Motor Control, 2007, 11, 86-102

Postural Sway and the Frequency of Horizontal Eye Movements

Thomas A. Stoffregen, Benoît G. Bardy, Cédrick T. Bonnet, Philip Hove, and Olivier Oullier

In two experiments, participants were asked to shift gaze to follow horizontal target oscillation to allow us to investigate relations between eye movements and postural dynamics. Postural sway variability was reduced during target oscillation when compared to sway while viewing a stationary target. The influence of target oscillation on sway was independent of target oscillation frequency. Similar results were obtained with measurements of the center of pressure (Experiment 1) and the displacement of body segments (Experiment 2). The overall results are not consistent with the view that eye movements and postural control compete for limited central processing resources. The results are consistent with the thesis of a functional integration of postural control with visual performance.

Key Words: sway, stance, perception, gaze, visual performance

Recent research provides ample evidence of interactions between supra-postural activity and the control of stance (Woollacott & Shumway-Cook, 2002). Supra-postural tasks are super-ordinate to the maintenance of posture (Stoffregen, Adolph, Gorday & Sheng, 1997). Many studies have shown that postural control is influenced by supra-postural tasks, such as visual search, verbal reaction time, and mental arithmetic, that have no intrinsic mechanical influence on the position or motion of the center of mass (e.g., Dault, Geurts, Mulder, & Duygens, 2001; Hunter & Hoffman, 2001; Kerr, Condon, & McDonald, 1985; Maylor & Wing, 1996; Stoffregen, Pagulayan, Bardy &, Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999; Teasdale, Bard, LaRue, & Fleury, 1993). Typically, effects of this kind have been interpreted in terms of cognitive processes, the most widely accepted thesis referring to a potential competition in the allocation of central processing resources (e.g., Woollacott & Shumway-Cook, 2002). An alternative interpretation is that posture may be controlled, at least in part, to facilitate the

---

Stoffregen is with the Human Factors Research Laboratory, University of Minnesota, Minneapolis, MN 55414. Bardy is with the Institut Universitaire de France & Motor Efficiency and Motor Deficiency Laboratory, Faculté des Sciences du Sport, Université de Montpellier 1, 34090 Montpellier, France. Bonnet is with the Center for the Ecological Study of Perception and Action, University of Connecticut, Storrs, CT 06269-1020. Hove is with the Dept of Psychology, University of Cincinnati, Cincinnati, OH 45221. Oullier is with the Laboratoire de Neurobiologie Humaine (UMR 6149), Université de Provence—CNRS, F-13331 Marseille Cedex 03, France.

performance of supra-postural tasks (Riccio & Stoffregen, 1988; Oullier, Bardy, Stoffregen, & Bootsma, 2002).

Stance and Gaze

Because body sway displaces the head in space, there are changes in the position of the eyes and, hence, in the direction of gaze (e.g., Stoffregen, Bardy, Bonnet, & Pagulayan, 2006). The greater the amplitude of body sway, the greater the resulting perturbation in the direction of gaze (Lee & Lishman, 1975; Paulus, Straube, Krafszyk, & Brandt, 1989). These changes in gaze might affect visual performance. However, the magnitude of any effect on visual performance would tend to vary with the difficulty of the visual task. Some visual tasks (e.g., reading, surgery) require precise control of the eyes, and even small deviations in the direction of gaze can lead to degradation in performance. Other visual tasks (e.g., looking at objects that are far away; Stoffregen et al., 1999) are less dependent on precise control of gaze direction. For these tasks, changes in gaze direction arising from body sway may have minimal impact on visual performance.

Stoffregen et al. (2006) found that the variability of body sway was reduced when participants used eye movements in shifting their gaze between visual targets, relative to sway during fixation of a stationary target. This effect was limited to eye movements that were visually guided. Eye movements that were made with the eyes closed had no effect on body sway (compared to sway when the eyes were closed and stationary). These results are consistent with the hypothesis that postural control was modulated adaptively to facilitate changes in the direction of gaze (Stoffregen et al., 2006). The results do not appear to be consistent with the hypothesis that postural control and the control of gaze compete for a limited pool of central processing resources (if we assume that shifts in gaze require more processing resources than stationary fixation).

Stoffregen et al. (2006) asked participants to shift their gaze to follow apparent motion of visual targets in the horizontal plane. In their study, the frequency of target motion was fixed at 0.5 Hz. Thus, it is possible that effects of this kind might be influenced by variations in the frequency of target motion. We know of only two studies that have examined body sway in the context of variations in the frequency of eye movements. Kikukawa and Taguchi (1985) recorded motion of the center of pressure (COP) during stationary visual fixation, and when participants looked at two targets that were lit alternately. They varied the frequency of motion of visual targets (with motions at 0.25, 0.5, 0.75, and 1.0 Hz). They tested a group of patients with peripheral vestibular disorders and a group of healthy controls. For the healthy group, means across participants suggested that sway amplitude may have been negatively correlated with the frequency of eye movements, with minimal sway at the highest frequency of target motion. The reduction in sway appeared to be concentrated in the medio-lateral (ML) sway axis. While these data are suggestive, they cannot be taken at face value. The amplitude of required eye movements (20°) was great enough to elicit movements of both the eyes and the head (cf. Hallett, 1986). In addition, Kikugawa and Taguchi provided no information about the appearance of the visual stimuli. They also did not report the number or duration of trials, or inferential statistical tests on their effects.

