conducted a study that potentially addresses the eye movement issue. Their study included a condition where participants’ eye fixation was at a midpoint in front of them and another condition where participants were instructed to follow a moving light. The latter condition consisted of fixations looking left and right at a rate of 0.5 Hz. They found that body sway variability (in terms of the center-of-pressure) was less when participants followed the moving light. In explanation of these results, the authors state, “The most logical conclusion is that the oculomotor system requires stabilization of posture to be able to hit the target light” (Oblak et al, 1985, p. 125). This account supports the general hypothesis that postural behavior facilitates visual performance and suggests further that eye movements can constrain postural sway independently of non-ocular variations in supra-postural task difficulty. However, it raises another question. Do supra-postural tasks that vary in difficulty influence postural behavior independently of eye movements?

Motivation for the present study
The work of Oblak et al. (1985), Stoffregen et al. (1999), and Stoffregen et al. (2000) demonstrated that postural behavior facilitates visual performance. The studies discussed above suggest that postural control does not always involve an attempt to minimize postural sway. Though previous research points toward the path of behavioral goals influencing behavior, many questions still remain unanswered. Although Stoffregen et al. (2000) eliminated the distance confound, an eye movement confound was introduced. The observed reduction in postural sway may be due to the mechanics of eye movements and the oculomotor system, instead of the difficulty of supra-postural task effects, per se.

The conclusions of Oblak et al. (1985) also point toward the mechanics of eye movements to explain the reduction in sway. In the absence of a task difficulty manipulation, they concluded that the oculomotor system requires a certain degree of postural stabilization when viewing a moving target. However, they could not break down the effects of postural sway by into separate axes (anterior-posterior and medio-lateral) and their methods and procedures were somewhat ambiguous. In order to generalize their results confidently, a partial replication of the relevant conditions needs to be conducted.

Previous instances of supra-postural visual tasks have been relatively simple. Examples include fixating a featureless target (Stoffregen et al., 2000), fixating the head of a tripod or a pattern on a wall (Stoffregen et al., 1999), and tracking a moving light (Oblak et al., 1985). Oblak et al. (1985) measured eye movements to confirm the assumption that participants actually performed the task. Other studies, excluding Stoffregen et al. (2000), did not include measures of visual performance. Research that
will manipulate more complex supra-postural tasks will require direct measures of visual performance.

The underlying hypothesis is that visual performance tasks that require more precise visual fixation should result in a decrease in postural sway variability. That is, postural sway should be modulated in order to achieve necessary levels of visual stabilization. To evaluate this hypothesis, three experiments were conducted that focus on (1) differences in postural behavior when tracking a moving versus a stationary target, and (2) differences in postural behavior when manipulating constraints on visual performance theoretically unrelated to eye movements.

Predictions

Experiment 1. Moving and stationary targets: Force data. This experiment was conducted to address the general hypothesis that supra-postural tasks that require more precise visual stabilization would result in less postural sway variability. This experiment attempts to strengthen the construct and ecological validity lacking in previous supportive research. I predicted that postural sway variability, in terms of center of pressure (COP), would decrease when fixating the moving target relative to the stationary target. COP was defined as the force resisting the force that the feet exerted on the surface of support.

Experiment 2. Moving and stationary targets: Kinematic data. The purpose of this experiment was to provide converging evidence in favor of the hypothesis that body sway can be modulated to support successful eye movements. Experiment 1 used
measurements of the COP, whereas the converging evidence in Experiment 2 would be in the form of direct, kinematic measurements of head and torso motion during fixation and eye movement tasks. I predicted the same outcomes as in Experiment 1.

Experiment 3. Target Detection. This experiment addressed the confound of eye movements and extended the current hypothesis into a more task-oriented domain. Participants had to perform a target detection task that varied in task difficulty. I predicted that more precise visual stabilization would be required when performing a target detection task under the conditions of lower target luminance levels, contrast ratio, and a smaller difference for discriminating a critical signal from a neutral one. I expected that the control of postural behavioral would facilitate visual performance for the harder task by decreasing sway variability.
EXPERIMENT 1

MOVING AND STATIONARY TARGETS: FORCE DATA

Previous research has suggested that the oculomotor system requires a greater degree of postural stabilization when viewing a moving target than during fixation of a stationary target (Oblak et al., 1985). In Experiment 1, I investigated the effects of intentional eye movements on body sway. I did this through a partial replication and refinement of the Oblak et al. study. The replication was partial because eye movements were measured in the Oblak et al. study whereas I did not measure eye movements; in addition, I did not repeat all of the conditions used by Oblak et al. I refined the Oblak et al. study by separately analyzing body sway in multiple axes. I assumed that static fixation would not require less precise visual stabilization than tracking an oscillating target. On this basis I predicted that the amplitude of body sway would be related to the degree of ocular stability required in the visual tasks. Specifically, I predicted that body sway would be reduced in amplitude during performance of the eye movement task, relative to sway during the stationary fixation task.

Method

Participants
Thirteen graduate and undergraduate students (11 males, 2 females) from the Université de Paris-Sud-XI participated as volunteers. All participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. Participants ranged in age from 17 to 26 years (mean = 21, median = 20, mode = 20), and in height from 164 to 183 cm (mean = 173.17 cm). Eight participants had corrected vision (glasses or contacts).

Apparatus

Center-of-pressure (COP) data, defined as the force resisting the force that the feet exerted on its support surface, were obtained using a force platform (AccuSway System, Advanced Mechanical Technology, Inc., Newton, MA). COP data were sampled at 25 Hz and stored on a computer for later analysis. Presentation of experimental stimuli was achieved using a standard experimental control application (PsyScope; Cohen, MacWhinney, Flat, & Provost, 1993), run on a Macintosh G3 computer with a 17 in. Apple Studio Display. The laboratory set-up is depicted in Figure 2.

Procedure

There were two experimental conditions, Stationary and Moving, corresponding to the two types of visual targets that were used. In each condition the visual target consisted of a filled red circle on a white background. The circle subtended approximately 1.15° of visual angle. In the Stationary condition, the visual target
Figure 2. Laboratory set up for Experiment 1. Moving and stationary targets, Force data.

appeared in the center of the display and remained there for the duration of the trial (65 s). In the Moving condition, the target was presented alternately in two positions. It first appeared 9.75 cm (5.5°) to the left of the center of the display for two seconds, at which point it disappeared, reappearing approximately 9.75 cm (5.5°) to the right of the center of the display where it was again visible for two seconds (maximum displacement approximately 19.5 cm subtending 11° of visual angle on the horizontal plane). Target motion was repeated for 65 seconds. The target stimuli are illustrated in Figure 3.

Each participant performed seven trials, six experimental and one control (eyes closed), each of which lasted for 65 seconds. Condition order was randomized (see Appendix A for condition orders). Participants were asked to stand approximately 100 cm from the display on top of the force plate. The display was adjusted so that the top of the screen was approximately level with the participant’s eye height. In all trials, participants were given the option of letting their arms hang down their sides, putting
their hands in their pockets, or holding their hands in front of or behind them. For each participants the first

**STATIONARY TARGET**

<table>
<thead>
<tr>
<th>Luminance Background</th>
<th>- 108.44 cd/m²</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>Luminance Target</td>
<td>- 26.07 cd/m²</td>
<td></td>
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<tr>
<td>Contrast Ratio</td>
<td>- 1:4</td>
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**MOVING TARGET**

<table>
<thead>
<tr>
<th>Luminance Background</th>
<th>- 108.44 cd/m²</th>
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<tr>
<td>Luminance Target</td>
<td>- 26.07 cd/m²</td>
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<td>Contrast Ratio</td>
<td>- 1:4</td>
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Figure 3. Target stimuli for Experiment 1. Moving and stationary targets: Force data, and Experiment 2. Moving and stationary targets: Kinematic data.
trial was a control trial, in which participants were instructed to stand with their eyes closed (feet approximately shoulder width). For the experimental trials, participants were instructed to stand with their feet together.

