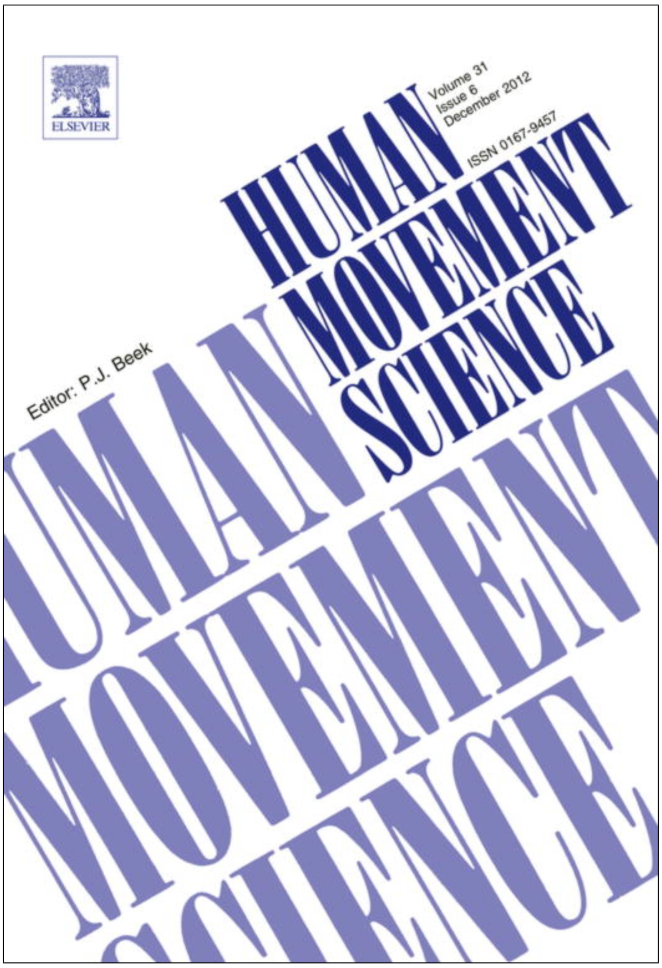
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Large lateral head movements and postural control

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ABSTRACT

Riccio and Stoffregen (1988) have suggested that task performance is the predominant constraint of change in postural control. To test this hypothesis, 12 healthy, young adults performed large lateral gaze shifts (left/right gaze shifts with a visual angle of 150° and at a frequency of 0.5 Hz or 1 Hz) and a control condition (looking at a stationary dot). Performance in the visual task was expected to be good under all conditions. In accordance with Riccio and Stoffregen's hypothesis, the center of pressure sway variability (range or standard deviation) was expected to be similar in the three visual tasks when a destabilizing, narrow stance was adopted. Indeed, body sway had to be restrained in narrow stance to adequately perform the task. In standard and wide stance conditions, the center of pressure sway variability was expected to be larger when gaze shifts were performed. Indeed, in these more stable stance conditions, the task could be performed successfully in minimizing energy expenditure, that is, in letting body sway increase naturally. The results were consistent with these expectations. On a practical level, intentional, large gaze shifts may not cause postural instability *per se*, even though postural sway may increase significantly.

1. Introduction

Humans may have adopted a bipedal stance because the latter enabled them to perform suprapostural tasks (Riccio & Stoffregen, 1988; Stoffregen, Smart, Bardy, & Pagulayan, 1999) such as grasping, pulling, carrying and looking around. Hence, some authors have suggested that postural control is not a goal by itself, but a means to achieve goals (Mitra & Fraizer, 2004; Riccio & Stoffregen, 1988; Smart,

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Mobley, Otten, Smith, & Amin, 2004; Smart & Smith, 2001; Stoffregen, Bardy, Bonnet, & Pagulayan, 2006; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). Along this line, Riccio and Stoffregen (1988) have suggested that postural control is adapted to facilitate performance in one or more on-going tasks. In their hypothesis, individuals adopt "goal-directed behavior" when interacting with their environment (Riccio, 1993). Stated differently, success in the task is believed to be of primordial importance for the postural control system. For example, the performance of lateral eye movements to track predictable, small (1° of visual angle) visual targets can be undermined by high postural sway (Stoffregen et al., 2006). Hence, postural sway was expected to be reduced in these gaze shift conditions. The task performance had to be difficult enough; otherwise no change in postural sway was expected. To test the "goal-directed" hypothesis, Stoffregen et al. (2006) and Stoffregen, Bardy, Bonnet, Hove, and Oullier (2007) asked healthy, young adults to perform gaze shifts by following a dot that appeared alternately on the left and right at a visual angle of 11°. Gaze shifts were performed at 0.5 Hz (Stoffregen et al., 2006) and at 0.5, 0.8 and 1.1 Hz (Stoffregen et al., 2007). In a control visual task, the subjects looked at a stationary dot directly in front of them. As expected, the participants exhibited significantly less body sway variability (as measured by the standard deviation of center of pressure and head and torso sway) in both mediolateral (ML) and anteroposterior (AP) axes when performing gaze shifts. In these studies, the participants did not move their head during the various visual tasks and achieved good performance levels. Riccio and Stoffregen's (1988) hypothesis has since been validated with other kinds of visual task (Balasubramaniam, Riley, & Turvey, 2000; Smart et al., 2004; Stoffregen et al., 2000). Also in these studies, the visual tasks were performed well and the participants only made tiny hand, head or/and eye movements.

