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Modulating postural control to facilitate visual performance

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Abstract

We explored relations between visual performance and postural control. Variability in postural sway was analyzed in the context of variations in supra-postural visual tasks. We varied target distance (near vs. far) and visual task (inspecting a blank target vs. counting the frequency of letters in a block of text). Variability in postural sway was reduced when participants fixated near targets as opposed to far targets. Also, postural sway during the visual search task was reduced relative to sway during inspection of blank targets. We argue that the search task placed more restrictive constraints on the visual system, and that postural sway was reduced to facilitate visual search. The results support the hypothesis that postural control is not an autonomous system, but is organized as part of an integrated perception–action system. Postural control can be used to improve visual performance. © 2000 Elsevier Science B.V. All rights reserved.

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1. Modulating postural control to facilitate visual performance

Research on vision typically concentrates on the eye and on cognitive and neural processes that are related to the eyes and their activity. Examples include visual physiology and visual cognition. This approach has been fruitful in producing research, but it may exclude some important aspects of ordinary vision. Gibson (1966) offered a revised and 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 eye, and that such movements can be controlled so as to facilitate vision (e.g., turning the head or walking to bring desired targets into the field of view). In this study, we investigate the influence of postural sway on vision. Specifically, we consider the possibility that some parameters of postural sway can be modulated in response to changes in visual tasks so as to facilitate visual performance.

1.1. Posture and supra-postural behavior

Research on postural control concentrates on “quiet stance”, in which participants are instructed to “look straight ahead and stand as still as possible” (Lee & Lishman, 1975, p. 90), or to “look at the center of the stimulus and stand relaxed” (Dijkstra, Schöner & Gielen, 1994a, p. 481). It is assumed that the participant’s main goal is the maintenance of postural stability, and that perceptual information is used primarily for the control of stance. Analysis and interpretation focus on relations between perceptual information and postural control actions. Typically, in research on quiet stance there is no experimentally controlled variation in supra-postural activity; that is, the participants are not asked to do anything other than maintain posture while attending to the perturbing stimulus (e.g., Dijkstra et al., 1994a; Dijkstra, Schöner, Giese & Gielen 1994b; Van Asten, Gielen & Denier van der Gon, 1988). This is unrepresentative in the sense that outside the laboratory people generally engage in other activities while standing, such as reading, manual manipulation, visual tracking, and walking. The quiet stance paradigm makes it difficult to evaluate the possibility that postural sway is detected and controlled with reference to these other behaviors.

We refer to tasks or behavioral goals that are super-ordinate to the control of posture as *supra-postural tasks*. Supra-postural tasks differ from postural control in that they are defined and evaluated in different terms. Reading, for example, is not evaluated in terms of the position or motion of the body’s

center of mass, the minimization of global optical flow, and so on. Postural motion can influence performance at supra-postural tasks (e.g., excessive sway can degrade reading), but performance of supra-postural tasks is measured in different terms (e.g., reading rate or comprehension). In general, values of postural control parameters do not provide information about supra-postural task performance. For example, a large excursion of the center of mass might lead to degraded reading performance (e.g., if the person began to fall over), or it might facilitate reading (e.g., if the person leaned forward to see text on a computer monitor).

1.2. Posture in the service of supra-postural activity

Riccio and Stoffregen (1988, 1991) (cf. Bernstein, 1967; Reed, 1988) argued that postural stabilization is not an end in itself, but is valuable only to the extent that it facilitates the achievement of other goals. Stance can be controlled in different ways, which will differentially impact the performance of other behaviors. This suggests that the success of postural control actions may be most appropriately defined in terms of their impact on the achievement of supra-postural goals. If so, it would be meaningless to suggest that postural control is successful only if it minimizes postural sway. Minimal sway will facilitate the achievement of many goals, but not all possible goals. For example, increased postural sway may facilitate exploration of the dynamics of the animal–environment interaction (Riley, Mitra, Stoffregen & Turvey, 1997).

The control of posture may be modulated adaptively so as to facilitate supra-postural activity (e.g., Aruin & Latash, 1995; Bardy, Marin, Stoffregen & Bootsma, 1999a; Belenkii, Gurfinkel & Paltsev, 1967; Feldman, 1966; Marin, Bardy, Baumberger, Fluckiger & Stoffregen, 1999; Riley et al., 1997; Riley, Stoffregen, Grocki & Turvey, 1999; Tuller, Fitch & Turvey, 1982; Vereijken, van Emmerik, Whiting & Newell, 1992). While these studies differ substantially, they share the fact that they did not use the quiet stance paradigm. Their findings suggest that the precision of postural stabilization may be a function of the degree of stabilization required for the performance of a given task. This, in turn, suggests that postural motion might differ across supra-postural tasks, with the differences being adaptively related to constraints imposed by the tasks.