Participants were shown an example of the Moving condition to ensure they fully understood the task. In both conditions, they were instructed to maintain constant eye fixation on the target. In the Moving condition they were instructed not to anticipate motion of the target. Between trials participants stepped off the platform for recalibration.

**Design & data analysis**

The main dependent variable was the positional variability of the COP. Variability was analyzed separately for the anterior-posterior (AP) and medio-lateral (ML) axes. Statistical tests were conducted on the mean standard deviation of the COP for trials per condition. The independent variable was target motion (Stationary/Moving). Two paired-samples t-tests were conducted, contrasting the conditions in the AP axis and the ML axis, respectively.

**Results**

The mean standard deviation of COP for trials are as follows; $M_{AP/Stationary} = 0.54$, $M_{ML/Stationary} = 0.37$, $M_{AP/Moving} = 0.41$, $M_{ML/Moving} = 0.32$. Paired-sample t-tests revealed that positional variability of the COP was reduced when participants looked at the
moving target, relative to sway during fixation of the stationary target. This was true in
the AP axis, \( t_{(12)} = 3.79, p < .05 \), and also in the ML axis, \( t_{(12)} = 2.42, p < .05 \). Effect
sizes for AP and ML mean COP standard deviation are as follows; \( d_{AP} = 1.07 \), \( d_{ML} =
0.65 \).\(^1\) Means are presented in Figure 4, and data from sample trials are illustrated in
Figure 5. As a check on the robustness of the analysis, non-parametric tests were
performed. Wilcoxon signed-rank (WSR) tests were consistent with the \( t \)-tests. See
Appendix B for values.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure4.png}
\caption{Graph of means for standard deviation of center-of-pressure (COP) in the anterior-posterior (AP) and medio-lateral (ML) axes for Experiment 1. Moving and stationary targets, Force data. Error bars represent the 95\% confidence interval.}
\end{figure}

\(^1\) 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 5. Exemplary COP plots for AP/ML for a Stationary and Moving trial in Experiment 1. Moving and stationary targets, Force data. Two participants are represented (AL & NS). Each block corresponds to 0.2cm².
Discussion

Analysis of the results of this experiment confirm the previously stated predictions. Postural sway variability was reduced in the AP and ML axes when viewing a moving target relative to a static one. These results support the conclusions of Oblak et al. (1985) that the oculomotor system requires stabilization of posture to be able to fixate on the moving target.

Visual performance. Previous research has focused on supra-postural visual tasks that either suppressed eye movements (e.g. Stoffregen et al, 1999), or did not differentiate possible effects of eye movements from variations in task difficulty (Stoffregen et al., 2000). The purpose of Experiment 1 was to determine whether posture could be functionally modulated in support of the control of eye movements, per se.

I assumed that fixating a static target or tracking a moving target would be easy enough to understand and execute that visual performance could be taken for granted, rather than being measured. Moreover, Oblak et al. (1985), who measured eye movements, reported accurate fixation and tracking using the same amplitude and frequency of target motion as in the present experiment. Despite the fact that both tasks were relatively easy, the postural data suggest that they were different enough to require differing levels of visual stabilization and control strategies in order to achieve optimal performance.

One of the constraints on visual performance mentioned previously was eccentricity. In Experiment 1, no eccentricity constraints were present during the fixation of a Stationary target. However, with the moving target visual performance became
vulnerable to eccentricity effects. Target motion removed the target from the area of
greatest visual acuity, the fovea. In order to avoid visual degradation of the target, some
adjustment was needed.

The potential effects of eccentricity may have been overcome through integration
of the visual system and the postural system to achieve the required state of visual
stabilization. To reiterate, the goal was to maintain visual stabilization relative to both
moving and stationary targets. Certain levels of postural sway variability could be
tolerated in each condition to achieve that goal. In accordance to the minimization of
energy expenditure view (Riccio & Stoffregen, 1988), I assume the amplitude of sway
variability when fixating the stationary target existed because it was the most energy-
efficient while still achieving visual performance. This same amount of sway variability
may have been more energy efficient relative to the reduction in sway variability found in
the Moving condition, but it could not facilitate the visual system’s maintaining constant
visual stabilization of the moving target.

**Multi-axis effects.** Oblak et al. (1985) did not separately analyze motion in the AP
and ML axes. Rather, they performed a single analysis on overall sway amplitude. The
present analysis and results add an important measure of detail. A particularly interesting
finding was the significant reduction in postural sway in the Moving condition for both
the AP and ML axes. The target moved in only one axis (ML, relative to the body), but
body sway was influenced in two axes. The reduction in ML body sway is of obvious
utility in promoting the stability of eye movements in the ML plane. The reduction in
sway in the AP axis is of less obvious utility for performance of the eye movement task.
It is consistent, however, with the study of Stoffregen et al. (2000), who found that
reductions in body sway were not always limited to the axis in which visual stability was most tightly constrained.

Generalizability. Experiment 1 followed Oblak et al. (1985) in evaluating postural motion in terms of the position of the COP. This contrasts with previous research on the postural facilitation of visual performance, which examined only the kinematics of body sway (Stoffregen et al., 1999; Stoffregen et al., 2000). Taken together, the extant data indicate that postural facilitation of visual performance can occur either at the level of the kinetics or kinematics of body sway. However, in the context of different measures of body sway two questions remain. First, there has not been any direction demonstration that both the kinetics and the kinematics of stance can be influenced by a given supra-postural task. Second, there has not been a demonstration that visual constraints relating to eye movements can influence the kinematics of stance. These issues are addressed in Experiment 2.
Chapter 3

EXPERIMENT 2

MOVING AND STATIONARY TARGETS: KINEMATIC DATA

The results from Experiment 1 support the general hypothesis that postural behavior can facilitate visual performance, as well as the specific hypothesis that body sway can be modulated to facilitate the control of eye movements. Experiment 1 operationalized body sway in terms of the positional variability of the COP. In Experiment 2, I attempted to provide converging evidence for the general and specific hypotheses by directly measuring the kinematics of postural sway, taking separate measurements of the positional variability of the head and torso. Again, the purpose of this experiment was to investigate the effects of a dynamic target versus a static target on postural sway. It was predicted that static fixation would not require as precise visual stabilization compared to tracking a target that repeatedly changed position resulting in more postural sway variability.

Method

Participants

Thirteen undergraduate students (7 males, 6 females) from the University of Cincinnati participated for course credit. Participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or
falls. Due to apparatus constraints, participant height was limited to a maximum of 183 cm. Height ranged between 157.5 cm and 183 cm (mean = 170 cm). Age ranged from 18 to 29 years (mean = 20, median = 19, mode = 18). Three participants had corrected vision (glasses or contacts).

**Apparatus**

Postural sway was recorded using a 6-df magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT). One receiver was attached to a bicycle helmet worn by the participant, while a second receiver was attached to the torso (approximately at the seventh cervical vertebra). Each receiver was sampled at 25 Hz, and the data were stored on a computer for later analysis.

Presentation of experimental stimuli was achieved using a standard experimental control application (PsyScope; Cohen et al., 1993), run on a Macintosh G3 computer with a 17 in. Apple Studio Display. See Figure 6 for a depiction of the laboratory set-up.