For large, rapid lateral gaze shifts involving the movement of heavy body segments such as the head and the trunk (Hollands, Ziavra, & Bronstein, 2004), one would expect postural sway and displacement of the body's center of mass (COM) to increase significantly. In such situations, the center of pressure (COP) would also increase significantly because COP displacement is larger than COM displacement and increase even more than COM displacement (Winter, 1995). In these conditions, does it mean that Riccio and Stoffregen's (1988) hypothesis is systematically wrong or not testable? We did not think so. In conditions with large body movements, their hypothesis could be tested and validated even if postural sway should be significantly greater than in a control condition with no intentional movement. If postural control were to be challenged by the adoption of a narrow stance position (increasing COP and postural sway, see Day, Steiger, Thompson, & Marsden, 1993; Mouzat, Dabonneville, & Bertrand, 2004), one would expect the postural sway to show similar characteristics in the large gaze shift and control conditions; success in the visual task would require the maintenance of postural stability. That is, postural sway would need to be strictly restrained to perform the task well because more sway would quickly lead to postural instability in narrow stance. In contrast, if postural control were to be made easier by placing the feet further apart than usual (i.e., wide stance), postural sway should be significantly greater in gaze shift conditions than in the control condition. It would be so if task performance is not worsened by increased postural sway. In such case, individuals would no longer need to constrain their sway as much as in narrow stance to avoid losing their energy inefficiently: Indeed, "actions that minimize movements require effort" (Riccio & Stoffregen, 1988 p. 283). A trade-off between task performance and energy expenditure would have to be adopted to keep the task performance high.

In the present study, we sought to determine whether postural control (represented by COP sway, cf., Winter, 1995) could be adjusted efficiently in order to successfully perform large, lateral gaze shifts (with a visual angle of 150° at 0.5 or 1 Hz) under different stance width conditions (narrow, standard and wide stances). In other words, our goal was to test Riccio and Stoffregen's (1988) hypothesis that task performance is the predominant constraint of change in postural control. We did so in conditions varying the difficulty of ML stance. We expected our results to be consistent with Riccio and Stoffregen's (1988) hypothesis. Gaze shifts were large and quick to ensure that COP sway variability would increase if the participants did not specifically restrain it. These gaze shifts also ensured that performance of the visual task was challenging. Overall, we expected individuals to succeed well in all visual tasks, without losing their balance. To perform the large gaze shift task efficiently in narrow stance, we expected COP sway variability to be actively controlled and thus to not increase significantly relative to the control condition (looking at a stationary dot). In contrast, COP sway variability in wide stance was expected to increase significantly when large gaze shifts were performed. In standard stance (the spontaneously chosen foot position), COP sway variability was expected to increase with gaze shifts in the same way (or to a lesser extent) as in wide stance. Indeed, in standard stance, the stability limits are extensive and enable the performance of large body movement while minimizing the risk of loss of balance (Holbein-Jenny, McDermott, Shaw, & Demchak, 2007; Riccio & Stoffregen, 1988). This type of result would be consistent with Riccio and Stoffregen's (1988) "goal-directed" hypothesis of postural control and at odds with classical expectations and interpretations found in the literature. In conventional theory, COP and/or postural sway should increase when two constraints (a large gaze shift task and narrow stance, in this case) are combined (Hunter & Hoffman, 2001; Woollacott & Shumway-Cook, 2002), except when task performance is worsened deliberately. The argument is that the central nervous system's fixed resources would have to be divided between controlling stance and perform the task (Hunter & Hoffman, 2001). Likewise, changes in COP and/or postural sway would cancel each other out if one constraint facilitates postural stability (wide stance, in our experiment) and the other worsens it (large gaze shifts). In the present study, we expected to see significant changes in COP sway variability in the ML axis but not in the AP axis. Indeed, the main effects of gaze shift found by Stoffregen et al. (2006, 2007) in the AP axis seemed to be caused by the need to minimize ocular accommodation for success in the visual task (cf., Stoffregen et al., 1999). The target was less than 1 m away from the participants in Stoffregen et al. (2006, 2007) while the target was further away in our experiment (2.1 m).

2. Methods

2.1. Participants

Twelve healthy, young adults (students from the University of Lille 2) participated in this study. All gave their written, informed consent to participation and the study was performed in accordance with the tenets of the Declaration of Helsinki. The group's mean age, body weight and height were 21.42 years ± 3.48, 61.00 kg ± 12.43 and 1.70 m ± 0.09, respectively.

2.2. Apparatus

A black dot was projected onto a panoramic display (radius: 2.1 m; height: 2.1 m; visual angle: 180°; Fig. 1) at the participant's eye height at three possible locations: forward, left or right. The dual-top force platform system (AMTI, Watertown, MA, USA) recorded COP sway at 100 Hz. The black dot was large enough (subtending a visual angle of 5°) to be quickly and easily perceived when projected 150° away.