In the studies cited above the supra-postural behaviors (e.g., arm movements) brought about changes in the position or motion of the center of mass. Ignoring movements of the center of mass would lead to inefficient

postural control or even loss of balance. For this reason, it might be argued that in previous research postural control was influenced by movements of the center of mass, and not by supra-postural tasks, per se. Research of this kind does not address the question of whether postural control might be modulated to facilitate the achievement of supra-postural goals that have little or no influence on the center of mass. Research that addresses this question is discussed in the next section.

1.3. Postural stabilization of visual fixation

Head motion relative to the illuminated environment causes optic flow (Gibson, 1986, 1966; Lishman & Lee, 1973). The magnitude of optic flow created by a given movement of the head is a function of the distance between each element of the surroundings and the point of observation: greater optical change will be produced relative to nearby objects. Lee and Lishman (1975) placed standing participants in a large lecture hall and measured their spontaneous (unperturbed) sway as they fixated objects at different distances. When participants looked at a distant wall, their anterior–posterior (AP) sway amplitude was large. When they fixated an object (a coat rack) that was placed directly in front of them, sway amplitude decreased. Lee and Lishman (1975) interpreted this distance effect in terms of a detection threshold; in the “near” condition the visual change accompanying body sway is more pronounced and therefore, presumably, more detectable. This finding has been replicated in a variety of studies using unperturbed sway (Bles, Kapteyn, Brandt & Arnold, 1980; Dijkstra, Gielen & Melis, 1992; Paulus, Straube, Krafczyk & Brandt, 1989), each of which has accepted the threshold interpretation proposed by Lee and Lishman (1975).

An alternative interpretation of the distance effect is that, different degrees of visual stabilization are required for successful fixation of objects at different distances. That is, the amount of visual instability that can be tolerated depends on how far away the person is looking. It may be that the influence of distance on posture should be a function of what the person is looking at. When one is looking at a distant object there is nothing to be gained by minimizing sway, regardless of the presence or absence of nearby objects or surfaces that are not fixated.

This hypothesis was evaluated by adding a condition to the experiment of Lee and Lishman (1975). Stoffregen, Smart, Bardy and Pagulayan (1999) instructed participants to ignore a nearby object while fixating a more distant target. The magnitude of optical flow generated by unperturbed sway in this

situation was greater for the nearby object than for the distant target, but this larger amplitude flow was irrelevant to the fixation task. If vision is used to stabilize posture, that is, if optical flow is always used to regulate sway, then the amplitude of postural sway should not be influenced by variations in fixation. However, if postural sway can be modulated so as to facilitate successful fixation while minimizing energy expenditure, then we would expect the flow corresponding to the nearby object to be “ignored”, resulting in sway similar to that, which occurs in the absence of nearby objects. In making these predictions Stoffregen et al. (1999) assumed that a consistent goal of all behavior is efficiency, that is, the organization of action in a manner that minimizes effort (energy expenditure) while maintaining achievement of task goals (Diedrich & Warren, 1995; Hoyt & Taylor, 1981; Riccio & Stoffregen, 1988; Sparrow & Newell, 1998). The type of control that is most efficient (i.e., least effortful) will vary across tasks. In relating postural control to supra-postural activity this would imply that participants should select postural control actions that minimize the effort required to control posture, while at the same time facilitating achievement of supra-postural task goals.

Stoffregen et al. (1999), crossed variations in fixation task (fixation of nearby and distant targets) with variations in the visual system (binocular versus monocular vision), in the spatial relation between fixation and postural control (changes in the orientation of the line of sight relative to the body), and variations in the geometry of optical flow produced by postural sway (radial versus lamellar optical flow; Stoffregen, 1985). Across these variations unperturbed postural sway was influenced by variations in the distance of fixated targets, independent of the distance of unfixated objects. This suggests a reinterpretation of effects of distance on unperturbed sway as reported by Dijkstra et al. (1992); Lee and Lishman (1975) and Paulus et al. (1989). More broadly, the influence of fixation distance raises questions about the assumption that postural control is organized independent of supra-postural activities. The supra-postural fixation task had no direct influence on the position or motion of the body's center of mass. Thus, the observed changes in postural sway cannot be attributed to mechanical constraints on posture (e.g., Nashner & McCollum, 1985). In addition, the influence of fixation distance reported by Stoffregen et al. (1999) indicates that optical flow resulting from body sway was not always used to minimize postural sway. Thus, observed changes in postural sway could not be attributed to variations in optical flow resulting from body sway (e.g., Schöner, 1991).

1.4. Different parameters of the oculomotor system

Stoffregen et al. (1999) operationalized variations in looking task in terms of variations in the distance of fixated targets. They did not vary the appearance of the fixation targets, and they did not vary the type of looking that was required. Thus, their work provides only a limited evaluation of the hypothesis that posture can be modulated to facilitate supra-postural looking. In the present study, we sought to expand the range of visual performance that might be facilitated by variations in postural control.