As noted above, Stoffregen et al. (2006) used visual targets that oscillated in the medio-lateral plane at the constant frequency of 0.5 Hz. If shifts in gaze lead to a reduction in the variability of body sway, then it seems reasonable to suppose that the degree of reduction might be related to the level of ocular precision required in different eye movement tasks. Moving the eyes rapidly may be more demanding than moving them slowly. In the present study, we varied the frequency of horizontal oscillation of visual targets. If more frequent eye movements demand more precise control of the oculomotor system, and if postural control is modulated (in part) to facilitate the performance of supra-postural visual tasks, then there could be a functional inverse relation between eye movement frequency and sway variability. Accordingly, our main hypothesis was that the variability of body sway would be negatively correlated with the frequency of visual target oscillation.

The angular displacement of our moving targets was 11°, which is within the range that normally elicits shifting of gaze without rotation of the head (Hallett, 1986). In addition, we conducted separate analyses of postural motion in the anterior-posterior (AP) and ML axes (Hunter & Hoffman, 2001). Stoffregen et al. (2006) measured head motion and confirmed that head rotation was not used in shifting gaze across horizontal displacements of 11°. Previous research relating posture to vision has sometimes found trial effects (e.g., Stoffregen et al., 2006). For this reason, in the present study we analyzed the data for possible trial effects. However, we did not make any predictions about possible trial effects.

Distinct Parameters of Sway

White, Post, and Leibowitz (1980) related postural sway to the frequency of eye movements. They instructed participants to alternate gaze between two target lights that were separated by 4° of horizontal visual angle. Participants were required to stand on one leg, and were instructed to fixate whichever light was illuminated. Three conditions were relevant to the present study (in the other conditions moving visual scenes were used to simulate the optical consequences of eye movements). In the control condition, only one target light was illuminated, producing stationary fixation. In two experimental conditions, the lights were illuminated alternately at 3 Hz or "aperiodically every few seconds" (White et al., 1980; p. 622). The dependent variable was the frequency of body sway in experimental versus control conditions. There was no difference between any of the conditions in the frequency of sway. In the present context, the primary limitation of this study was the absence of a systematic variation in the frequency of eye movements.

In Experiment 1, we collected data using a force platform, which allowed us to maintain a link with previous research (e.g., Kikukawa & Taguchi, 1985; White et al., 1980). In Experiment 2, we directly measured kinematics of the head and torso using a magnetic tracking system. By comparing results from Experiments 1 and 2, we were able to assess the possibility that eye movements would influence both displacements of the center of pressure and the kinematics of the head and torso. This comparison is important because there is a variable relation between the kinematics of body segments and displacements of the center of pressure. Kinetics and kinematics may be correlated under some conditions (e.g., in the laboratory), but under many normal circumstances relations between these levels are equivocal and extremely complex (Bardy, Marin, Stoffregen, & Bootsma, 1999; Newell, van Emmerik, Lee, & Sprague, 1993; Riccio & Stoffregen, 1988).

In Experiment 2, we analyzed the positional variability of the head and torso. In addition, we computed the dominant frequency of head and torso motion, separately for the anterior-posterior and medio-lateral axes, as a function of experimental conditions. These data permitted us to evaluate the hypothesis that the frequency of postural movement might be influenced by the frequency of eye movements. Reliable relations between the frequencies of eye movements and postural motion might indicate the existence of coupling between these functions. Numerous studies have documented strong coupling between frequency and amplitude in multilimb coordination, and between body motion and external events (e.g., Bardy et al. 1999, 2002; Oullier et al., 2002). While amplitude-frequency coupling is known to exist in these situations, it cannot be assumed to exist in the present context.

Participants were treated in accordance with the "Ethical Principles of Psychologists and Code of Conduct" (American Psychological Association, 1992) and each experiment received approval from local institutional review board committees. The experiments were conducted at the University of Paris XI.

Experiment 1

In most research, the presence of eye movements has been a dichotomous variable—moving versus stationary. Variations in the frequency of eye movements are uncommon (e.g., White et al., 1980; cf. Hallett, 1986). Studies of manual movement have observed inverse relations between the amplitude and frequency of oscillation (e.g., Kay, Kelso, Saltzman, & Schöner, 1987). Such an inverse relation has also been reported in the context of intentional postural oscillations in the anterior-posterior plane of motion (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Oullier et al., 2002). This effect inspired us to predict that the amplitude of postural sway would scale negatively to the frequency of eye movements. This prediction was based on the assumption that more rapid saccades would require more precise control of the eyes which would, in turn, be facilitated by greater reductions in the variability of body sway.

Method

Participants. Twelve students from the University of Paris XI (Orsay, France) participated on a volunteer basis. There were nine females and three males. Height ranged from 164 cm to 180 cm (mean = 173 cm), and age ranged from 21 to 47 years (mean = 29.8 years).

Apparatus and Procedure. Center-of-pressure (COP) data were obtained using a force platform (AccuSway System, Advanced Mechanical Technology, Inc., Newton, MA). The manufacturer lists the resolution of this force platform as "infinity." COP data were sampled at 25 Hz and stored on a computer for later analysis. Visual stimuli were generated using PsyScope (Cohen, MacWhinney, Flat, & Provost, 1993), and presented on a Macintosh G3 computer with a 43 cm

Apple Studio Display. Data collection and stimulus presentation were controlled by a single experimenter.

Participants were instructed to stand on the force platform with their feet together. There were four conditions; one in which the target was stationary, and three in which the target was displaced laterally. In each condition, the visual target consisted of a filled red circle on a white background. Luminance of the background was approximately 108 cd/m^2, and luminance of the target was approximately 26 cd/m^2. The contrast ratio was approximately 1:4. Participants were asked to stand on the force platform with their eyes 100 cm from the display. At this distance, the target circles subtended approximately 1.15° of visual angle. In the stationary target condition, the visual target appeared in the center of the display and remained there for the duration of the trial. In the three target oscillation conditions, apparent motion of the target occurred at 0.5 Hz, 0.8 Hz, and 1.1 Hz.