An eye tracker (SensoMotoric Instruments, Teltow, Germany) was used to record performance in the visual tasks. The eye tracker was attached to a headset worn by the participants. The iViewX

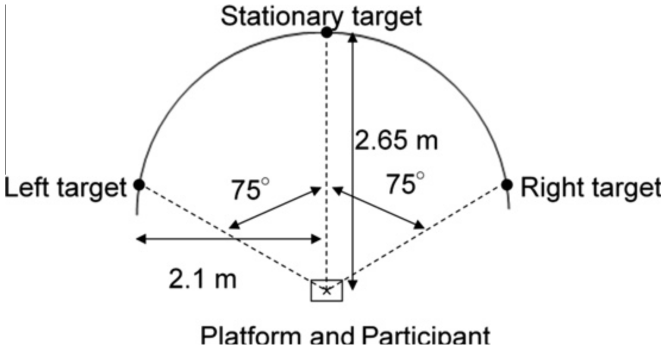

Fig. 1. Description of the experimental setting (not drawn to scale). The participant stood on a force platform in the test room at a distance of 2.65 m from a semicircular, panoramic display. The target (a black dot, subtending a visual angle of 5°) was presented either in a stationary position in front of the participant or alternately on the left and right at a visual angle of 150°. The dot's position was recorded with a computer program and projected onto the screen by three cameras.

system recorded the pupil position at a sampling rate of 50 Hz. The recorded video showed the visual environment and (as a cross) where the right eye was looking. The participants were told that the experimental session would not be valid if they failed to look through the small window (disappearance of the cross on the video) of the oculometer in front of their right eye. The cross disappeared on the video if the difference in angular motion between the head and the eye was greater than 20° on each side.

2.3. Conditions

With three visual tasks and three stance widths, there were nine experimental conditions in all. In the stationary gaze condition, the participants had to look at a stationary dot in front of them (Fig. 1). In the two gaze shift conditions, the participants had to track a dot that appeared alternately to their left and right at a visual angle of 150° (Fig. 1) at 0.5 Hz or 1 Hz. Gaze shifts had to be performed as quickly as possible once the target had completely disappeared (but with no anticipation; cf., Stoffregen et al., 2006, 2007). In the narrow stance condition, the feet were close together (Fig. 2) but remained on separate force platforms. In the standard stance condition, the participants chose their preferred stance width. In the wide stance condition, participants chose their stance angle but had to align one part of the foot with the outer edge of the corresponding platform (Fig. 2). The participants could choose some aspects of their foot position to be best at ease. We did not completely impose the foot position because it can lead the participants to feel uncomfortable (Kapteyn et al., 1983; McIlroy & Maki, 1997), especially when performing large gaze shifts.

In each condition, the participants had to relax with their arms extended along their side. The instruction of moving naturally the head and/or the body to perform gaze shifts was repeated several times throughout the experiment. Each condition consisted of two 35-s trials. The order in which the conditions were performed was randomized.

2.4. Procedure

The participants stood in bare feet during the experiment. At the beginning of the study, they placed their feet on two papers taped to each force platform. The foot position was marked with a pen. The instructions about the conditions were given. Next, the participant put the headset on and the eye tracker was calibrated. To check that the participant had understood the experimenter's instructions, two pre-trials were performed in the 1 Hz gaze shift condition. The test session was performed immediately thereafter.

2.5. Data analysis

BeGaze software (SensoMotoric Instruments, Teltow, Germany) was used to analyze eye movement data. For the two gaze shift conditions, the gaze shift frequency and amplitude were analyzed as in Stoffregen et al. (2006, 2007). The speed of transition from one target to the other and the number of targets not hit were also analyzed. For all three visual conditions, the time spent by the

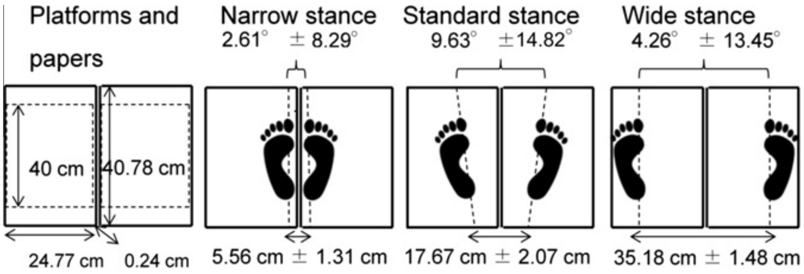

Fig. 2. Representation of the dimensions of the platforms and papers (leftmost panel) and the foot positions adopted by the participants in narrow, standard and wide stance conditions. The mean values and standard deviations of the stance width and stance angle are given for each stance width.

right eye on the target was analyzed (relative to the duration of the trial or only when the target was reached).

For postural control, the range and standard deviation of COP sway were analyzed as reported by other researchers (Day et al., 1993; Mouzat et al., 2004; Stoffregen et al., 2006, 2007). These variables served as measures of COP sway variability in the AP and ML axes when gaze shifts and stance widths were changed.

One-way analyses of variance (ANOVAs) were used to compare task performance in all three visual conditions or in the two gaze shift conditions only. One sample *t*-tests were used to compare the characteristics of standard stance (stance width and stance angle) adopted by the twelve participants to normative data (McIlroy & Maki, 1997). Center of pressure sway variables were analyzed with two-factor (gaze shift, stance width) repeated measures ANOVAs. Post-hoc Newman-Keuls tests were used to analyze the main effects of gaze shift in each of the three stance width conditions (narrow, standard and wide stances). The thresholds for statistical significance were set to $p < .05$ for the main analyses and $p < .01$ for the post-hoc analyses (to avoid type I error).