Visual performance depends on control of several parameters of the oculomotor system. One of these is focus: in most situations the system operates to minimize blur in the fovea. Focus can be controlled by adjustments of the lens. Another factor is binocular convergence; more precise control of convergence was required with the nearby target. Convergence is controlled by rotating the eyes relative to one another. The experiments of Stoffregen et al. (1999) suggest that appropriate focus and convergence may also be maintained through variations in body sway, consistent with Gibson's (1966) expanded concept of the visual system. The need to adjust accommodation and convergence can be eliminated by placing all targets at the same distance. When this is done, postural adjustments may be used to optimize other parameters of visual performance.

In the present experiment, we contrasted variations in target distance with variations in the type of ocular control that was required for adequate performance of visual tasks. Following Stoffregen et al. (1999), and Lee and Lishman (1975), we predicted that sway amplitude would be reduced during viewing of nearby targets. There were two visual tasks: (1) generalized inspection of a blank target, and (2) visual search for target letters in a block of text. We assumed that visual search would require more precise control of eye movements than inspection of the blank target. For this reason, we predicted that during a visual search task postural sway would be reduced in amplitude relative to sway during the generalized inspection tasks. In addition, we predicted that the effect of target distance on sway would be greater for the visual search task than for the inspection task.

The visual search task provided a means to assess visual performance. We evaluated the success of visual search in terms of the speed and accuracy of target detection. This allowed us to assess relations between visual performance and postural sway. In addition, we sought to examine the reorganization of posture in response to on-line changes in the distance of visual targets (this was not addressed by Stoffregen et al., 1999). Accordingly,

changes between near and far targets took place during experimental trials. Our study differed from that of Stoffregen et al. (1999) in that we did not include a condition in which participants ignored a nearby target while fixating a distant target. For this reason our data are not directly relevant to the issue of whether postural sway is influenced by the distance of objects, per se, as opposed to the distance of fixation.

2. Method

The experiment was carried out in accordance with ethical guidelines laid down by the West Campus Human Subjects Committee of the University of Cincinnati.

2.1. Participants

Twenty-four undergraduates at the University of Cincinnati (mean age of 20, ranging in age from 18 to 44) participated for course credit. Participants were screened for any history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. In addition, we accepted only those participants who were less than 1.9 m tall (this is explained below). They were randomly divided into two groups of 12, the *inspection group* and the *search group*.

2.2. Apparatus

The laboratory set-up is illustrated in Fig. 1. In all conditions there were two visual targets, one near and one far. The far target was in a fixed position in the upper half of the field of view. The height of the near target was adjusted for each participant so that the upper edge of the near target was aligned with the lower edge of the far target. This minimized the visual adjustments that were needed to switch between targets. Limits on the adjustability of target height prohibited us from using participants who were more than 1.9 m tall.

For the *inspection group*, the near target consisted of a sheet of plain white paper, 13.5 cm × 17 cm. The far target consisted of a piece of white poster board, 1.0 m × 1.2 m. Each target subtended a visual angle of 16.5° × 20°. For the *search group* the near target consisted of a sheet of white paper,

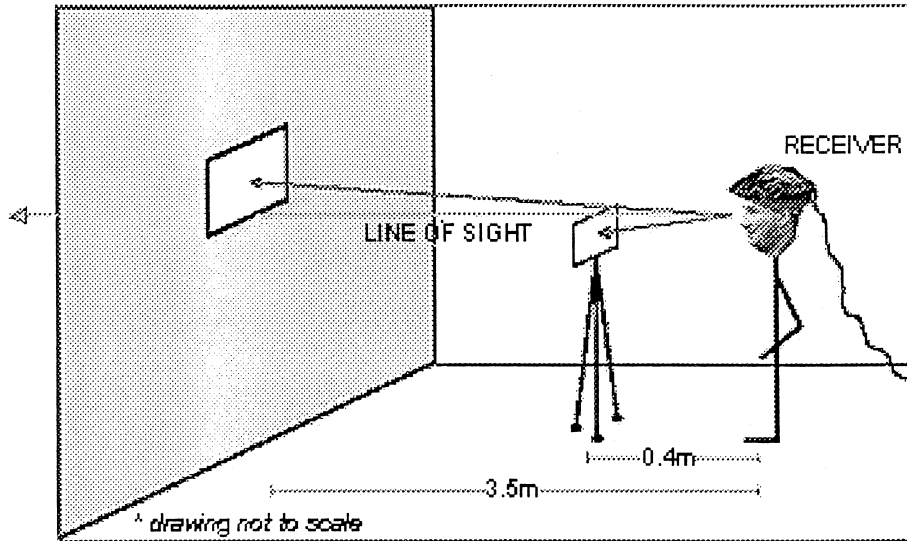


Fig. 1. Experimental set-up.