The visual targets were identical to the targets in Experiment 1. The circle subtended approximately 1.15° of visual angle horizontally and vertically. Luminance of the background was approximately 108.44 cd/m² for both conditions. Luminance of the target was approximately 26.07 cd/m². Display luminance was calculated using a luminance meter (LS-100, Minolta Camera Co., Ltd., Japan). The contrast ratio was approximately 1:4. See Figure 3 for the target stimuli.
Procedure

Each participant performed seven trials, each of which lasted for 65 seconds. Condition order was randomized (see Appendix A for condition orders). Participants donned the bicycle helmet with the receiver attached to the back of it. Experimenters
attached the second receiver using medical tape. Participants stood 100 cm from the display, with their feet on a marked line on the floor. The display was adjusted so that the top of the screen was level with the participant’s eye height. In all trials, participants were given the option of letting their arms hang to their sides, putting their hands in their pockets, or holding their hands in front of or behind them. Whichever position they chose, they were asked to keep the same position for each trial, and not to move their hands during trials. For the first trial (eyes closed), participants were instructed to stand with their feet approximately shoulder width. For the remaining trials, participants were instructed to stand with their feet together.

Conditions and stimuli were identical to those used in Experiment 1. To minimize the possibility of fatigue or other adverse side effects of prolonged stance (Smart, Pagulayan, & Stoffregen, 1998), participants were required to sit and take a break after Trial 4.

Design & data analysis

The dependent variables were the positional variability of the head and torso. These were operationalized as the mean standard deviation of the head and torso, analyzed separately for the AP and ML axes. The independent variable was target motion (Stationary/Moving). Four paired-samples t-tests were conducted; Head/AP, Head/ML, Torso/AP, and Torso/ML.

Results
The mean values of the standard deviation of position are presented in Table 1. Raw position data from representative trials are presented in Figure 7. The t-tests indicated that there was a reduction of sway variability during presentation of the moving target. In the AP axis, this was true both for the head, $t_{(12)} = 2.68, p < .05$, and for the torso $t_{(12)} = 2.77, p < .05$, with effect size of $d = 0.74$, and $d = 1.57$, respectively. By contrast, sway variability in the ML axis was not influenced by the experimental conditions, either for the head, $t_{(12)} = 0.94, p > .05$, or for the torso $t_{(12)} = -0.89, p > .05$. As a test of the robustness of these analyses, non-parametric tests were performed. Wilcoxon signed-rank (WSR) tests were consistent with the t-tests. See Appendix B for values.

Table 1. Means table for head and torso position in the anterior-posterior (AP) and medio-lateral (ML) axes (N=13) for Experiment 2. Moving and stationary targets: Kinematic data.
7.1 Head Position

Figure 7. Exemplary anterior-posterior (AP) plots of Head and Torso position for a
Stationary and Moving trial while standing for Experiment 2. Moving and stationary targets: Force data.

7.2 Torso Position
Results from Experiment 2 confirmed my predictions and provided converging evidence consistent with the findings of Experiment 1. Postural sway variability in the AP axis was reduced when fixating a moving target relative to a stationary one. However, the pattern of results was not identical to the results of Experiment 1, in which significant effects were observed for both AP and ML axes. This discrepancy underlines the value of evaluating different measures of body sway; it also raises questions about possible functional implications of both the similarities and differences between the two experiments.

In Experiment 1, the supra-postural task effect was demonstrated for both the AP and ML axes, while in Experiment 2 there was a significant effect of condition (for both head and torso position) only in the AP axis. The results of Experiment 2 are puzzling because, as noted earlier, the lateral nature of target movement would seem to place little constraint on the stability of the visual system in the AP axis. With respect to the hypothesis that task-specific changes in body sway are adaptive, facilitating performance of supra-postural tasks, the challenge of this finding is to determine how changes in body sway in the AP axis could facilitate control of eye movements in the ML axis. This issue will be considered at greater length in the General Discussion. For the present it is sufficient to note that, at a minimum, the control of eye movements was associated with significant reduction in the kinematics of both the head and torso.

Experiments 1 and 2 provided support for the claim that the control of posture can be influenced by supra-postural tasks. The purpose of these experiments was to
investigate relations between eye movements and body sway under conditions in which other factors, such as target distance and the cognitive content of tasks were held constant. Together with the findings of Oblak et al. (1985), Experiments 1 and 2 make it clear that eye movements alone are sufficient to influence the organization of body sway.

A separate issue raised by the work of Stoffregen et al. (2000) concerns the possibility that body sway might be influenced by variations in the difficulty of supra-postural tasks when there was no variation in the distance of visual targets, and when none of the supra-postural tasks required eye movements. This is addressed in Experiment 3.
Stoffregen et al. (2000) found adaptive variations in body sway in response to changes in the difficulty of supra-postural visual tasks. Their results supported the general hypothesis that body sway can be modulated to support visual performance, but raised questions about the specific aspects of visual performance that may be related to body sway. Specifically, the study of Stoffregen et al. confounded variations in the need for positional stability of the eyes with variations in overall ocular stasis or movement. The “easy” task used by Stoffregen et al. was stationary fixation of a featureless target, while the “hard” task was visual search, in which participants were instructed to find and count instances of target letters embedded in text. The easy and hard tasks differed in at least two ways. On the one hand, the hard task required eye movements (to scan the text), while the easy task did not. On the other hand, the hard task required precise stabilization of the eyes within fixations (so as to be able to read letters in the text); in the easy task there was no fixation point, so the position of the eyes was only weakly constrained. The confound resulting from these differences made it difficult to interpret the reduction in body sway observed during performance of the hard task. The effect might have resulted from the need to generate and control a series of eye movements, from the need for precise fixation in reading letters, or from both. Experiments 1 and 2 showed that the control of eye movements is sufficient to modulate body sway. Experiment 3 was designed to evaluate the possibility that body sway might vary
adaptively with variations in the level of ocular stability required during stationary fixation.

New easy and hard tasks were developed. Neither task required eye movements. The tasks differed in the static discriminability of targets. In the easy task, targets differed from distractors in ways that were so obvious that they might be detected over a wide area of the retina. Thus, good performance at the easy task might be accomplished without precise control of fixation (i.e., some degree of ocular drift could be tolerated). In the hard task, the differences between targets and distractors were very subtle, such that they could be reliably discriminated only if the targets were foveated. This meant that good performance at the hard task required precise control of eye position relative to the targets. It was predicted that this precise control of eye position would result in less postural sway.

*Seated posture.* In addition to studying the integration of visual performance with standing posture, in Experiment 3, I also examined the possible integration of visual performance with seated posture. The reason for this was to increase the generalizability of the study because many supra-postural tasks are performed while sitting. I predicted that the supra-postural task effect found during upright stance would also appear when the participants were sitting.

**Method**

*Participants*
Forty-eight undergraduate students (23 males, 25 females) from the University of Cincinnati participated for course credit. Participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. Participant height was limited to a maximum of 183 cm due to apparatus constraints. Height ranged between 155 cm and 183 cm (mean = 168 cm). Age range was between 18 and 29 (mean = 20, median = 19, mode = 19). Nineteen participants had corrected vision (glasses or contacts). Participants were randomly assigned to two groups of 24, Standing and Sitting.

Apparatus

Postural sway was recorded using a 6-df magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT). Head and upper body (torso) position were detected using one receiver attached to the back of a bicycle helmet worn by participants, with a second receiver attached to the torso (approximately at the seventh cervical vertebra). Receivers were sampled at 25 Hz, and the data were stored on a computer for later analysis.

Presentation of experimental stimuli was achieved using a standard experimental control application (PsyScope; Cohen et al., 1993), run on a Macintosh G3 computer with a 17 inch Apple Studio Display. PsyScope was also used to collect data on supra-postural task performance. The set-up is depicted in Figure 6.