Correlation analyses between task performance and postural sway were not performed because they may not test or invalidate Riccio and Stoffregen's (1988) hypothesis. Indeed, the relationship between the difficulty of the visual task and COP sway may be non-linear. There may be limits beyond which COP sway can increase or decrease less extended that limits beyond which task difficulty can increase or decrease.

In order to avoid transients, the three first seconds and the two last seconds of the COP and eye movement data from each trial were not analyzed.

3. Results

3.1. Foot position

Stance width was defined as the distance between the heel centers. The stance angle was defined as the angle between the lines going through the middle of the big toe and the heel center for each foot. As in McIlroy and Maki (1997), the inter-individual variability in foot positions was relatively large (Fig. 2). However, no significant difference was found in standard stance between our study and their study, $t(11) = 1.11$, $p > .05$ and $t(11) = -1.02$, $p > .05$, for stance width and stance angle, respectively.

3.2. Task performance

The time spent by the right eye on the target was almost maximal in the stationary gaze condition (see Table 1). Under the 0.5 Hz and 1 Hz conditions, the eyes could not remain on the target all the time because the participants performed 14 and 29 large gaze shifts from one side to the other, respectively (Table 1). When the eyes were on (or had reached) the target in the three visual conditions, the eye stayed within the target the same proportion of time ($Fs < 2.48$, $p > .01$; Table 1). In the 0.5 Hz and 1 Hz conditions, the participants shifted their gaze at the requested frequency. In both the gaze shift conditions, the cross recorded by the eye tracker almost never disappeared. This showed that the participants performed gaze shifts at or only slightly less than the requested 150° amplitude. Under both the 0.5 and 1 Hz conditions, the participants moved their eyes from one target to the other at the same velocity and hit similarly proportions of targets ($Fs < 4.56$, $p > .01$; Table 1). In gaze shift conditions, the gaze slightly overshot the target or just failed to reach it in only 0.95% of the presentations. As requested, the participants moved their eyes as soon as the target disappeared (in 93.83% of the presentations).

3.3. Effects of conditions on COP sway variability

3.3.1. Mediolateral range

The ANOVA showed a significant interaction between stance width and gaze shift for the ML range ($F(4,44) = 3.81$, $p < .05, n_p^2 = .20$; Fig. 3A), a significant main effect of gaze shift ($F(2,22) = 15.80$, $p < .05$,

Table 1
Visual performance in the three visual tasks. In the stationary gaze condition, the target (black dot; 5° of visual angle) was presented in a stationary position in front of the participant. In the 0.5 Hz and 1 Hz conditions, the target dot appeared alternately on the left and right alternatively right at a visual angle of 150° and at a frequency of 0.5 Hz or 1 Hz, respectively. The dependent variables (representing visual performance) were the time spent by the eye on the target (in seconds), the time spent by the eye on the target once the latter was reached (as a percentage of time), the transition time from one target to the other (in seconds) and the proportion of targets not reached by the eye after the transition (as a percentage of the total number of targets displayed).

Conditions	Time on target (s)	Time on target when reached (% time)	Transition time (s)	Percentage of targets not reached (% relative to all gaze shifts)
Stationary dot	29.19 ± 1.15	97.31 ± 5.24	/	/
0.5 Hz	20.22 ± 1.64	97.66 ± 3.49	0.70 ± 0.12	0.93 ± 0.09
1 Hz	13.80 ± 2.55	98.11 ± 2.60	0.56 ± 0.09	0.97 ± 0.05

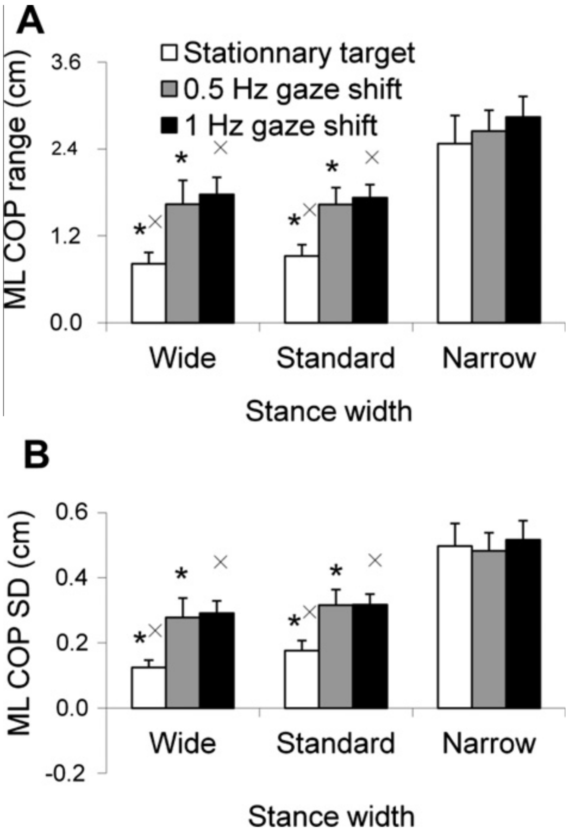

Fig. 3. Significant gaze shift vs. stance width interaction effects in the ANOVAs (additionally showing significant main effects of gaze shift and stance width). (A) Range of the center of pressure displacement in the mediolateral (ML) axis; (B) Standard deviation (*SD*) of the center of pressure displacement in the ML axis. The target (a black dot, subtending a visual angle of 5°) was presented either in a stationary position in front of the participant (stationary target) or alternately on the left and right at a visual angle of 150° and at a frequency of 0.5 Hz (the 0.5 Hz gaze shift condition) or 1 Hz (the 1 Hz gaze shift condition). Unit: centimeters (cm). Error bars represent the standard error of the mean. In each stance width, the significant post-hoc effect of gaze shift was shown by * and ×, $p < .05$.