In the target oscillation conditions, the target was presented in two positions, alternating between positions to produce apparent motion. The target first appeared 9.75 cm to the left of the center of the display, at which point it disappeared, reappearing approximately 9.75 cm to the right of the center of the display (maximum displacement approximately 19.5 cm, subtending 11° of visual angle in the horizontal plane). The 11° gaze shifts required in the 0.5 Hz, 0.8 Hz, and 1.1 Hz conditions were well within the range that typically is accomplished with eye movements alone, that is, without supporting head movements (Hallett, 1986).

In the stationary target condition, participants were instructed to maintain their gaze on the target continuously. In the 0.5 Hz, 0.8 Hz, and 1.1 Hz conditions, they were instructed to shift their gaze so that they were always looking at the target's current position, and not to anticipate motion of the target. Participants were shown an example of the 0.5 Hz condition to ensure they fully understood the task. Participants were not given any instructions relating to head rotation, that is, they were not told to use only eye movements in following the target. Participants were not informed that the frequency of target oscillation would vary across trials. Between trials, participants stepped off the platform so that it could be recalibrated. Each participant performed 12 trials (three in each of the four conditions), each of which lasted 65 s. Condition order was counter-balanced across participants.

Data Analysis. The main dependent variable was the positional variability of the COP (operationalized as the standard deviation of the COP displacements), which was analyzed separately for the ML and AP axes. Statistical tests were conducted to compare the mean standard deviation of the COP across participants for each trial and condition. The independent variables were conditions and trials. Separate repeated measures ANOVAs were conducted on data in the ML and AP axes with conditions and trials as factors.

Results

Summary data (collapsed across trials) are presented in Figure 1. For each significant effect of conditions in the ANOVAs, planned *t*-tests were conducted. These *t*-tests were not independent and for this reason, we applied the Bonferroni inequality method to adjust the criterion alpha for the *t*-tests.

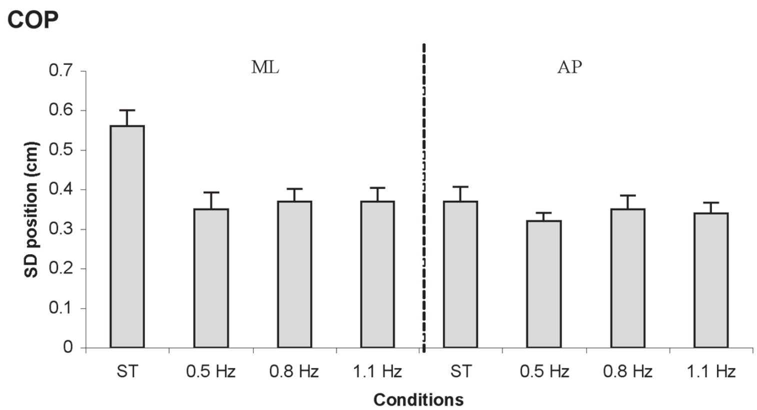

Figure 1—Means of the standard deviation of center-of-pressure (COP) in the anterior-posterior (AP) and medio-lateral (ML) axes for Experiment 1. ST: Stationary visual target; 0.5 Hz: Apparent motion of the visual target at 0.5 Hz; 0.8 Hz: Apparent motion of the visual target at 0.8 Hz; 1.1 Hz: Apparent motion of the visual target at 1.1 Hz. Error bars represent the standard error of the mean.

COP ML. There was a significant main effect of condition, $F(3, 33) = 32.20$, $p < .05$, partial $\eta^2 = .24$.* The main effect of trials was not significant, $F(2, 22) < 1$, ns, and the Condition × Trials interaction was not significant, $F(2, 22)$, < 1, ns.

Planned comparisons revealed that in each of the moving target conditions sway was significantly reduced relative to the stationary target condition (0.5 Hz: $t(11) = 7.03$, $p < .0167$; 0.8 Hz: $t(11) = 6.50$, $p < .0167$; 1.1 Hz: $t(11) = 8.05$, $p < .0167$). However, there were no differences in sway between the frequency conditions, $F(2, 22) < 1$, ns, in each case.

COP AP. The main effect of condition was not significant, $F(3, 33) = 1.08$, $p > .05$. The main effect of trials was significant, $F(2, 22) = 3.62$, $p < .05$, partial $\eta^2 = .08$. The Condition × Trials interaction was not significant, $F(2, 22) < 1$, ns. Post-hoc analysis (Scheffe's test) revealed that trial 1 and trial 3 differed, $p = .046$. For trial 1 and trial 3, the mean and standard deviation were 0.327 cm (± 0.115 cm) and 0.371 cm (± 0.142 cm), respectively.

Discussion

A reduction in the variability of ML sway during eye movements (relative to sway during stationary fixation) was observed at each frequency. This helps to generalize the finding of Stoffregen et al. (2006) of reduced sway during eye movements.

*We estimated the effect size using the partial η^2 statistic.

The absence of a condition effect in the AP axis differs from Stoffregen et al., who found effects of eye movements on motion of the head and torso in both the ML and AP axes. The difference between Experiment 1 and the earlier study may arise from the use of different dependent variables (COP displacements vs. head and torso motion). Motion of the center of pressure is affected by motion of the head and torso, but is also affected by other types of motion. Because it is an integrated variable, COP may be less sensitive to the frequency effect in AP observed at the local level in Stoffregen et al. (2006). The lack of differences in sway with changes in frequency does not support the hypothesis that sway amplitude would scale to the speed of eye movements.