13.5 cm × 17 cm, on which there were printed lines of text in English. The text block was made using a sans-serif 12 point Avant Garde font. There were four different text blocks for use on different trials, each consisting of 13 or 14 lines of text. The far target consisted of a piece of white poster board, 1.0 m × 1.2 m, which was also printed with English text. Again, four different blocks of text were used on different trials. The texts and font were the same as those used on the near target, except that on the far target the font size was 90 points. The visual angle of individual letters was the same for the near and far targets.

Postural sway was recorded using a magnetic tracking system (Flock of Birds, Ascension Technologies, Burlington, VT). Head position was sampled at 50 Hz from a receiver attached to the back of a bicycle helmet worn by the participant. Data from the tracking system were stored on disk for later analysis.

2.3. Procedure

Participants donned the bicycle helmet with the Flock of Birds receiver, and were asked to stand with their heels on a mark on the floor. In this position, they were 0.4 m from the near target, and 3.5 m away from the near

target. The height of the bottom of the far target was fixed at 1.3 m. The height of the near target was scaled to each participant so that the top of the near target appeared to reach the bottom edge of the far target. In all conditions participants were asked to stand comfortably, facing forward without moving their feet.

There were eight trials for each participant. The duration of each trial was 100 s, with postural data being collected for the latter 90 s. Participants began each trial fixating the appropriate target. During trials participants were instructed to switch targets (i.e., from far to near, or vice versa) by the experimenter, who said “switch”. In half the trials switching occurred at 30 s intervals (so that there were two switches per trial), while in the remaining trials switching occurred after 45 s (one switch per trial). Participants were told they were allowed to look anywhere within the appropriate target without rotating the head. They were also told to avoid moving their head when alternating between targets.

For the *search group* participants were instructed to count the frequency of a given letter during each trial. On different trials four different target letters were used; A, R, N, and S. Within trials the same text was used on the near and far targets. Participants were told that when they switched they were to continue counting in the new text block at the position where they had left off in the previous block. Participants were instructed that, if they finished a text block before the end of a trial, they were to start back at the top of the text, and continue the total frequency count. At the end of each trial, participants reported where they were in the text when the trial ended and the number of targets that they had detected.

A given target letter could be used on multiple trials for a given participant. However, each target letter was used with only one text block. This ensured that between trials participants did not count the same letter in the same text block more than once. The number of target letters in individual text blocks ranged from 47 to 78.

2.4. *Design and data analysis*

The principal dependent variable was the variability of head position in the anterior–posterior axis (along the line of sight). This was operationalized as the standard deviation of head position. The mean variability for postural sway was calculated for the latter half of each looking interval within each trial. This was done because we were interested in the mean of a stable state;

we wished to exclude the period immediately following a switch, which was expected to contain changes in variability. A mixed design (one between, one within) analysis of variance (ANOVA) was performed on variability during each interval (near target or far target). The within factor was target distance (near/far), and the between factor was supra-postural task (Search group/Inspection group).

For the Inspection group, visual performance was not measured; following Stoffregen et al. (1999) we took for granted that the participants maintained their gaze on the target. For the Search group, visual performance was evaluated in terms of search accuracy. Accuracy was determined by comparing the number of targets reported to the actual number occurring in the text that was scanned. Percent correct was calculated by dividing the total frequency of occurrences reported by the frequency of actual occurrences in the amount of text that was reported as being scanned. A one-sample K–S test was performed on the distribution of errors.

3. Results

Visual performance. Across trials and participants the mean percentage correct was 90.1%. The mean number of errors per trial was 6.13. We could not collect data on the text location at which participants switched between the near and far targets, and so we were not able to evaluate search performance as a function of target distance. However, a one-sample K–S test performed on the number of errors per trial indicated that the distribution of errors did not substantially differ from a normal distribution, $z = 0.884$, $P = 0.415$. These results suggest that participants followed our instructions to search for target letters, and that they did so with substantial accuracy.

Postural motion. Figs. 2 and 3 illustrate postural motion over time as a function of target distance and visual task for representative trials. A one-between, one-within mixed design ANOVA conducted on the data revealed a main effect for target distance, $F_{(1, 232)} = 33.045$, $P < 0.05$, accounting for 12.5% of the variance. As predicted, variability in postural sway was significantly less for the near target (mean = 0.584 cm) than for the far target (mean = 0.701 cm). There was also a main effect of supra-postural task, $F_{(1, 232)} = 24.050$, $P < 0.05$, accounting for 9.6% of the variance. As predicted, sway variability during visual search (mean = 0.533 cm) was lower than during inspection (mean = 0.757 cm).