$\eta_p^2 = .37$) and a significant main effect of stance width ($F(2,22) = 23.75$, $p < .05$, $\eta_p^2 = .41$; Fig. 3A). Post-hoc analyses showed that the participants swayed significantly more in the 0.5 Hz and 1 Hz conditions than in the stationary gaze condition, in both standard and wide stances ($p < .01$). In the narrow stance condition, there were no significant ML range differences between the stationary gaze and gaze shift conditions ($p > .01$).

3.3.2. Anteroposterior range

Only the main effect of stance width was significant ($F(2,22) = 3.46$, $p < .05$, $\eta_p^2 = .20$; Fig. 4).

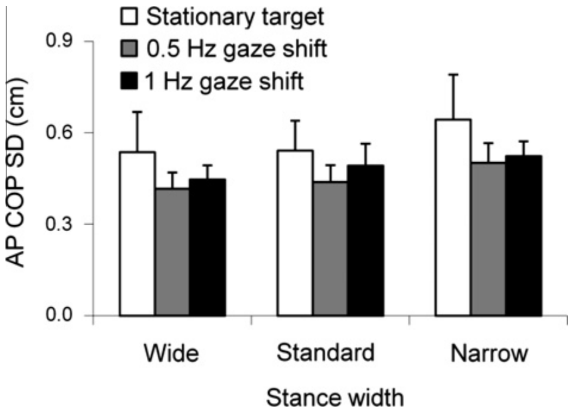

Fig. 4. Significant main effect of stance width in the ANOVA for range of the center of pressure displacement in the anteroposterior (AP) axis. The conditions are defined in Fig. 2. Unit: centimeters (cm). Error bars represent the standard error of the mean. In each stance width, there were no significant post-hoc effect of gaze shift. $p < .05$.

3.3.3. Mediolateral standard deviation

The stance width-gaze shift interaction was significant for the ML standard deviation ($F(4,44) = 9.13$, $p < .05$, $n_p^2 = .31$; Fig. 3B). There were also significant main effects of stance width ($F(2,22) = 10.82$, $p < .05$, $n_p^2 = .33$) and gaze shift ($F(2,22) = 27.58$, $p < .05$, $n_p^2 = .42$; Fig. 3B). The results of post-hoc analyses of the ML standard deviation of COP sway were similar to those for ML range of COP sway.

3.3.4. Anteroposterior standard deviation

The ANOVA did not reveal any significant effects ($Fs < 2.03$, $p > .05$).

3.4. Differential effects of gaze shift on COP sway

Table 2 shows the COP sway range and standard deviation for the two gaze shift conditions minus the COP sway range and standard deviation for the stationary gaze condition. In the ML axis, it can be seen that the closer the feet, the smaller the difference between the respective COP sway variabilities in the gaze shift and stationary gaze conditions. In the AP axis, COP sway variability (range and standard deviation) was slightly (but not significantly) higher in the stationary gaze condition than in the two gaze shifts conditions.

4. Discussion

The present study sought to determine whether the control of COP displacement is goal-directed and not "posture-directed". The goal-directed hypothesis was validated by two key observations. First,

Table 2
Differences in COP sway between the two gaze shift conditions and the stationary gaze condition (0.5 Hz gaze shift minus the stationary dot and 1 Hz gaze shift minus the stationary dot). Table 2 reports means and standard deviations of the COP sway range and standard deviation (*SD*) in the mediolateral (ML) and anteroposterior (AP) axes in the three stance width conditions (wide, standard and narrow stances).

		ML range	ML *SD*	AP range	AP *SD*
0.5 Hz gaze shift - stationary dot	Wide stance	0.82 ± 0.80	0.15 ± 0.16	−0.34 ± 1.27	−0.12 ± 0.39
	Standard stance	0.71 ± 0.54	0.14 ± 0.12	−0.05 ± 0.81	−0.10 ± 0.22
	Narrow stance	0.17 ± 0.74	−0.01 ± 0.12	−0.20 ± 1.08	−0.14 ± 0.38
1 Hz gaze shift - stationary dot	Wide stance	0.96 ± 0.47	0.17 ± 0.10	−0.11 ± 1.40	−0.09 ± 0.41
	Standard stance	0.80 ± 0.35	0.14 ± 0.08	0.20 ± 0.61	−0.05 ± 0.20
	Narrow stance	0.37 ± 0.75	0.02 ± 0.09	−0.19 ± 1.52	−0.12 ± 0.44

the participants had very high mean success rates in the challenging visual tasks. Second, the maintenance of success under gaze shift conditions required a strict control of ML COP sway variability in the narrow stance but not in the wide and standard stances.