The experimental stimuli were pairs of vertical lines presented on the display screen (Figure 8). Each pair consisted of two lines, separated horizontally by 1.55° of
Figure 8. Target stimuli for Experiment 3. Target Detection.
visual angle. One pair constituted the neutral signal, and the other pair constituted the critical signal. In both the Easy and Hard tasks the neutral signals consisted of lines that were equal in height (1.95° of visual angle). In the critical signals, the lines differed in height.

For critical signals in the Easy task the left line had a vertical extent of 1.95° of visual angle, while the right line had a vertical extent of 2.35° of visual angle. For critical signals in the Hard task the left line had a vertical extent of 1.95°, while the vertical extent of the right line was 2.12°. Displays for the Easy and Hard tasks also differed in color. In the Easy condition all target lines were black, while in the Hard condition they were light gray.

Luminance of the display background was 108.44 cd/m² for all conditions. For the Easy task the luminance of the target color was 4.19 cd/m². This resulted in a contrast ratio of approximately 1:26, which conforms with the ANSI/HFS standard (1988) for optimum display legibility (Grandjean, 1987a). It also conforms to other display guidelines (Cushman & Crist, 1987; Procter & Van Zandt, 1994). The actual luminance of the target was limited to 103.22 cd/m² because of the target size and small visual angle. For the Hard task the luminance of the target color was 77.44 cd/m², resulting in a contrast ratio of approximately 1:1. Luminance of the actual target was 104.84 cd/m², again due to the small size (thickness) of the target lines. Luminance was calculated using a luminance meter (LS-100, Minolta Camera Co., Ltd., Japan).
Procedure

Each participant performed seven trials, each of which lasted for 65 seconds. Condition order was randomized (see Appendix C for condition orders). Participants donned the bicycle helmet with the receiver attached to the back of it, and the second receiver was attached to the back at the 7th cervical vertebrae, using cloth medical tape. Participants stood or sat 100 cm from the display. Display height was adjusted so that the top of the screen was approximately level with the participant’s eye height. Participants in the Standing group were instructed to stand with their feet approximately shoulder width. Participants in the Sitting group were instructed to sit with their feet flat on the floor directly in front of them approximately shoulder width. For the first trial, participants were instructed to keep their eyes closed. In the remaining trials, participants held an Apple USB mouse in the palm of their preferred hand. Standing participants held both arms down at their sides. Sitting participants held their non-preferred hand down at their sides and their preferred hand was held at their waist.

Participants were shown an example of the Easy trial to ensure that they fully understood the task. The first two experimental trials (learning trials) always consisted of one Easy and one Hard trial. Presentation order of those two trials was randomized across participants. The remaining four trials consisted of two Easy and two Hard trials, which were presented in random order. A short rest break was imposed on participants after trial 4 for both Standing and Sitting participants.

For a given trial, a pair of stimulus lines was presented on the display once per second. The stimulus appeared for 200 ms, with 800 ms before the next pair appeared. A
total of 60 pairs were presented, including 40 neutral signals and 20 critical signals. Presentation order of the targets was randomized by the experimental control software. The participants’ task was to detect the presence of the critical signal, and to indicate the appearance of each critical signal by rapidly pressing the button on the mouse. Participants were not informed of the total number of stimuli, or of the frequency of occurrences of neutral and critical signals. However, they were told the frequency was equal across trials.

At the end of the experiment, participants were asked to briefly describe each condition in terms of how they thought their performance was, if they resorted to guessing, and if their efforts were more physical (constraining their body) or mental (intense concentration). They were also asked which condition they considered more difficult.

**Design & data analysis**

**Postural data.** The data were evaluated using one-within, one-between analyses of variance, with Stance (*Sitting* vs *Standing*) being the between-subjects factor and task difficulty being the within-subjects factor. As in Experiment 2, the dependent variable was the mean, across participants, of the standard deviation of position. In Experiment 3, data from trials 1 and 2 were not included in the primary analyses. The purpose of this exclusion was to avoid possible learning effects, that is, the possibility that functional relations between postural sway and visual task performance did not exist at the beginning of the experiment, but emerged over time as participants became acclimated to
the experimental tasks. Planned analyses were conducted on the data from trials 3-6. Separate ANOVAs were conducted on the postural data from the head and torso, in each of the AP and ML axes, for a total of 4 ANOVAs (Head/AP, Head/ML, Torso/AP, and Torso/ML).

**Visual task data.** Visual task performance was evaluated in terms of signal detection theory (Green & Swets, 1966). For each participant, $d'$ (an index of perceptual sensitivity, that is, the detectability of the critical signals) was calculated by combining hits and false alarms across the latter two 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. The performance criterion for inclusion in the study was $d' > 3.5$ for the Easy condition and $d' < 3.0$ for the Hard condition. Participants who did not meet these criteria were replaced to achieve the targeted sample size of 48.

**Results**

**Visual performance.** The mean value of $d'$ across groups was 4.08 for the Easy condition, and 1.95 for the Hard condition. Thus, for the sample used in this study, the Easy task can be described as ‘easy’ whereas the Hard task can be considered ‘moderately difficult’ (Craig, 1984). This coincides with the subjective statements about task difficulty given by participants (see Appendix D). Eleven participants (approximately 19% of the original sample) who did not meet the performance criterion were replaced.
Postural sway. The means are presented in Figures 9 - 12. The main effect of stance (Standing, Sitting) was statistically significant for all cases: AP motion of the head, $F_{(1,46)} = 37.88, p < .05$; ML motion of the head, $F_{(1,46)} = 27.03, p < .05$; AP motion of the torso, $F_{(1,46)} = 46.45, p < .05$; and ML motion of the torso, $F_{(1,46)} = 35.27, p < .05$. In each case postural sway variability was lower during sitting. It is not surprising that sway was reduced during sitting, and the effect is not of theoretical interest. There were no significant main effects of task difficulty in any of the analyses ($F_{(1,46)} < 0.22, p > .05$, in each case). See Appendix E for analyses related to checking assumptions related to ANOVA.

![Figure 9](image_url)

**Figure 9.** Graph of means for Head position in the anterior-posterior (AP) axis; stance (Stand/Sit) and task difficulty (Easy/Hard). Error bars represent the 95% confidence interval. Experiment 3. Target Detection.
Figure 10. Graph of means for Head position in the medio-lateral (ML) axis; stance (Stand/Sit) and task difficulty (Easy/Hard). Error bars represent the 95% confidence interval. Experiment 3. Target Detection.

Figure 11. Graph of means for Torso position in the anterior-posterior (AP) axis; stance (Stand/Sit) and task difficulty (Easy/Hard). Error bars represent the 95% confidence interval. Experiment 3. Target Detection.
Exploratory analyses

As noted above, in conducting the pre-planned analyses on the postural data, I excluded the first two trials. I assumed that participants might need some exposure to the supra-postural signal detection tasks in order to achieve an adequate level of visual performance. If this was true, changes in visual performance over the first two trials may have been accompanied by changes in postural control. Beyond this, there may have been changes in both visual performance and postural control across the course of the experiment. I conducted several post-hoc analyses to evaluate this possibility.

Visual performance. I began by evaluating per-trial performance on the supra-postural signal detection tasks. For the first presentation of the Easy condition 54.2% of participants (13 each in the Sitting and Standing groups) did not achieve the requisite level of visual performance of $d' > 3.5$ (by criterion, all participants met the criterion for
the mean of the 2nd and 3rd presentations). In the post-hoc analysis, $d'$ values were calculated separately for each presentation. On the second presentation of the *Easy* condition 35.4% (8 in the *Standing* group, and 9 in the *Sitting* group) of participants did not meet the performance requirement, while on the 3rd presentation 33.3% (7 *Standing*, 9 *Sitting*) did not meet the criterion. Figure 13, depicting performance across participants for each presentation, demonstrates that performance seemed to increase for the *Easy* condition. In the primary performance analysis, all participants met the inclusion criterion for their performance on the second and third trials combined. That is, those who did not meet the criterion in the second or third presentation separately performed well enough on the other trial so that their combined score was sufficient to meet the performance requirements.