Kikukawa and Taguchi (1985) reported a trend toward reduced ML sway with increasing frequency of eye movements. No such trend was observed in Experiment 1.

Experiment 2

One purpose of this second experiment was to determine whether the findings from Experiment 1, in which we measured the COP, would generalize to measures of head and torso motion. As noted at the beginning of this article, it cannot be assumed that effects which occur in forces applied to the surface of support will also appear in the kinematics of any given body segment. In Experiment 2, we predicted that positional variability of the torso and head would be reduced when participants shifted their gaze between different target positions, relative to variability when participants viewed a stationary target. However, we did not predict that the pattern of results would be identical to Experiment 1. Stoffregen et al. (2006) found that eye movements (at a single, fixed frequency) were associated with reductions in positional variability of the head and torso in both the AP and ML axes. We predicted that these effects would also obtain in Experiment 2, that is, we predicted that positional variability of both head and torso motion, in both AP and ML axes, would be reduced at each frequency of target motion, relative to the stationary target condition. As in Experiment 1, we predicted that the amplitude of postural sway would scale negatively to the frequency of eye movements.

In Experiment 2, we measured eye movements, using electro-oculography (EOG), to confirm that participants shifted their gaze as instructed. Finally, we tested the hypothesis that the frequency of eye movements would influence the frequency of postural sway. We did this by comparing the dominant frequencies of head and torso motion when the eyes were moving with dominant frequencies during stationary fixation (cf. White et al., 1980). Given the existence of trial effects in related studies (e.g., Stoffregen et al., 2006) we excluded from Experiment 2 individuals who had participated in Experiment 1.

Method

Participants. Twelve undergraduate students (nine males, three females) from the University of Paris XI participated on a volunteer basis. None had participated in Experiment 1. Participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. Height ranged between 160 cm and 192 cm (mean = 174 cm). Age ranged from

21 to 29 years (mean = 22). Four participants had corrected vision (glasses or contact lenses).

Apparatus and Procedure. Eye position and movement were measured using a standard EOG system (Biopac Systems, Inc., Goleta, CA). Eye position was sampled at 62.5 Hz. The EOG system was calibrated before each trial, using the method recommended by the manufacturer. The EOG electronics unit was positioned immediately to the participants' right. This was done because the cables connecting the electrodes to the EOG electronics unit were 114 cm long. Postural data (head and torso motion) were measured using a magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT), with each receiver sampled at 47 Hz. One receiver was attached to a bicycle helmet worn by the participant, while a second receiver was attached to the skin between the shoulders (approximately at the seventh cervical vertebra) using cloth medical tape. Each receiver was sampled at 25 Hz, and the data were stored on a computer for later analysis. Visual stimuli were generated using PsyScope (Cohen et al., 1993), and presented on a Macintosh G3 computer with a 43 cm Apple Studio Display.

Participants donned the bicycle helmet with the receiver attached to the back of it and the experimenter attached the second receiver to the neck. Participants were asked to stand 100 cm from the display. The display was adjusted so that the top of the screen was approximately level with the participant's eye height. Participants were instructed to stand with their feet together.

The conditions were the same as in Experiment 1 (stationary target, 0.5 Hz, 0.8 Hz, and 1.1 Hz), using the same stimuli and instructions as in Experiment 1. There were three trials in each of the four conditions, each of which lasted 65 s. Condition order was counter-balanced across participants.

Results

Eye Movements. In the stationary target condition, the standard deviation of horizontal eye position was 4.1°. For the moving target conditions the between-subjects mean and standard deviation of horizontal eye position were as follows: 0.5 Hz condition = 11.2° (1.1°); 0.8 Hz condition = 11.3° (0.9°); 1.1 Hz condition = 11.2° (0.9°).

We also analyzed the frequency of eye movements. We did this by counting the total number of eye movements in each trial, and dividing by the duration of the trial. Across trials and participants, the mean and standard deviation of eye movement frequency were as follows: 0.5 Hz condition = 0.48 Hz (0.01 Hz); 0.8 Hz condition = 0.77 Hz (0.01 Hz); 1.1 Hz condition = 1.04 Hz (0.01 Hz). Taken together, the data on eye movement amplitude and frequency suggest that participants successfully followed our instructions to shift their gaze at the amplitude and frequency of target motion.

Postural Sway. The main dependent variables were the standard deviation of head and torso position, analyzed separately for the ML and AP axes. Summary data (collapsed across trials) are presented in Figure 2. Separate repeated measures ANOVAs were conducted on ML and AP motion of the head, and on ML and AP motion of the torso with conditions and trials as factors. When the main effect of conditions was significant, we conducted planned t-tests. There were three planned