4.1. Task performance

In previous studies, visual performance in gaze shift conditions was (when described) always good (e.g., Rey, Lê, Bertin, & Kapoula, 2008; Stoffregen et al., 2000, 2006, 2007). Consistently, our participants performed the visual tasks as requested in terms of amplitude, frequency and timing. There was no need to repeat any of the trials, showing that all visual tasks were easily performed in each stance condition. Overall, visual performance was identical under all three stance conditions (Table 1). Therefore, the participants adopted appropriate postural coordination for both stability and efficiency in the visual tasks. This interpretation is grounded on the fact that the visual gaze shift conditions were very well performed although they were demanding and not easy to perform.

4.2. Postural coordination in large gaze shift conditions

Hollands et al. (2004) have published a detailed analysis of postural coordination under large gaze shift conditions (a gaze shift towards a target located 45°, 90° or 135° away from the center). Their results clearly revealed the sequencing of movement onset and similarity in terms of the head, upper body and feet movements made during performance of the various gaze shifts (Hollands et al., 2004). They also showed significant interaction between the eye movement and whole-body movements. Hollands et al.'s (2004) study and our study are complementary. Indeed, we did not measure body coordination (because it was already done) but we studied COP sway variability (a parameter that was not reported by Hollands et al., 2004).

4.3. To maintain task efficiency, COP sway variability was controlled in narrow stance

It is well known that individuals sway significantly more in narrow stance than in wider stance conditions (Day et al., 1993; Kirby, Price, & MacLeod, 1987; Mouzat et al., 2004). Indeed, the vertical projection of the COM is closer to the ML stability limits in narrow stance than it is in other stance width conditions. This is probably why ML COP sway had to be restrained in narrow stance when the participants wanted to succeed in the task without losing their balance. Our results were consistent with this hypothesis. The participants' main objective was to succeed in the task (Riccio & Stoffregen, 1988) and, in narrow stance, they achieved this by stabilizing posture (Figs. 3A and B; Table 2). In other words, COP sway variability was controlled in narrow stance to maintain task efficiency. This result thus validated Riccio and Stoffregen's (1988) hypothesis that postural control is goal directed. Although the participants swayed significantly more in narrow stance than in the standard and wide stances (as expected; see Figs. 3A and B), they clearly controlled their narrow stance posture well because they had similarly high performance levels under all three visual conditions (Table 1). Importantly, healthy, young participants were not unstable *per se* in narrow stance but merely exhibited greater overall levels of COP sway than in wider stance conditions.

4.4. COP sway variability can increase in wide stance without impairing task performance

Compared with standard stance, wide stance can reduce COP/postural sway in a moving room (Stoffregen, Yoshida, Villard, & Bardy, 2010), onboard a boat (Stoffregen, Villard, & Yu 2009; Yu, Yank, Villard, & Stoffregen, 2010) and on a moving platform (Henry, Fung, & Horak, 2001; Wing, Clapp, & Burgess-Limerick, 1995). The greater the stance width, the lower postural sway (Chang, Wu, Hung, & Chiu, 2009; Stoffregen et al., 2009). In contrast to these previous studies, the participants in our study had to move their head and possibly their body. In wide stance, COP sway variability in the gaze shift task was significantly greater than in the stationary gaze condition increased (Figs. 3A and B; Table 2). This was probably because the participants could still perform the task well although their COP sway naturally increased in gaze shift conditions. Indeed, as explained in the introduction, large gaze shift imposed COM and COP to increase. Since the task performance was not worsened even in increasing COP sway, it can be concluded that the participants achieved their goal with maximum efficiency in minimizing their effort (Stoffregen et al., 1999; Warren, 1984). In other words, the participants did not constrain their COP sway as much in wide stance as in narrow stance because they could keep the same level of task performance with greater sway. The minimization of effort in wide stance may result from a lower contribution by postural mechanisms to stance control. Indeed, Henry et al. (2001) found that the electromyographic signal generated by the postural muscles was less intense in wide stance than in standard stance during challenging, unpredictable platform movements.

In summary, when the main objective was to succeed in a visual task, the combination of ML constraints (gaze shifts and narrow stance) did not increase ML COP sway, whereas the reduction of ML constraints (adoption of a wide stance) significantly increased ML COP sway. These findings are consistent with Riccio and Stoffregen's (1988) hypothesis that task performance has a primordial influence on postural control. The minimization of effort will also change postural control as long as the task can be performed successfully (Riccio & Stoffregen, 1988). These findings are at odds with conventional interpretations found in the literature (e.g., Hunter & Hoffman, 2001; Woollacott & Shumway-Cook, 2002) in which the addition of two or more constraints should either increase postural sway or decrease the task performance (e.g., Hunter & Hoffman, 2001; Woollacott & Shumway-Cook, 2002). This is supposedly the case because limited central processing resources have to control postural sway and perform the required task simultaneously (Boisgontier, Mignardot, Nougier, Olivier, & Palluel, 2011; Pellecchia, 2003; Woollacott & Shumway-Cook, 2002). This is usually referred to as dual-task interference. If two experimental constraints have opposing effects on postural stability, the overall result will depend on which constraint is stronger (if task performance is maintained). As already mentioned above, our study results are not consistent with these conventional assumptions. As a primary goal, task performance was always high (Table 1). In close stance, COP sway was restrained to avoid a decrease in task performance (Figs. 3A and B; Table 2). Stance width produced more significant main effects and greater effect sizes than gaze shift did, whereas the COP sway variability actually increased significantly in large gaze shift conditions (with no reduction in task performance levels).