*Figure 13.* Graph of mean $d'$ across participants, for Experiment 3. Presentation refers to the first (P.I), second (P.II), and third (P.III) in each of the *Easy* and *Hard* conditions.
Postural sway. I first considered the possibility of general differences in body sway between the first presentation of each of the two supra-postural visual tasks (trials 1 and 2) and subsequent presentations (trials 3-6). I did this by comparing the mean of sway variability across the first two trials with the mean across the last four trials. In the Sitting group there was not a significant difference in overall postural sway variability between trials 1-2 and trials 3-6 ($M_{1-2} = 0.22$ cm; $M_{3-6} = 0.21$ cm). There were also no significant differences when the data were broken down by head/torso and task difficulty (Easy/Hard); the means are presented in Table 2. For this reason, no further analyses were conducted on the Sitting group. Similarly, in the Standing group there was not a significant difference in overall sway variability between trials 1-2 and 3-6 ($M_{1-2} = 0.43$ cm; $M_{3-6} = 0.39$ cm), $t_{(23)} = 1.99$, $p > .05$. However, when broken down by condition, axis, and task, significant differences were revealed for head and torso motion in the AP axis, in the Easy condition; $t_{\text{Head}(23)} = 2.18$, $p < .05$, $t_{\text{Torso}(23)} = 2.19$, $p < .05$. In the Easy condition, AP sway variability was greater in trials 3-6 than in trials 1-2. The means are presented in Figure 14. There was not a significant difference between trials 1-2 and 3-6 in the ML axis, for either head or torso motion.

Learning effects for the Standing group. I next considered the possibility that for the Standing group, body sway might have changed gradually over the course of the experiment, and that changes in sway might have differed for the two supra-postural tasks. I did this by looking for trends in sway across the three presentations of each experimental (i.e., task) condition. Recall that each experimental condition was presented three times for each participant. Figure 15 illustrates head and torso variability for each presentation of task difficulty for the AP and ML axes. P.I represents the first
Figure 14. Graph of means for Head and Torso position in the AP axis for task difficulty (Easy/Hard) for learning trials (trials 1-2) and experimental trials (trials 3-6) while standing. Experiment 3. Target Detection.
encounter of an *Easy* or *Hard* trial. *P.II* and *P.III* represent the second and third presentations of the *Easy* or *Hard* condition. The figure clearly indicates differences in sway across presentations of the Easy and Hard conditions.

A straight line was fit to each condition across presentations. The slope, intercept, and proportion of variance accounted for each condition are presented in Table 3. For both the head and torso, sway variability in the AP and ML axes was greater for each successive presentation of the *Easy* condition. In each case the slope was positive. However, only the slopes for the ML axes (head and torso) differed significantly from zero; *Head/Easy/ML, F*(1,70) = 4.51, *p* < .05, *Torso/Easy/ML, F*(1,70) = 4.98, *p* < .05.

Slopes for AP sway did not significantly differ from zero; *Head/Easy/AP, F*(1,70) = 2.51, *p* > .05, *Torso/Easy/AP, F*(1,70) = 2.94, *p* > .05.

Across presentations of the *Hard* condition, slopes were negative (see Table 3). AP sway variability exhibited an inverted U pattern, peaked at the second presentation,
Figure 15. Graph of means for postural sway variability for each presentation in the AP and ML axis, for Experiment III. Presentation refers to the first (P.I), second (P.II), and third (P.III) encounter of each condition (Easy and Hard).
Table 3. Table of slopes, intercepts, and \( r^2 \) across presentations for standing. Experiment 3. Target Detection.

<table>
<thead>
<tr>
<th></th>
<th>EASY</th>
<th></th>
<th>HARD</th>
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<tbody>
<tr>
<td></td>
<td>slope</td>
<td>intercept</td>
<td>( r^2 )</td>
<td>slope</td>
</tr>
<tr>
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<td>0.50</td>
<td>0.82</td>
<td>-0.01</td>
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<tr>
<td>HEAD/ML</td>
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</tr>
<tr>
<td>TORSO/ML</td>
<td>0.05</td>
<td>0.15</td>
<td>0.98</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

with lower values in the first and third presentations. Across presentations of the Hard condition none of the slopes differed significantly from zero (all \( F \)’s < 1.0).

To determine whether the final level of sway variability differed for the two supra-postural tasks, paired samples \( t \)-tests were performed on the third presentation of each condition, separately for head and torso position in the AP and ML axes. In the AP axis there were significant reductions in variability for the Hard task, relative to the Easy task for both the head and torso, \((M_{\text{Head/Easy}} = 0.65, M_{\text{Head/Hard}} = 0.56) t_{(23)} = 1.90, p < .05, (M_{\text{Torso/Easy}} = 0.60, M_{\text{Torso/Hard}} = 0.48) t_{(23)} = 2.66, p < .05\). In the ML axis, there was a significant difference in motion of the torso, \((M_{\text{Torso/Easy}} = 0.30, M_{\text{Torso/Hard}} = 0.23) t_{(23)} = 1.90, p < .05\), but not in motion of the head, \((M_{\text{Head/Easy}} = 0.35, M_{\text{Head/Hard}} = 0.27) t_{(23)} = 1.64, p > .05\). Raw data from a representative trial are presented in Figure 16.

These analyses provide evidence for two types of learning effects. First, over trials participants learned to improve their visual performance. Second, and more
important, over trials participants learned how to control their body sway differentially (and adaptively) for the two visual tasks.

![Exemplary anterior-posterior (AP) plots of Torso position for an Easy and Hard trial while standing.](image)

**Figure 16.** Exemplary anterior-posterior (AP) plots of Torso position for an Easy and Hard trial while standing.

**Discussion**

*Primary analyses.* As expected (and, indeed, as required for this experiment), visual performance differed for the *Easy* and *Hard* tasks, with better performance (in terms of target detection) in the *Easy* task. However, the primary analyses offered no support for the hypothesis that body sway would be reduced during performance of a task that required more precise control of eye position.

Analysis of the *Sitting* group revealed no effects of condition or presentation. The same supra-postural task effects predicted for *Standing* were also predicted for *Sitting*. This manipulation was included to try to extend the applicability of the results to seated posture. The general hypothesis of the influence of supra-postural tasks on the control of posture is not limited to upright stance. It is believed that posture can facilitate supra-
postural goals from any position depending on the particular situation. It is not clear why there were no condition or presentation effects in the Sitting group. One possibility is that the dependent variables were not sufficiently sensitive to pick up existing effects. Another possibility is that functional effects were masked by the particular seated posture that was employed. People sit in a wide variety of ways (e.g., both feet on the ground, legs crossed, hands resting on legs or tabletop), and functional relations between vision and posture may be more detectable in some configurations than in others.

Exploratory analyses of learning. Exploratory analyses suggested that posture could be modulated in support of the differing visual demands of the Easy and Hard tasks, but that this integration of posture and visual performance needed to be learned. Postural sway variability (torso) in the AP axis was reduced when performing the Hard target detection task relative to the Easy task. The learning of task-specific integration of visual performance and posture was not limited to the AP axis, but occurred also in the ML axis. Across trials, body sway changed as a function of the difficulty of the supra-postural task. In early trials, body sway was low for both tasks, suggesting that participants adopted a cautious strategy. Over trials, sway increased during performance of the Easy task, but not during performance of the Hard task, so that at the end there was a significant difference in sway amplitude for the two tasks. This suggests that over trials participants learned that greater sway could be tolerated without sacrificing performance of the Easy task.