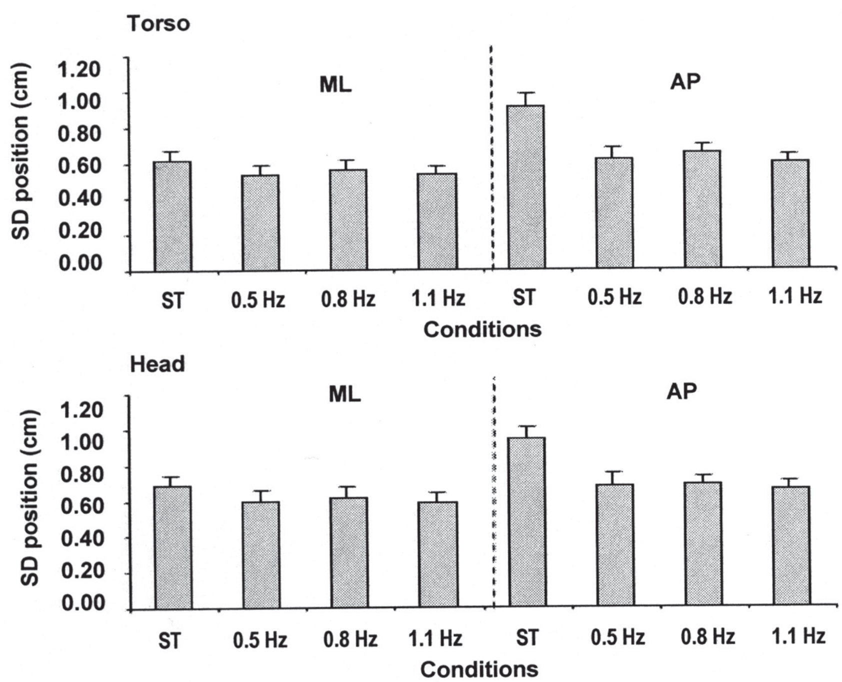

Figure 2—Means of the positional variability of the head and torso in the AP and ML axes, Experiment 2. ST: Stationary visual target; 0.5 Hz: Apparent motion of the visual target at 0.5 Hz; 0.8 Hz: Apparent motion of the visual target at 0.8 Hz; 1.1 Hz: Apparent motion of the visual target at 1.1 Hz. Error bars represent the standard error of the mean.

t-tests for each dependent variable, which required us to adjust the criterion alpha to .0167 (Bonferroni inequality).

Torso ML. The main effect of conditions was significant, $F(3, 33) = 4.7$, $p < .05$, partial $\eta^2 = .05$. The main effect of trials was not significant, $F(2, 22) = 1.18$, $p > .05$, nor was the Conditions × Trials interaction, $F(6, 66) = 1.01$, $p > .05$.

Planned *t*-tests revealed that sway in the 0.5 Hz and 0.8 Hz conditions was significantly less than in the stationary target condition (stationary target vs. 0.5 Hz: $t(11) = 3.245$, $p < .0167$; stationary target vs. 0.8 Hz: $t(11) = 3.049$, $p > .0167$). Sway in the stationary target condition did not differ from sway in the 1.1 Hz condition [$t(11) = 2.544$, $p > .0167$]. The differences in sway between the eye movement conditions were not significant.

Torso AP. The main effect of conditions was significant, $F(3, 33) = 15.79$, $p < .05$, partial $\eta^2 = .14$. The main effect of trials was significant as well, $F(2, 22) = 4.03$,

$p < .05$, partial $\eta^2 = .08$, and the Conditions × Trials interaction was significant, $F(6, 66) = 2.27$, $p < .05$, partial $\eta^2 < .01$.

Planned *t*-tests revealed that in each of the eye movement conditions sway was significantly less than in the stationary target condition (stationary target vs. 0.5 Hz: $t(11) = 4.88$, $p < .0167$; stationary target vs. 0.8 Hz: $t(11) = 5.05$, $p < .0167$; stationary target vs. 1.1 Hz: $t(11) = 4.79$, $p < .0167$). The differences in sway between the three eye movement conditions were not significant.

Head ML. The main effect of conditions was significant, $F(3, 33) = 4.78$, $p < .05$, partial $\eta^2 = .04$. The main effect of trials was not significant, $F(2, 22) < 1.0$, ns; nor was the Conditions × Trials interaction, $F(6, 66) < 1.0$, ns.

Planned *t*-tests revealed that sway in the 0.5 Hz condition was significantly less than in the stationary target condition [$t(11) = 2.99$, $p < .0167$]. Sway in the stationary target condition did not differ from sway in the 0.8 Hz and 1.1 Hz conditions (stationary target vs. 0.8 Hz: $t(11) = 2.66$, $p > .0167$; stationary target vs. 1.1 Hz: $t(11) = 2.64$, $p > .0167$). The differences in sway between the three eye movement conditions were not significant.

Head AP. The main effect of conditions was significant, $F(3, 33) = 12.76$, $p < .05$, partial $\eta^2 = .11$. The main effect of trials also was significant, $F(2, 22) = 6.26$, $p < .05$, partial $\eta^2 = .13$, and the Conditions × Trials interaction was significant, $F(6, 66) = 2.27$, $p < .05$, partial $\eta^2 < .01$.

Planned *t*-tests revealed that in each of the eye movement conditions sway was significantly less than in the stationary target condition (stationary target vs. 0.5 Hz: $t(11) = 4.885$, $p < .0167$; stationary target vs. 0.8 Hz: $t(11) = 4.777$, $p < .0167$; stationary target vs. 1.1 Hz: $t(11) = 4.764$, $p < .0167$). The differences in sway between the three eye movement conditions were not significant.