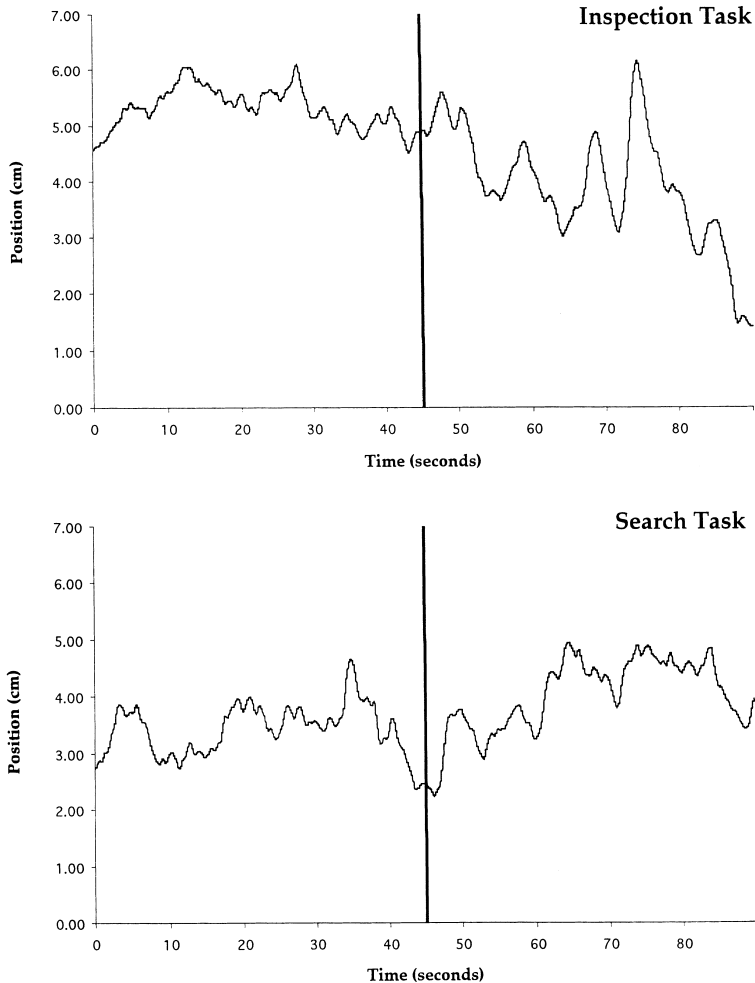


Fig. 2. Raw position data (representative trials) showing anterior–posterior motion for trials on which participants switched from near target to far target. The vertical line marks the point of the switch.

There was a significant interaction between distance and supra-postural task, $F_{(1, 232)} = 6.228, P < 0.05$, accounting for 2.6% of the variance (see Fig. 4). During inspection the difference in variability between near and far targets was larger than during the search task. A post-hoc Neuman–Keuls test performed on the search group indicated that there was a significant effect of target distance, $q = 0.59, P < 0.05$. Thus, the main effect of target distance exists independently for each of the supra-postural tasks.