Much of the postural control literature focus on areas such as stability borders in the elderly (Blaszczyk et al., 1993; Blaszczyk et al., 1994), visual stabilization of posture (Paulus et al., 1989), and effects on posture of supra-postural tasks (Balasubramaniam et
al., 2000; Marin et al., 1999; Stoffregen et al., 1999; Stoffregen et al., 2000). Other research attempts to examine the relationship between postural stability and a moving visual environment (Dijkstra, Schöner, & Gielen, 1994; Lee & Lishman, 1975; Van Asten, Gielen, Van der Gon, 1988). In research relating posture to vision, it has generally been assumed that participants were highly practiced and/or experienced with the use of optical flow for the perception and control of body sway. If so, postural activity could be expected to be at an asymptotic level. For those that have considered the possibility that changes in postural control might occur over the course of a single experiment, no effects of learning or adaptation were found (Bardy, Warren, & Kay, 1996, 1999). It is possible that postural learning may be routine in the context of more complex supra-postural tasks (Balasubramaniam et al.). Existing data might be reanalyzed in search of trial effects similar to those reported here and other studies where evidence of postural learning has been found (Horak & Nashner, 1986). Horak and Nashner found postural responses to external perturbations to be dependent not only upon current environmental conditions, but also upon experience on previous trials using different support surfaces.
In three experiments I examined relations between postural control and performance of supra-postural visual tasks. My general hypothesis was that variations in supra-postural visual tasks would influence postural control, and that the changes in posture would be functional, that is, would tend to promote visual performance. The results of each of the experiments are consistent with this general hypothesis. Supra-postural tasks that required more precise visual stabilization were associated with reductions in the positional variability of body sway. This was true for supra-postural tasks that required ocular saccades (Experiments 1 and 2), and it was true for supra-postural tasks whose performance would not be facilitated by saccades (Experiment 3).

In Experiments 1 and 2, body sway was reduced when participants were required to use eye movements to track moving targets (relative to fixation of a stationary target). In Experiment 3, body sway was reduced when subjects performed a more difficult target detection task, relative to sway during performance of an easier detection task.

Experiment 3 also revealed a learning effect in body sway: The functional relation between body sway and task demands developed over trials. The implications of these findings are discussed below.

Posture in the service of other goals
It has been proposed that postural control is modulated to achieve supra-postural tasks (Riccio & Stoffregen, 1988). Stoffregen et al. (1999) demonstrated this in the context of postural support for fixation of visual targets at different distances from the participant. Stoffregen et al. (2000) found the same effect for the contrast between stationary fixation and a text search task. The latter study did not distinguish between variations in eye movements (stationary versus moving) and variations in task difficulty (hard versus easy). In the present study I examined each of these separately.

*Postural stabilization of eye movements*

In Experiments 1 and 2, I evaluated the hypothesis that posture might be modulated to facilitate the control of eye movements necessary for visual performance. These experiments were, in part, replications of a study by Oblak et al. (1985). In each experiment, participants either fixated a stationary target, or used saccadic eye movements to follow a target that oscillated from side to side. Experiment 1 replicated the finding of Oblak et al. that the eye-movement task influenced control of the COP during stance. Eye movements were associated with reductions in body sway, in both the AP and ML axes, relative to sway during fixation of a stationary target. In Experiment 2, I measured motion of the head and torso and found that in terms of these body kinematics the eye-movement effect held only in the AP axis, a significant departure from the findings of Oblak et al. However, taken together, Experiments 1 and 2 clearly show a functional relation between body sway and supra-postural tasks requiring eye movements.
These results help to clarify the effects reported by Stoffregen et al. (2000). The present data (together with those of Oblak et al., 1985) strongly support the hypothesis that body sway can be controlled so as to facilitate visual performance tasks that require controlled eye movements. This relates to the more general hypothesis of Stoffregen et al. (1999), who argued that postural sway facilitates the performance of supra-postural tasks. They found that postural control was independent of optical flow and was not driven by flow in an autonomous manner. The present experiments did not explicitly address optical flow, but tasks were employed requiring simple visual fixation. At a more general level, the variations in postural behavior subserved different types of supra-postural tasks in both Stoffregen et al. and in the present experiments.

Although a reduction in sway was found for both AP and ML axes in Experiment 1, in Experiment 2, I identified a difference in postural sway only in the AP axis. Why this difference in results? One possibility is that body sway in the AP and ML axes may serve different functions. Balasubramaniam et al. (2000) employed a precision aiming task in which standing participants were instructed to maintain a handheld light beam within the bounds of a specified target region. Analysis of the associated body sway suggested that the roles of AP and ML sway were dependent upon the orientation of the body to the target. When the target was placed directly in front of an actor, body movements in the AP axis did not have to be constrained to the level of lateral movements, due to the constraints of the task. Reduction in lateral movements would serve to facilitate task performance. Balasubramaniam et al. suggested that ML sway facilitated supra-postural performance, with control of body orientation per se being shifted to the AP axis. When orientation was changed so that the body did not face the
target directly (the target remained visible due to a head turn), the relative amplitude of AP and ML sway reversed, suggesting that their roles may have reversed, as well. The postural system changed its behavior adaptively to accommodate altered supra-postural task constraints.

The findings and interpretation of Balasubramaniam et al. (2000) may apply to the present study. A change in body orientation during performance of the visual fixation task could reveal differences in AP and ML subsystems. Functional effects might be detected in the variability of body sway, or in nonlinear measures of postural behavior (e.g., Balasubramaniam, Riley, & Turvey, 2000; Riley, Balasubramaniam, Mitra, & Turvey, 1998; Riley, Balasubramaniam, & Turvey, 1999).

The ocular requirements for achieving visual performance in Experiments 1 and 2 were similar to those used in previous research (Oblak et al., 1985; Stoffregen et al., 2000). Those supra-postural task manipulations required controlled variations in eye movements to achieve accurate visual performance. The eyes reliably rotated to follow the lights (Oblak et al., 1985) and the eyes reliably scanned through a block of text (Stoffregen et al., 2000). These outcomes suggest that supra-postural tasks that require eye movements constrain postural sway in a variety of situations.

**Postural stabilization of stationary fixation**

Experiment 3 was designed primarily to vary the demands on the positional stability of the eyes. In Experiment 3, eye movements would not facilitate visual performance. Successful performance of both the Hard and Easy tasks depended upon
stationary fixation. The tasks differed in the extent to which the eyes, during fixation, must be held still, as opposed to drifting.

In Experiment 3, the requirement for positional stability was manipulated in several ways, one of which was by varying the size of the critical signals relative to the size of the neutral signals. When critical and neutral signals differed very little in size, precise fixation was required in order to discriminate between them. In the *Easy* task, good performance could be maintained while tolerating a greater level of ocular drift. Similar manipulations in demand might be achieved by varying the temporal parameters of target presentation. For example, an increase in the rate of target presentation might reduce the amount of ocular drift that could be tolerated. Similarly, a change from regular presentation (i.e., one target per second), to irregular presentation (i.e., targets presented at random intervals) could also increase the demand on positional stability of the eyes.

When participants were presented with a hard target detection task, postural behavior was found to facilitate visual performance by reducing sway variability. Reduction in target luminance, contrast ratio, and size difference for the critical signal apparently required greater visual stabilization relative to the easier task, even though both tasks depended upon stationary fixation.

Beyond this, Experiment 3 raises the possibility that posture might be modulated in support of supra-postural task demands that are cognitive rather than visual, per se. The *Hard* task required greater positional stability of the eyes than the *Easy* task, but it may also have been harder in a cognitive sense, as well. It is almost certainly the case that the *Hard* task produced a greater level of mental effort. Could this have influenced body sway, independent of the requirements for ocular control? This question could be
answered by varying independently levels of ocular stability and mental workload associated with supra-postural tasks.