Frequency Analysis. For the torso data, we identified the principal peak in the power frequency spectrum for each trial, which we refer to as the dominant frequency. We recorded the magnitude and frequency of this peak, and from these we computed the mean frequency of the principal peak and the mean amplitude of the principal peak, as a function of conditions. We conducted a *t*-test comparing the magnitude of power in each condition (separately for AP and ML) against zero. Each of these tests was significant, each $t(32) > 5.4$, $p < .05$, confirming the validity of our frequency analysis. An analysis of variance for motion in the AP axis revealed that the magnitude of power at the dominant frequency (i.e., the frequency of the principal peak) did not differ across conditions, $F(3, 33) = 2.15$, $p > .05$. The main effect of trials, and the Trials × Conditions interaction were also not significant, $F(2, 22) < 1.0$, and $F(6, 66) = 1.15$, $p > .05$, respectively. In the ML axis, the main effects of conditions and trials, and the Conditions × Trials interaction were all non-significant, $F(3, 33) < 1$, $F(2, 22) < 1.0$, and $F(6, 66) = 1.05$, $p > .05$, respectively. Similar ANOVAs performed on the frequency at which the principal peak occurred yielded no significance, each $F < 1.33$, $p > .05$. These results allow us to conclude that the dominant frequency of torso motion was not influenced by the presence or frequency of eye movements.

We next evaluated the hypothesis that postural effects of the frequency of eye movements might be found only at frequencies at which the eyes moved. To do this, we conducted a spectral analysis of motion of the body at each of the frequencies of target motion. Computations were done separately for the head and torso, for the AP and ML axes. We analyzed the data separately for each of the three frequencies at which we calculated power. For each frequency of measured power, we conducted two-factor ANOVAs on conditions and trials. Significant effects were found only for head motion in the ML axis, where the main effect of conditions was significant for power measured at 0.8 Hz, $F(3, 33) = 3.80$, $p < .05$, partial $\eta^2 = .23$. A post-hoc Scheffe analysis revealed that there was a difference between the 0.8 Hz condition and the stationary target condition, $p < .05$. The means and standard deviations for the 0.8 Hz and stationary target conditions were 0.0139 (0.006) and 0.0095 (0.007), respectively. The main effect of conditions was not significant for power measured at either of the other frequencies, each $F(3, 33) < 1.7$, $p > .05$. There were no significant main effects of trials, each $F(2, 22) < 2.25$, $p > .05$. The Trials × Conditions interactions also were not significant, each $F(6, 66) < 1.45$, $p > .05$.

Discussion

At each frequency of target motion, the variability of head position with moving targets was less than with the stationary target, in both the AP and ML axes. The presence of condition effects in the AP axis differs from Experiment 1, in which we found a significant effect of conditions on displacements of the COP only in the ML axis. The differences between Experiments 1 and 2 may arise from the use of different dependent variables (head and torso motion vs. COP motion); (cf. Newell et al., 1993). As in Experiment 1, the influence of eye movements on the variability of postural sway did not vary with the frequency of target motion. The lack of differences in sway variability with changes in target frequency does not support our hypothesis that sway amplitude would scale negatively to the frequency of target motion.

Variations in the frequency of target oscillation did not influence the dominant frequency of torso motion. This result replicates White et al. (1980), who also found no relation between eye movements and the dominant frequency of sway. We separately examined the spectral power of head motion at each of the frequencies of target oscillation. When we examined the power of 0.8 Hz head motion in the ML axis, we found greater power when the target oscillated at 0.8 Hz than when the target was stationary. There were no effects at any other frequency of head or torso motion, or for any other frequency of target oscillation. These results suggest that there may be coupling of ML head motion with eye movements, but only at relatively high frequencies of eye movements. Whether such coupling exists and has some functional basis can be resolved through future research. Overall, the frequency analysis results suggest that the influence of eye movements on postural motion was only weakly related to the frequency of eye movements.

General Discussion

In two experiments, we found that postural motion of the body was reduced when participants were instructed to shift their gaze to follow a moving target, relative to body sway during fixation of stationary targets. Positional variability of sway and the frequency of head and torso oscillations were not influenced by the frequency of eye movements. These are the major findings of this study and they provide support for the general hypothesis that body sway can be controlled, in part, so as to facilitate the achievement of supra-postural task goals. Two additional findings are also noteworthy. First, the influence of eye movements on body sway was observed separately in terms of the forces used to control stance (i.e., positional variability of the COP), and in terms of motion of the torso and head. Second, the angular displacement of visual targets was small enough so that required shifts in gaze could be accomplished without supporting head movements. We discuss these results below.

Postural Facilitation of Dynamic Gaze

In this study, postural motion was reduced during visually guided eye movements, relative to sway during fixation of a stationary target. This finding confirms and extends a similar finding reported by Stoffregen et al. (2006). Our findings are compatible with the idea that posture is not controlled in an automatic or reflexive manner (Woollacott & Shumway-Cook, 2002). However, our findings do not conform with the assumption that postural control competes with other, simultaneous activities for a shared, limited capacity pool of central cognitive processing resources (Dault et al., 2001; Lajoie, Teasdale, Bard, & Fleury, 1993; Maylor & Wing, 1996; White et al., 1980; Woollacott & Shumway-Cook, 2002; Yardley, Gardner, Leadbetter, & Lavie, 1999). Hunter and Hoffman (2001) explicitly predicted that postural control and simultaneous eye movements would compete for central processing resources. In their view, if the combined central processing demand of the two tasks exceeds the central processing resources that are available, then there should be a performance decrement in one or both of the combined tasks. If the combined central processing demand of the two tasks does not require more central processing resources than are available, then performance of the two tasks should be unaffected by the combination. This view has no apparent basis for predicting the result obtained in our experiments and in those of Stoffregen et al., in which postural sway was reduced when participants looked at a moving target, relative to sway during stationary fixation.