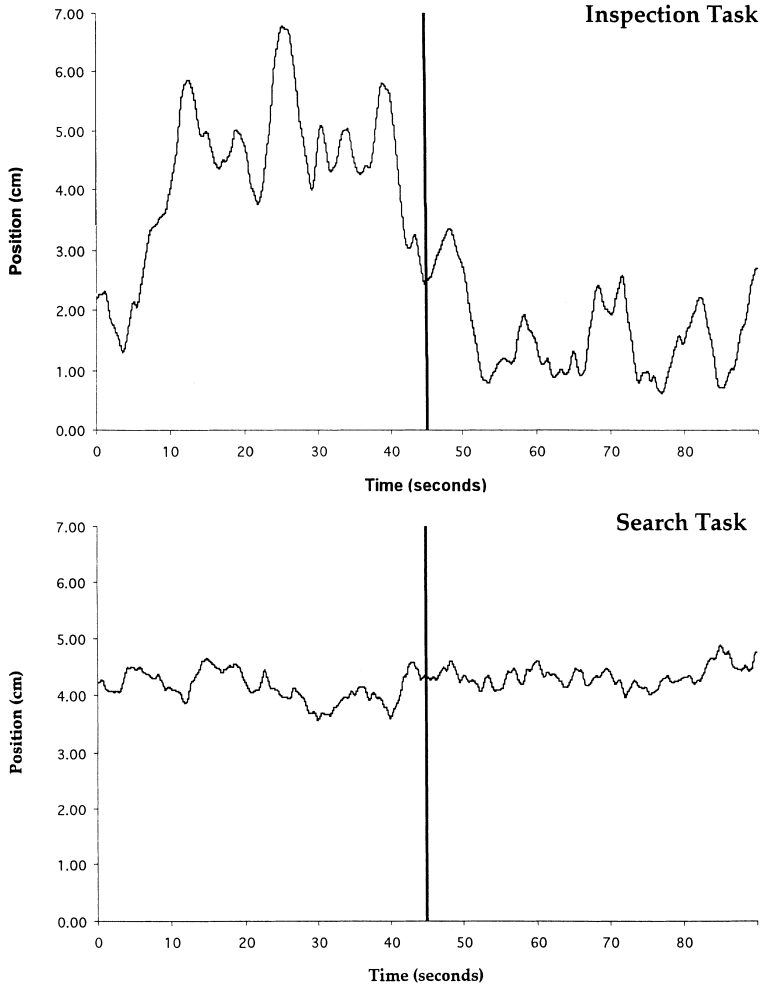


Fig. 3. Raw position data (representative trials) showing anterior–posterior motion for trials on which participants switched from far target to near target. The vertical line marks the point of the switch.

4. Discussion

Standing participants inspected blank targets or searched for target letters in blocks of text. Targets were at two different distances, and participants switched from nearby to distant targets within trials. We measured postural motion as a function of target distance and the nature of the visual task. Variability in postural sway was reduced when participants looked at nearby

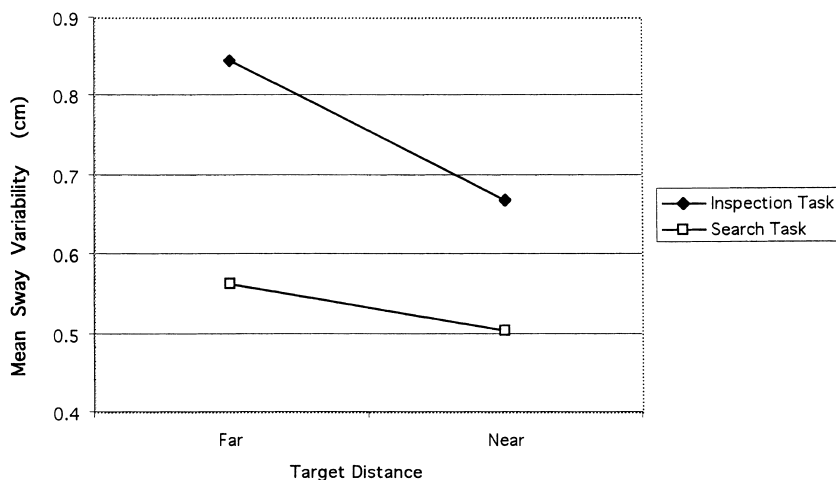


Fig. 4. Interaction between target distance and supra-postural task.

as opposed to distant targets. Also, postural sway during the visual search task was reduced relative to sway during inspection of blank targets. There was also a significant interaction between visual task and target distance; for the Inspection group the difference in sway between far and near targets was greater than for the Search group. These effects are discussed in turn.

4.1. Changes in looking distance

Stoffregen et al. (1999) varied fixation distance independent of physical distance by instructing participants to fixate distant targets while ignoring nearby targets. They found that postural sway was related to the distance of fixation, and was not “captured” by the nearest object (regardless of fixation). Reduced variability in sway made it easier to maintain stable fixation of the nearby target. For reasons of projective geometry greater levels of postural sway could be tolerated while maintaining successful fixation of the distant target. Thus, the relation between fixation distance and postural motion was functional. In the present study, we sought to extend previous work by varying target distance within trials. Our objective was to show that postural sway would be dynamically restructured to reflect on-line changes in target distance. Postural sway data were analyzed separately for the two target distances, and confirmed that within-trial changes in looking distance led to within-trial functional changes in the organization of sway.

4.2. Visual task

A major goal of our study was to increase the generality and ecological validity of the effects reported by Stoffregen et al. (1999). They focused on the relation between postural control and optical flow. For this reason the supra-postural task that they employed was not representative of ordinary looking outside the laboratory. Participants were asked to “stare intently” at the targets, but were not asked to see anything in particular, or to do anything about whatever they might see. In essence, the task was fixation for the sake of fixation. In the present study, we included a task for which accurate control of the visual system, rather than being an end in itself, subserved the pickup of particular information from the environment. Performance of the visual search task was defined in terms of accuracy of detected target letters, rather than in terms of stable fixation, or optical flow. Participants performed the visual search task as instructed, and they achieved a reasonable level of performance. This suggests that there were real differences in the demands made on vision in the inspection and visual search conditions. This extends the general finding of Stoffregen et al. (1999) suggesting that the organization of postural sway is acutely sensitive to and robustly influenced by variations in supra-postural tasks which have no mechanical effects on body motion.