The experiments in the present study address postural support for two different types of constraints on the visual system. These are the control of saccadic eye movements and the control of positional stability of the eyes in the absence of saccadic eye movements. The results resolve the ambiguity in the study of Stoffregen et al. (2000): In their study, the significant effect of supra-postural tasks upon body sway could have resulted from the task-based difference in eye movements or from the task-based difference in the need for positional stability of the eyes. This raises a new question: Are the postural constraints imposed by eye movement tasks and ocular positional stability additive? In the present study these constraints were separated across experiments, and the present data cannot be directly (i.e., statistically) compared to the data of Stoffregen et al. Thus, further research will be needed in order to determine whether or not the postural effects of different, but simultaneous, constraints on visual performance are additive.

*Measurement of visual behavior*

While my primary question concerned how constraints on ocular stability might influence body sway, in none of the experiments did I measure eye movements directly. The simple reason for this was that technology needed for measurement of eye movements was not available. In part for this reason, the experiments were designed so that direct measurement of eye movements would not be needed. In the first two
experiments, I assumed that visual performance (tracking of target motion) was adequate. I assumed such because visual fixation of an object is relatively simple, and participants could be assumed to be, in effect, experts at the task. Eye movements were measured by Oblak et al. (1985), who confirmed, using the same task as in Experiments 1 and 2 of the present study, that participants do move their eyes appropriately. In Experiment 3, the supra-postural task was more complex. Visual performance was evaluated in terms of perceptual sensitivity, rather than in terms of the positional stability of the eyes *per se*. The data are consistent with my arguments about variations in the degree of ocular stability required in different conditions. However, in future research it would be desirable to contrast variations in body sway with direct measurement of the saccadic and positional stability of the eyes.

*Postural learning*

Post-hoc analyses of Experiment 3 revealed significant trial effects on both body sway and signal detection. The data suggest that there was an experience-based development of the functional relation between posture and visual performance. It seems that the easier target detection task involved some level of perceptual-motor learning similar to the postural learning effects reported by Mark, Balliet, Craver, Douglas, and Fox (1990). Their supra-postural task was to identify one’s own maximum sitting height. In one experiment, participants were presented with a novel situation in which they had to wear 10 cm blocks on their feet. Visual performance was not immediately accurate. Overall, participants underestimated their actual maximum sitting height. However,
performance accuracy gradually increased over trials in that the difference between perceived maximum sitting height and actual maximum sitting height diminished over the course of the experiment (Mark et al., 1990).

In my experiment, sway variability in the AP axis was reduced when performing the first presentation of the *Easy* task as compared with the latter presentations. Simultaneously, participants demonstrated a performance increase. The data suggest that some perceptual-motor learning may have occurred. Apparently, participants began with a conservative strategy, reducing sway to a very low level while they "checked out" the difficulty of each task. Participants appear to have concluded that this minimal sway was required for performance of the *Hard* task, but that they could "ease off" on body sway while maintaining adequate performance of the *Easy* task.

Similar to the Mark et al. (1990) study, visual performance improved over time. In addition, data from Experiment 3 and Mark et al. suggest that when presented with somewhat difficult supra-postural tasks, postural behavior over time can reveal certain properties of the task which can either increase visual performance (task accuracy) or maintain levels of visual performance using a more efficient strategy (less constrained postural sway). Severing the relationship between vision and posture can cause visual performance to suffer. Mark et al. included an experiment that restricted participants visual field by requiring them to view the sitting device through a monocular peephole. Without the use of normal body movements to estimate maximum sitting height, visual performance was not accurate, nor did it increase over time.

In terms of the *Hard* task, visual performance did not seem to change over time. Consistent with this, sway variability in the ML axis also did not change over time.
These results suggest that the degree of visual stabilization required to achieve a particular level of visual performance remained constant. It is possible that participants could not achieve a greater level of perceptual sensitivity to the target criterion. The trial effect on body sway in the AP axis is more peculiar. In the AP axis sway did not differ when comparing the first and last presentation. However, during the second presentation of the *Hard* task, sway variability was greater than in either the first or last presentation. One interpretation of this is that postural exploration may have taken place during the second presentation. If it occurred, this exploration was carried out in a way that did not affect performance on the visual task. The fact that sway variability returned to its original level during the third presentation of the *Hard* task does not necessarily mean that any postural exploration undertaken during the second presentation was without effect. It may be that exploration during the second presentation led to an adaptive reorganization of body sway during the third presentation that simply was not reflected in the measured variability of body position. Such a reorganization might have taken place with respect to other parameters of sway, such as its temporal structure (e.g., Riley et al., 1997), or in terms of the coupling of motions of the head and torso (e.g., Oullier, Bardy, Bootsma, & Stoffregen, 1999). Further analysis is required to properly address this issue.

*Applications*

In this section, I briefly discuss possible implications of the present findings for the design and use of a variety of human-machine systems. One such area is the use of Head-Mounted Displays (HMDs) that incorporate head tracking technology. Another
area is gaze-based control systems. In these cases, I will argue that my results can motivate a new understanding of how perception and action are integrated in technological situations, and of how postural control, in particular, may influence the utility or success of human-machine systems that place a premium on visual performance.

In virtual reality systems users commonly are presented with visual displays that are slaved to the head, using head-mounted displays (HMDs) that are either opaque or see-through (the latter are referred to as augmented-reality, AR). In ordinary situations visual stimulation is coupled to body sway, because body sway gives rise to optical flow that influences the entire visual field (i.e., any display plus the background). By contrast, in basic HMD systems, changes in visual stimulation are decoupled from body sway. When the display is mounted on the head, body sway does not cause changes in visual stimulation. With AR-HMD systems, body sway is decoupled from the HMD display, but not from the outside world seen through the display. When it is decoupled from visual stimulation, body sway cannot be used to facilitate visual performance². In such situations ocular stabilization that is required for visual performance must be achieved by some means other than the modulation of body sway. If body sway is a common means of stabilizing vision, then we would expect the use of HMDs to lead to degradations in visual performance, at least until alternate means of ocular stabilization could be identified and brought to bear. For example, during HMD use, ocular stabilization might rely, moreso than usual, on adjustments of the eyes, themselves. This might place

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² Note that this is not a product of electronic or computer technology, per se, but simply of the fact of looking at something that is attached to the head (e.g., an object affixed to a rod extending from a helmet).
unusually rigorous demands on the eye muscles which might, in turn, explain the
tendency of some HMDs to be associated with eyestrain (Howarth, 1999).

Technological development is making it possible to track the orientation and
movement of the head at high speed (i.e., at high sampling rates), in real time. This
means that the output of head tracking systems can be used as control inputs for a variety
of online functions. In principle, this means that HMDs could be coupled to body sway,
reproducing the relationship between body sway and visual stimulation that characterizes
ordinary vision. But this cannot be assumed; the application of on-line tracking
technology may cause its own problems. For instance; if only the head is tracked, then
the visual display system will be unable to distinguish motions of the head that are caused
by head movements per se (e.g. head turns), from motions that are caused by body sway.
This could be a problem because in natural situations head motions can differ from body
motions when stabilizing vision as found in the current experiments.