Our results are compatible with a different view of relations between postural control and supra-postural activity (Riccio & Stoffregen, 1988). In general, we do not view postural control as being in competition for central processing resources with concurrent supra-postural activities. This is because for many activities performance of supra-postural tasks may be influenced by postural motion. Because postural motion can influence the performance of supra-postural tasks, functional integration of postural control with supra-postural activity would be adaptive. In such circumstances, postural control would serve a dual function; on the one hand, to avoid falling, and on the other hand, to optimize performance of supra-postural tasks (e.g., Massion, 1992). For most healthy adults (and specifically for the participants in our study) the risk of falling is slight, and so facilitation of supra-postural performance may play a stronger role in the organization of postural control. This view leads to the prediction that body sway may be reduced when such reductions can facilitate supra-postural performance (or, conversely, increased when such increases can facilitate supra-postural performance). When we look at moving targets, the success of eye movements (i.e., the maintenance of visual targets within the fovea) may be compromised by excessive body sway (among other things). Thus, reducing sway could be one way to facilitate the viewing of moving targets, as suggested by our results.

The present results, and those of Stoffregen et al. (2006) and others (e.g., Hunter & Hoffman, 2001; Kikukawa & Taguchi, 1985; Oblak, Gregoric, & Gyergyek, 1985) are consistent with the idea that the control of dynamic gaze is not limited to the muscles that act on the eyes (e.g., Steinman, Kowler, & Collewijn, 1990) and head, but can extend to muscles acting on the torso. The results are also consistent with Gibson's (1966) broader assertion that the entire body is part of the visual system. These results underline the fact that looking is an act; it is something that people do, rather than being merely a response to external stimulation. The act of looking (i.e., the stable control of the eyes relative to targets of interest) can be influenced by movements of a variety of body parts and, as indicated by our experiments, by movements of the entire body [see also Anderson et al. (2001)].

We have suggested that reductions in sway variability may have facilitated shifts in gaze in our experiments. We do not claim, however, that gaze stabilization would always imply reductions in sway. Visual performance might sometimes be facilitated by increasing the overall magnitude of sway, provided that the increased motion served to facilitate gaze. One recent study is consistent with this idea. Glasauer, Schneider, Jahn, Stupp, and Brandt (2005) measured sway and eye movements. Participants stood heel to toe and looked at stationary targets, or at targets that moved with sinusoidal horizontal oscillations at 0.33 Hz, 12° amplitude. Glasauer et al. found an increase in RMS sway in the ML axis during viewing of moving targets. This effect might be interpreted as conflicting with our finding that sway variability tended to be reduced when participants looked at moving targets. However, such an interpretation can be questioned. Stoffregen et al. (2006) suggested that in the study of Glasauer et al. ML postural oscillations may have become coupled with the horizontal smooth pursuit movements used to track the visual targets. Coupling of ML sway with horizontal eye movements could have been functional, because it could have facilitated performance in the visual tracking task. Such an effect would be consistent with our general hypotheses.

The idea that ML sway could become coupled to horizontal eye movements suggests that the frequency of eye movements should influence the frequency of sway. Our finding that the frequency of sway was not influenced by the frequency of eye movements appears to contradict this hypothesis. However, details in experimental methodology suggest an alternative interpretation. As noted above, participants in the study of Glasauer et al. (2005) stood heel to toe, while the feet were side by side in the current study (and in Stoffregen et al., 2006). Heel to toe stance decreases mechanical stability in the ML axis and, accordingly, tends to lead to an increase in overall sway in the ML axis. Another feature of heel to toe stance is that it is unpracticed for typical adults, compared to a stance in which the feet are side by side. It may be that the effects observed by Glasauer et al. arose from these features of heel to toe stance, and do not reflect general relations between posture and eye movements. The issue of experience could be addressed by repeating the Glasauer et al. study using as participants gymnasts who have extensive experience on the balance beam (which mandates skill in heel to toe stance).

The pattern of results in Experiments 1 and 2 were not identical, which suggests that eye movements may have different effects on the forces and movements related to stance (cf. Newell et al., 1993). This difference underscores the value of evaluating different measures of sway (COP displacement vs. torso and head movement). For postural motion in the AP axis, significant effects of conditions were found only in measurements of head and torso kinematics, which suggests that measurements of body motion may be a more sensitive way to assess relations between postural control and supra-postural tasks, a position that was argued—a priori—by Riccio and Stoffregen (1988).

Newell et al. (1993) argued that variability may not be an appropriate dependent variable to use in operationalizing the concept of postural stability. We agree that variability is a poor measure of postural stability, and we have not used it in this way. We have used positional variability as a metric for the amplitude of body sway, without interpreting variability in terms of greater or lesser stability. In part, the present study (together with those of Stoffregen et al., 1999, 2000, 2006) support the conclusions of Newell et al. Our position is that no measure of postural behavior, by itself, can be used to measure postural stability. In our view, the stability of postural control can be assessed only in the context of constraints imposed by supra-postural tasks (Riccio & Stoffregen, 1988, 1991).

Sway Amplitude and Eye Movement Frequency

We evaluated the hypothesis that the variability of body sway would scale negatively with the frequency of oscillation of visual targets. This hypothesis was not confirmed. It may be important to note, however, that a contrasting hypothesis (that the variability of postural motion would scale positively with target frequency) also was not confirmed (cf. Glasauer et al., 2005). This latter hypothesis might be derived from the idea that posture and supra-postural tasks compete for a limited pool of central processing resources, if it is assumed that greater central resources are required for the control of faster eye movements.

The absence of negative scaling between postural variability and target frequency could have several causes, four of which are enumerated here: (1) the range of frequencies of target oscillation may have been too narrow to elicit an effect; (2) there may be a plateau or upper limit in the degree of ocular demand associated with the frequency of eye movements; (3) the relationship between ocular demand (as a function of the frequency of eye movements) and body sway may be non-linear; and (4) the frequency of eye movements may not be related to ocular demand in any interesting or important way. Each of these possibilities is compatible with the general hypothesis of a functional relation between postural control and visually guided eye movements.