The main effect of visual task allows us to rule out an alternative explanation of the main effect of target distance (see also Stoffregen et al., 1999). Effects on postural sway that were restricted to variations in the distance of fixated targets might occur if there were greater sensitivity to motion at the depth plane of fixation (this effect would be similar to figure-ground segregation in depth). If the visual system were preferentially sensitive to motion at the depth plane of fixation, then sensitivity to optical flow generated by the near target would be reduced during fixation of the far target. However, depth-related variations in sensitivity to visual motion cannot explain the main effect of visual task in the present experiment, since each task was presented at both the far and near distances.

Our analysis suggests that there might be a decline in visual search performance if participants were forced to increase their sway. This might be accomplished mechanically (e.g., by perturbation of the support surface, or by requiring participants to stand on a balance beam), or it might be done by instruction (e.g., by requiring participants to engage in deliberate body sway during visual search).

The use of blank and text targets might suggest that differences in postural sway might result from the difference in the visual stimuli (i.e., the targets),

rather than differences in the visual tasks. In effect, this would mean that postural sway was affected by the type of texture in optical flow. Postural responses to optical flow are known to be influenced by flow geometry (i.e., radial versus lamellar flow, Bardy, Warren & Kay, 1999b; Stoffregen, 1985), and motion parallax (e.g., Bardy, Warren, & Kay, 1996a; Riley, Balasubramaniam, Mitra & Turvey, 1998). However, no existing theory of postural control predicts that posture should be influenced by the two-dimensional texture of the visible environment (e.g., Schöner, 1991), and similar types of postural responses have been observed of a wide variety of target patterns, such as random squares (e.g., Warren, Kay & Yilmax, 1996), checkerboards (e.g., Van Asten et al., 1988), and simulated marble (e.g., Stoffregen, 1985). Finally, postural responses to optical flow are known to be robust even when the visual targets are defocused to the limits of static pattern detection (Leibowitz, Shupert-Rodemer & Dichgans, 1979). Thus, there is no reason to suspect that posture would be affected by the variation in the appearance of the visual targets.

4.3. The distance by task interaction

The difference in sway variability between far and near targets was greater for the Inspection group than for the Search group. This is consistent with the hypothesis that the visual search task imposed more restrictive constraints on postural motion than did the inspection task. Thus, the organization of postural sway was influenced more greatly by variation in the visual task than by variation in target distance. This suggests that variations in the visual task imposed more restrictive constraints on postural motion than were imposed by variations in target distance. This is important because constraints varied by the task manipulation differed qualitatively from the constraints varied by the distance manipulation. The constraints varied by the task manipulation were not defined in terms of optical flow or projective geometry (as was the case with the distance manipulation). Thus, the combined effect of task and distance implies that posture was simultaneously influenced by at least two qualitatively different types of constraints.

5. Conclusion

The present study, together with Stoffregen et al. (1999), indicates that people do not always attempt to minimize postural sway. The amplitude of

sway is greater in some situations, and less in others. Given this, we can ask what factors determine the extent to which a person will attempt to minimize sway. The present study shows that sway amplitude can be modulated adaptively in the service of the performance of supra-postural visual tasks. The amplitude of postural sway was selectively controlled to support the achievement of different types of visual tasks, independent of target distance. The present findings, together with those of Stoffregen et al. (1999) are consistent with ecologically-based analyses of postural control (e.g., Riccio & Stoffregen, 1988; Slobounov, Slobounova & Newell, 1997). This contrasts with theories in which supra-postural goals have no explicit (i.e., explanatory or predictive) role in the organization of postural control (e.g., Nashner & McCollum, 1985; Schöner, 1991). Our results indicate that optical flow is not always used for the control of stance in an “autonomous” fashion (Schöner, 1991).

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References

- Aruin, A. S., & Latash, M. L. (1995). The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. *Experimental Brain Research*, *106*, 291–300.
- Bardy, B. G., Marin, L., Stoffregen, T. A., & Bootsma, R. J. (1999a). Postural coordination modes considered as emergent phenomena. *Journal of Experimental Psychology: Human Perception & Performance*, *25*, 1284–1301.
- Bardy, B. G., Warren, W. H., & Kay, B. A. (1996). Motion parallax is used to control postural sway during walking. *Experimental Brain Research*, *111*, 271–282.
- Bardy, B. G., Warren, W. H., & Kay, B. A. (1999b). The role of central and peripheral vision in postural control during walking. *Perception & Psychophysics*, *61*, 1356–1368.