Overall, variability of COP sway may not be correctly studied and interpreted if the need to achieve the task's goal is not the main cause of behavioral changes. In other words, postural control may not be a primary task (e.g., Bloem, Grimbergen, Gert van Dijk, & Munneke, 2006; Woollacott & Shumway-Cook, 2002). The action task may prompt an adaptation of postural control so that performance is maintained or facilitated. As such, "successful" postural control may not equate simply to the minimization of postural sway (Stoffregen et al., 1999). In our experiment, individuals swayed more in dynamic gaze shifts conditions than in static conditions (Figs. 3A and B). However, the good visual task performance shows that they were "dynamically" and "statically" stable under these conditions, respectively. Taken as a whole, our results show that postural instability and postural variability are not equivalent (Newell, van Emmerik, Lee, & Sprague, 1993; van Emmerik & van Wegen, 2002). A reference is absolutely necessary for giving meaning to COP and/or postural variability and this reference should be the task (Riccio & Stoffregen, 1988).

4.5. Results in standard stance

In a post-hoc analysis, the standard stance and wide stance conditions were found to have yielded similar results (Figs. 3A and B; Table 2). Three reasons could explain why COP sway did not increase more in wide stance than in standard stance when large gaze shifts were performed. It may have been the case that standard stance was already wide enough (cf., Riccio & Stoffregen, 1988) to sufficiently stabilize postural control when large gaze shifts were performed. Alternatively, in the 1 Hz condition, the participants seemed to be engaged in continuous head motions while it was not the case in the 0.5 Hz condition (Table 1). In the 1 Hz condition, the participants did not have enough time to (re)stabilize their body before starting the new gaze shift. As such, they could not allow to let their COM and COP move too much away, thus explaining why they had to restrain their sway in the 1 Hz condition more than in the 0.5 Hz condition. Alternatively, wide stance naturally increases the stiffness of the leg-pelvis structure (Day et al., 1993; Winter, Patla, Prince, & Ishac, 1998). In wide stance, body motions may be naturally constrained by this passive stiffness, thus eliminating the freedom of COP to move further than in standard stance. Overall, COP sway variability in this experiment was related to performance constraints, but also to the individual characteristics, as suggested by Slobounov and Newell (1994).

4.6. Changes expected in the ML axis

According to the literature, lateral gaze shifts are associated with significantly lower COP/postural sway in the AP axis (relative to a control, stationary gaze condition; Rey et al., 2008; Stoffregen et al., 2006; Stoffregen et al., 2007). The effect was caused by the need to minimize ocular accommodation for success in the visual task (cf., Stoffregen et al., 1999). The screen was less than 1 m away from the participants in some or all of the conditions described by Stoffregen et al. (2006, 2007) and Rey et al. (2008). In our experiment, we did not expect a significant, main effect of gaze shift in the AP axis because the target dot was far away (2.1 m). It is noteworthy that AP COP sway variability was slightly lower under gaze shift conditions (see Table 2), whereas ML COP sway variability was significantly higher (Figs. 3A and B). Only a main effect of stance width was found for AP COP range (Fig. 4). This effect mostly showed that narrow stance significantly increased COP sway compared with other stance widths, as in Day et al. (1993).

4.7. Perspectives and conclusion

None of the literature studies appear to have shown that lateral gaze shift can significantly increase COP/postural sway variability when the participants placed their feet side-by-side. This may be because (i) the participants were instructed not to move their head or body (Rey et al., 2008; Rougier & Garin, 2006; Schulmann, Godfrey, & Fisher, 1987; Uchida, Hashimoto, Suzuki, Takegami, & Iwase, 1979) or (ii) COP/postural motions were not measured (Fukushima, Asaka, Ikeda, & Ito, 2007; Hollands et al., 2004) or were only poorly described in book chapters (Brandt, 1999; Brandt, Paulus, & Straube, 1986). Our results further suggest that intentionally guided gaze shifts require both postural coordination and dynamic postural stability. This information is important because intentionally driven gaze shift conditions require the displacement of many body parts (see Henry et al., 2001). In particular, older adults display a narrower stance width than young adults (McIlroy & Maki, 1997). Thus, one way of preventing ML instability (Maki, Holliday, & Topper, 1994) and the risk of ML falls could be a recommendation to increase stance width but not necessarily restraining intentional lateral body movement. In future work, we hope to confirm that stance width can be a true ML stabilizing factor in the elderly adults – especially when they have to perform tasks such as large gaze shifts.

References

Balasubramaniam, R., Riley, M. A., & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture, 11*, 12–24.

Boisgontier, M., Mignardot, J.-B., Nougier, V., Olivier, I., & Palluel, E. (2011). Le coût attentionnel associé aux fonctions exécutives impliquées dans le contrôle postural. *Science & Motricité, 74*, 53–64.

Bloem, B. R., Grimbergen, Y. A. M., Gert van Dijk, J., & Munneke, M. (2006). The "posture second" strategy: A review of wrong priorities in Parkinson's disease. *Journal of the Neurological Sciences, 248*, 196–204.

Brandt, T., Paulus, W., & Straube, A. (1986). Vision and posture. In W. Bles (Ed.), *Disorders of posture and gait* (pp. 160–161). Oxford: Elseiver.