AR systems are intended to be used to aid those who require a high degree of
precision where proper alignment of the virtual image is essential. One problem in AR
systems is the time difference between the moment the system measures position and
orientation of a tracker and when the image is created to correspond to that particular
position. This can cause problems with alignment during motion (Azuma, 1997). Is it
possible that the same types of postural movements found when fixating static targets
could interfere with the alignment of augmented virtual objects? To address this
question, visual fixation tasks while using AR systems could be performed to assess
whether misalignment occurs during static and moving fixations. If a greater degree of
misalignment occurs during static fixations than can be attributable to postural sway
movements, the next step would be to determine whether that level of misalignment is not functional in more realistic situations. To the extent that this would be true, one recommendation would be to train users to not spend extended periods of time fixating on the virtual images.

Postural motion often causes changes in visual stimulation. Newer technologies are creating situations where the stabilization of visual targets is not dependent upon postural behavior. As with head tracking, information about the direction of gaze can be used either to control visual displays (Borah, 1998; State et al., 1996) or for control of systems such as cameras, or weapons. An example of the former is the "eyeline of sight interface" (L. J. Hettinger, personal communication, June 8, 2000), which uses online information about the direction of gaze to place vital information (e.g. airspeed indicator) in the direction of gaze at all times. In the situation where a pilot had no other visual cues, the effect of the visual target slaved to the head may cause an increase in body movement because stabilization of the visual targets would not be dependent upon postural behavior. To test this prediction, one could replicate the current experiments, but add a condition where the visual targets are presented using a fully immersive VR headset. With no change in the optics directly caused by body movements, I would predict that postural sway variability would increase. In this situation, an increase in body sway would no longer have any influence on visual performance, so that greater levels of sway could be tolerated (Stoffregen et al., 1999).

Future research
The present studies motivate more research to investigate the relationship between visual performance and postural sway. For example, different frequencies of moving targets can be studied to determine whether there is a point where the benefits of constraining postural sway break down. This would allow us to identify limits of postural motion that can facilitate visual stabilization. Another research question that needs to be addressed is postural learning. With more complex supra-postural tasks, it would be interesting to pursue how body movements potentially explore new tasks and progress towards optimal efficiency.

Implications of human factors issues motivate further research in visual performance and perceptual-motor limitations. For example, research should investigate how much lag can be detected and tolerated. It is possible that technology could progress to a point where a particular amount of lag can be tolerated. Other types of applied research could assess the usefulness of projecting magnified images as opposed to using magnifying lenses or microscopes. It is possible that error rates and subjective responses of discomfort would decrease when visual precision requirements are decreased.

**Conclusion**

The present research suggests that postural behavior can be used to facilitate the achievement of other tasks. Variability in body sway was reliably influenced by properties of supra-postural visual tasks. One implication of this finding is that theories of postural control must take into account the existence and nature of supra-postural tasks. This research provides more empirical support for the idea that postural sway is
organized with reference to constraints imposed by performance demands of supra-
postural tasks while addressing some limitations of previous supportive research (e.g.
Stoffregen et al., 2000; Stoffregen et al., 1999).
References


Appendix A

Condition orders for Experiment 1 : Moving and stationary targets: Force data, and Experiment 2. Moving and stationary targets: Kinematic data.

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<th>Condition Orders</th>
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| move | static | move | move | move | static |
| move | move | move | static | static | static |
| static | static | static | move | static | static |
| move | static | move | move | move | move |
| static | move | static | static | static | move |

* ec = eyes closed
Appendix B

Non-parametric analyses for Experiments 1 and 2. (Wilcoxon Signed-Rank Tests)

Experiment 1

AP
\[ T = 4 \ (n = 13), \ p < .05 \]

ML
\[ T = 17 \ (n = 13), \ p < .05 \]

Experiment 2

AP/Head  \[ T = 15 \ (n = 13), \ p < .05 \]
AP/Torso,  \[ T = 11 \ (n = 13), \ p < .05 \]

ML/Head  \[ T = 47 \ (n = 13), \ p > .05 \]
ML/Torso,  \[ T = 45 \ (n = 13), \ p > .05 \]
Appendix C

Experiment 3. Target detection Condition Orders

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* ec = eyes closed
Trials 3-6 were included in the analysis.
Appendix D

Experiment 3. Target detection. A sample of subjective statements describing the two conditions (*Easy*, *Hard*).

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<tr>
<th>Easy Condition</th>
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<td>“easy”</td>
<td>“harder to see”</td>
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<tr>
<td>“pretty easy”</td>
<td>“took more effort”</td>
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<tr>
<td>“easier to see”</td>
<td>“deceiving, misleading”</td>
</tr>
<tr>
<td>“much easier”</td>
<td>“difficult to see”</td>
</tr>
<tr>
<td>“don’t need to concentrate as much”</td>
<td>“pretty tough”</td>
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<tr>
<td>“easier, more obvious”</td>
<td>“took both mental and physical effort”</td>
</tr>
<tr>
<td>“fairly easy”</td>
<td>“little difficult”</td>
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<tr>
<td>“easier, but still had to concentrate”</td>
<td>“more challenging”</td>
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<tr>
<td>“pretty easy once I got used to it”</td>
<td>“wasn’t as obvious”</td>
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<tr>
<td>“easier to distinguish”</td>
<td>“frustrating”</td>
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<tr>
<td></td>
<td>“harder to notice difference”</td>
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<td></td>
<td>“had to be alert”</td>
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<tr>
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<td>“took more cognitive effort”</td>
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<tr>
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<td>“had to think a little more”</td>
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<td>“more mental, not really physical effort”</td>
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<td></td>
<td>“doable, just had to concentrate”</td>
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<td></td>
<td>“annoying”</td>
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<td></td>
<td>“tightening up because of stress level”</td>
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Appendix E

Analyses for checking assumptions related to ANOVA in Experiment 3.

Cochran’s C suggested heterogeneity of variance in the ML axis for both head and torso position, but suggested homogeneity of variance for the AP axis. However, all of the variance ratios for stance (Stand, Sit) were less than 4:1, which conforms with Myers & Wells (1995) general guideline for assessing homogeneity of variance. Thus, homogeneity of variance should not pose a problem ($\sigma^2_{\text{Stand}} = .006, \sigma^2_{\text{Sit}} = .006$ [Head/AP]; $\sigma^2_{\text{Stand}} = .003, \sigma^2_{\text{Sit}} = .001$ [Head/ML]; $\sigma^2_{\text{Stand}} = .005, \sigma^2_{\text{Sit}} = .005$ [Torso/AP]; $\sigma^2_{\text{Stand}} = .002, \sigma^2_{\text{Sit}} = .001$ [Torso/ML]).

The data were discretized to assess normality. Each group was categorized into no more than 20 groups (Snedecor & Cochran, 1967). When compared to a normal distribution, interpretation of the $\chi^2$ goodness of fit test suggested a departure from normality for Torso/ML, for both the Easy and Hard visual tasks. This should not pose a problem, because the $F$-test is relatively robust in terms of normality unless the departure from normality is extreme (Myers & Wells, 1995). The distribution of the remaining groups did not depart from normality.

\begin{table}[h]
\centering
\begin{tabular}{llcc}
\hline
\text{Cochran’s C} & $C(23,2)$ & $p$ & $\chi^2$ & $p$ \\
\hline
\text{Head} & \text{Easy} & 0.56 & > .05 & 4.84 & > .05 \\
& \text{Hard} & 0.57 & > .05 & 4.85 & > .05 \\
\text{AP} & \text{Easy} & 0.71 & < .05 & 7.50 & > .05 \\
& \text{Hard} & 0.79 & < .05 & 6.31 & > .05 \\
\text{ML} & \text{Easy} & 0.60 & > .05 & 3.65 & > .05 \\
& \text{Hard} & 0.61 & > .05 & 8.30 & > .05 \\
\text{Torso} & \text{Easy} & 0.74 & < .05 & 13.16 & < .05 \\
& \text{Hard} & 0.78 & < .05 & 10.21 & < .05 \\
\hline
\end{tabular}
\end{table}