Conclusion

Our results suggest that one function of postural control is to stabilize the visual system so as to facilitate the accuracy of small changes in the direction of gaze. Beyond this, our results, together with those of Stoffregen et al. (1999, 2000, 2006) suggest that there may be movement signatures of the difficulty of different supra-postural tasks.

One important area for future research concerns the dynamics of body sway and eye movements. Body sway is periodic motion and in our experiments eye movements were also periodic. Body sway is known to have characteristics of dynamical systems, such as stable coordination modes, sudden transitions between modes, critical slowing down, and hysteresis (e.g., Bardy et al., 1999, 2002; for a review, see Oullier, Marin, Stoffregen, Bootsma, & Bardy, 2006). When following the motion of oscillating targets, ocular control may also function as a dynamical system, in which case we might expect to observe coupling of the dynamics of the postural and ocular systems (e.g., phase locking). The present study suggests that any dynamical coupling of these systems should be functional, that is, it should facilitate visual performance.

Author's Note

Portions of the data were reported at the XI International Conference on Perception and Action, Storrs, CT, June, 2001.

Acknowledgments

Preparation of this article was supported by Enactive Interfaces, a network of excellence (IST contract #002114) of the Commission of the European Community, the National Science Foundation (BCS-0236627, INT-9603315), the University of Paris XI, and the Institut Universitaire de France. O. Oullier was supported by the Initiative Program of the Fondation de l'Académie des Sciences. We thank Michael A. Riley for comments on a draft of this article, Omar Merhi, Valerie Neverman, Didier Casalta, and Delphine Bernardin for their help with data collection and analysis, Dave Irwin and Gordon Legge for conversations and encouragement regarding this project, and Albert Gaudin, who provided the AMTI force plate.

References

American Psychological Association (1992). Ethical Principles of Psychologists and Code of Conduct. Washington, DC: American Psychological Association.

Anderson, D.I., Campos, J.J., Anderson, D.E., Thomas, T.D., Witherington, D.C., Uchiyama, I., & Barbu-Roth, M.A. (2001). The flip side of perception-action coupling: Locomotor experience and the ontogeny of visual-postural coupling. *Human Movement Science*, **20**, 461-487.

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

Bardy, B.G., Oullier, O., Bootsma, R.J., & Stoffregen, T.A. (2002). The dynamics of human postural transitions. *Journal of Experimental Psychology: Human Perception & Performance*, **28**, 499-514.

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

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

Gibson, J.J. (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.

Glasauer, S., Schneider, E., Jahn, K., Strupp, M., & Brandt, T. (2005). How the eyes move the body. *Neurology*, **65**, 1292-1293.

Hallett, P.E. (1986). Eye movements. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of human perception and performance* (Vol. 1, Ch. 10). New York: Wiley.

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

Kay, B.A., Kelso, J.A.S., Saltzman, E.L., & Schöner, G. (1987). The space-time behavior of a single and bimanual rhythmical movement: Data and model. *Journal of Experimental Psychology: Human Perception & Performance*, **13**, 178-192.

Kerr, B., Condon, S.M., & McDonald, L.A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology: Human Perception and Performance,* **11**, 617-622.

Kikukawa, M., & Taguchi, K. (1985). Characteristics of body sway during saccadic eye movement in patients with peripheral vestibular disorders. In M. Igarashi and F.O. Black (Eds.), *Vestibular and visual control on posture and locomotor equilibrium* (pp. 355-359). New York: Karger.

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

Lee, D.N., & Lishman, J.R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, **1**, 87-95.

Massion, J. (1992). Movement, posture and equilibrium: interaction and coordination. *Progress in Neurobiology*, **38**, 35-56.

Maylor, E.E, & Wing, A.M. (1996). Age differences in postural stability are increased by additional cognitive demands. *Journal of Gerontology*, **51B**, 143-154.

Newell, K.M., van Emmerik, R.E.A., Lee, D., & Sprague, R.L. (1993). On postural stability and variability. *Gait & Posture*, **4**, 225-230.

Oblak, B., Gregoric, M., & Gyergyek, L. (1985). Effects of voluntary eye saccades on body sway. In M. Igarashi and F.O. Black (Eds.), *Vestibular and visual control on posture and locomotor equilibrium* (pp. 122-126). New York: Karger.

Oullier, O., Bardy, B.G., Stoffregen, T.A., & Bootsma, R.J. (2002). Postural coordination in looking and tracking tasks. *Human Movement Science*, **21**, 147-167.

Oullier, O., Marin, L., Bootsma, R.J., Stoffregen, T.A., & Bardy, B.G. (2006). Variability in postural coordination dynamics. In K. Davids, S. Bennett & K.M. Newell (Eds.). *Movement system variability* (pp. 25-47). Champaign, IL: Human Kinetics.

Paulus, W., Straube, A., Krafszyk, 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.

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

Riccio, G.E., & Stoffregen, T.A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology,* **3***,* 195-240.

Steinman, R.M., Kowler, E., & Collewijn, H. (1990). New directions for oculomotor research. *Vision Research,* **30**, 1845-1864.

Stoffregen, T.A., Adolph, K.E., Gorday, K.M., & Sheng, Y.Y. (1997). Toddler's postural adaptations to different support surfaces. *Motor Control,* **1***,* 119-137.

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

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

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

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

White, K.D., Post, R.B., & Leibowitz, H.W. (1980). Saccadic eye movements and body sway. *Science*, **208**, 621-623.

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

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