Brandt, T. (1999). *Eye movements, oculomotor disorders, and postural balance. Vertigo: Ist Multisensory Syndromes*. London: Springer, p. 428–429.

Chang, Y.-H., Wu, H.-W., Hung, W., & Chiu, Y.-C. (2009). Postural responses in various bases of support and visual conditions in the subjects with functional ankle instability. *International Journal of Sport and Exercise Science, 1*, 87–92.

Day, B. L., Steiger, M. J., Thompson, P. D., & Marsden, C. D. (1993). Effect of vision and stance width on human body motion when standing: Implications for afferent control of lateral sway. *The Journal of Physiology, 469*, 479–499.

Fukushima, J., Asaka, T., Ikeda, N., & Ito, Y. (2007). Postural control during downward head movements in young subjects. *Journal of Physical Therapy Science, 19*, 205–212.

Henry, S. H., Fung, J., & Horak, F. B. (2001). Effect of stance width on multidirectional postural responses. *Journal of Neurophysiology, 85*, 559–570.

Holbein-Jenny, M. A., McDermott, K., Shaw, C., & Demchak, J. (2007). Validity of functional stability limits as a measure of balance in adults aged 23–73 years. *Ergonomics, 50*, 631–646.

Hollands, M. A., Ziavra, N. V., & Bronstein, A. M. (2004). A new paradigm to investigate the roles of head and eye movements in coordination of whole-body movements. *Experimental Brain Research, 154*, 261–266.

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

Kapteyn, T. S., Bles, W., Njiokiktjien, C. J., Kodde, L., Massen, C. H., & Mol, J. M. (1983). Standardization in platform stabilometry being a part of posturography. *Agressologie, 24*, 321–326.

Kirby, R. L., Price, N. A., & MacLeod, D. A. (1987). The influence of foot position on standing balance. *Journal of Biomechanics, 20*, 423–427.

Maki, B. E., Holliday, P. J., & Topper, A. K. A. (1994). Prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *Journal of Gerontology, 49*, M72–M84.

McIlroy, W. E., & Maki, B. E. (1997). Preferred placement of the feet during quiet stance. Development of a standardized foot placement for balance testing. *Clinical Biomechanics, 12*, 66–70.

Mouzat, A., Dabonneville, M., & Bertrand, P. (2004). The effect of feet position on orthostatic posture in a female sample group. *Neuroscience Letters, 365*, 79–82.

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

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

Pellecchia, G. L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait and Posture, 18*, 29–34.

Rey, F., Lê, T.-T., Bertin, R., & Kapoula, Z. (2008). Saccades horizontal or vertical at near or at far do not deteriorate postural control. *Auris Nasus Larynx, 35*, 185–191.

Riccio, G. E. (1993). Information in movement variability: About the qualitative dynamics of posture and orientation. In K. M. Newell & D. M. Corcos (Eds.), *Variability and motor control* (pp. 317–357). Champaign, IL: Human Kinetics.

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

Rougier, P., & Garin, M. (2006). Performing saccadic eye movements or blinking improves postural control. *Motor Control, 11*, 213–223.

Schulmann, D. L., Godfrey, B., & Fisher, A. G. (1987). Effects of eye movements on dynamic equilibrium. *Physical Therapy, 67*, 1054–1057.

Slobounov, S. M., & Newell, K. M. (1994). Postural dynamics as a function of skill level and task constraints. *Gait and Posture, 2*, 85–93.

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

Smart, L. J., & Smith, D. L. (2001). Postural dynamics: Clinical and empirical implications. *Journal of Manipulative and Physiological Therapeutics, 24*, 340–349.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., Hove, P., & Oullier, O. (2007). Postural sway and the frequency of horizontal eye movements. *Motor Control, 11*, 86–102.

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*, 203–230.

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.

Stoffregen, T. A., Villard, S., & Yu, Y. (2009). Body sway at sea for two visual tasks and three stance widths. *Aviation, Space and Environmental Medicine, 80*, 1039–1043.

Stoffregen, T. A., Yoshida, K., Villard, S., & Bardy, B. G. (2010). Stance width influences postural stability and motion sickness. *Ecological Psychology, 22*, 169–191.

Uchida, T., Hashimoto, M., Suzuki, N., Takegami, T., & Iwase, Y. (1979). Smoking-induced body sway and its suppression by periodic saccades. *Neuroscience Letters, 13*, 219–224.

van Emmerik, R. E. A., & van Wegen, E. E. H. (2002). On the functional aspects of variability in postural control. *Exercise and Sport Sciences Reviews, 30*, 177–183.

Yu, Y., Yank, J. R., Villard, S., & Stoffregen, T. A. (2010). Postural activity and visual vigilance performance during rough seas. *Aviation, Space and Environmental Medicine, 81*, 1–8.

Warren, W. H. Jr., (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 683–703.

Wing, A. M., Clapp, S., & Burgess-Limerick, R. (1995). Standing stability in the frontal plane determined by lateral forces applied to the hip. *Gait and Posture, 3*, 38–42.

Winter, D. A. (1995). Human balance and postural control during standing and walking. *Gait and Posture, 3*, 193–214.

Winter, D. A., Patla, A. E., Prince, F., & Ishac, M. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology, 80*, 1211–1221.

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.