- Belenkii, V. Ye., Gurfinkel, V. S., & Paltsev, Ye. I. (1967). Elements of control of voluntary movement. *Biophysics*, 12, 154–161.
- Bernstein, N. A. (1967). *The coordination and regulation of movements*. Oxford: Pergamon.
- Bles, W., Kapteyn, T. S., Brandt, T., & Arnold, F. (1980). The mechanism of physiological height vertigo: II Posturography. *Acta Otolaryngologica*, 89, 534–540.
- Diedrich, F. J., & Warren, W. H. (1995). Why change gaits? Dynamics of the walk–run transition. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 183–202.
- Dijkstra, T. H., Gielen, C. C., & Melis, B. J. (1992). Postural responses to stationary and moving scenes as a function of distance to the scene. *Human Movement Science*, 11, 195–203.
- Dijkstra, T. H., Schöner, G., & Gielen, C. C. (1994a). Temporal stability of the action–perception cycle for postural control in a moving visual environment. *Experimental Brain Research*, 97, 477–486.
- Dijkstra, T. H., Schöner, G., Giese, M. A., & Gielen, C. C. (1994b). Frequency dependence of the action–perception cycle for postural control in a moving visual environment: Relative phase dynamics. *Biological Cybernetics*, 71, 489–501.
- Feldman, A. G. (1966). Functional tuning of the nervous system during control of movement or maintenance of a steady posture: III. Mechanographic analysis of the execution by man of the simplest motor tasks. *Biophysics*, 11, 766–775.
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton–Mifflin.
- Gibson, J. J. (1986). *The ecological approach to visual perception*. Mahwah, NJ: Lawrence Erlbaum [Original work published in 1979].
- Hoyt, D. F., & Taylor, C. R. (1981). Gait and the energetics of locomotion in horses. *Nature*, 292, 239–240.
- Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, 1, 87–95.
- Leibowitz, H., Schupert–Rodemer, C., & Dichgans, J. (1979). The independence of dynamic spatial orientation from luminance and refractive error. *Perception & Psychophysics*, 25, 75–79.
- Lishman, J. R., & Lee, D. N. (1973). The autonomy of visual kinaesthesia. *Perception*, 2, 287–294.
- Marin, L., Bardy, B. G., Baumberger, B., Fluckiger, M., & Stoffregen, T. A. (1999). Interaction between task demands and surface properties in the control of goal-oriented stance. *Human Movement Science*, 18, 31–47.
- Nashner, L. M., & McCollum, G. (1985). The organization of postural movements: A formal basis and experimental synthesis. *The Behavioral and Brain Sciences*, 8, 243–252.
- Paulus, W., Straube, A., Krafzyk, S., & Brandt, T. (1989). Differential effects of retinal target displacement, changing size and changing disparity in the control of anterior/posterior and lateral body sway. *Experimental Brain Research*, 78, 243–252.
- Reed, E. S. (1988). Applying the theory of action systems to the study of motor skills. In O. Meijer, & K. Roth, *Studying complex movement skills: The motor–action controversy* (pp. 45–86). Amsterdam: North Holland.
- Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3, 195–240.
- Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science*, 7, 265–300.
- Riley, M. A., Balasubramaniam, R., Mitra, S., & Turvey, M. T. (1998). Visual influences on center of pressure dynamics in upright posture. *Ecological Psychology*, 10, 65–91.
- Riley, M. A., Mitra, S., Stoffregen, T. A., & Turvey, M. T. (1997). Influences of body lean and vision on unperturbed postural sway. *Motor Control*, 1, 229–246.
- Riley, M. A., Stoffregen, T. A., Grocki, M. J., & Turvey, M. T. (1999). Postural stabilization of light touch. *Human Movement Science*, 18, 795–817.
- Schöner, G. (1991). Dynamic theory of action–perception systems: The moving room paradigm. *Biological Cybernetics*, 64, 455–462.

- Slobounov, S. M., Slobounova, E. S., & Newell, K. M. (1997). Virtual time-to-collision and human postural control. *Journal of Motor Behavior*, 29, 263–281.
- Sparrow, W. A., & Newell, K. M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin and Review*, 5, 173–196.
- Stoffregen, T. A. (1985). Flow structure versus retinal location in the optical control of stance. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 554–565.
- Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 1641–1658.
- Tuller, B., Fitch, H. L., & Turvey, M. T. (1982). The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. In J. A. S. Kelso, *Human motor behavior: An introduction* (pp. 253–270). Mahwah, NJ: Lawrence Erlbaum.
- Van Asten, W. N. J. C., Gielen, C. C. A. M., & Denier van der Gon, J. J. (1988). Postural adjustments induced by simulated motion of differently structured environments. *Experimental Brain Research*, 73, 371–383.
- Vereijken, B., van Emmerik, R. E. A., Whiting, H. T. A., & Newell, K. M. (1992). Freezing degrees of freedom in skill acquisition. *Journal of Motor Behavior*, 24, 133–142.
- Warren, W. H., Kay, B., & Yilmaz, E. (1996). Visual control of posture during walking: Functional specificity. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 818–838.