COGNITIVE SCIENCE
A Multidisciplinary Journal

Functional Synergy Between Postural and Visual Behaviors When Performing a Difficult Precise Visual Task in Upright Stance

Cédrick T. Bonnet,[a] Sébastien Szaffarczyk,[a] Stéphane Baudry[b]

[a]*Laboratoire de Sciences Cognitives et Affectives, University of Lille, CNRS*
[b]*Laboratory of Applied Biology and Neurophysiology, Université Libre de Bruxelles, FNRS*

Abstract

Previous works usually report greater postural stability in precise visual tasks (e.g., gaze-shift tasks) than in stationary-gaze tasks. However, existing cognitive models do not fully support these results as they assume that performing an attention-demanding task while standing would alter postural stability because of the competition of attention between the tasks. Contrary to these cognitive models, attentional resources may increase to create a synergy between visual and postural brain processes to perform precise oculomotor behaviors. To test this hypothesis, we investigated a difficult searching task and a control free-viewing task. The precise visual task required the 16 young participants to find a target in densely furnished images. The free-viewing task consisted of looking at similar images without searching anything. As expected, the participants exhibited significantly lower body displacements (linear, angular) and a significantly higher cognitive workload in the precise visual task than in the free-viewing task. Most important, our exploration showed functional synergies between visual and postural processes in the searching task, that is, significant negative relationships showing lower head and neck displacements to reach more expended zones of fixation. These functional synergies seemed to involve a greater attentional demand because they were not significant anymore when the cognitive workload was controlled (partial correlations). In the free-viewing task, only significant positive relationships were found and they did not involve any change in cognitive workload. An alternative cognitive model and its potential subtended neuroscientific circuit are proposed to explain the supposedly cognitively grounded functional nature of vision–posture synergies in precise visual tasks.

Keywords: Postural control; Postural sway; Visual tasks; Cognitive models; Young adults

Correspondence should be sent to Cédrick T. Bonnet, SCALab, UMR CNRS 9193, Faculté de médecine, pôle recherche, 5e étage, 1, place de Verdun, 59045 Lille Cedex, France. E-mail: cedrick.bonnet@chru-lille.fr

1. Introduction

One characteristic of upright stance is continuous body oscillation even when individuals try to be as steady as possible (Reynolds, 2010; Zok, Mazzà, & Cappozzo, 2008). The cognitive demand, or attentional resources, required to control upright standing is usually studied by comparing center of pressure (COP) and/or body oscillation in single versus dual tasks (Lacour, Bernard-Demanze, & Dumitrescu, 2008; Woollacott & Shumway-Cook, 2002). In the single control task, individuals only have to stand as steady as possible, whereas in dual tasks they have to stand as steady as possible while performing a secondary task. In existing cognitive models, the performance of postural control and/or the secondary task is assumed to be lower when the tasks are performed together than when they are performed individually (Swan, Otani, Loubert, Sheffert, & Dunbar, 2004; Woollacott & Shumway-Cook, 2002). The model of limited attentional resources (Woollacott & Shumway-Cook, 2002) indeed states that the more difficult the secondary task, the fewer attentional resources available for the task performance and postural control, decreasing thereby the task performance and/or postural stability. A more recent model, the U-shaped nonlinear interaction model (Lacour et al., 2008), nuances such assumption by incorporating the possibility that an easy secondary task can improve postural stability (Lacour et al., 2008; Vuillerme & Nafati, 2007). The increase in postural stability during easy cognitive tasks is assumed to reflect a shift of postural control to subcortical structures so that upright stance can be controlled more automatically, hence leaving free attentional resources to succeed in postural control and to perform the secondary task (Lacour et al., 2008). Nonetheless, both models should predict that (very) difficult precise visual tasks may decrease balance stability compared with the stationary-gaze task because the central nervous system (CNS) needs to divide attentional resources to perform the dual task (by definition, "dual-tasks" refers to a duality to perform two tasks at the same time). However, previous works unanimously indicate that healthy, young adults oscillate significantly less when they perform a precise visual task than a control visual task (Rougier & Garin, 2007; Stoffregen, Hove, Bardy, Riley, & Bonnet, 2007; Uchida, Hashimoto, Suzuki, Takegami, & Iwase, 1979; White, Post, & Leibowitz, 1980), even during difficult visual tasks (Mitra, Knight, & Munn, 2013; Stoffregen et al., 2007).

Both purely cognitive models (limited attentional resources and U-shaped nonlinear interaction models) as well as the ecological (Riccio & Soffregen, 1988) and adaptive resource-sharing models (Mitra, 2004) are concerned with the understanding of postural control without taking into account the control of oculomotor behavior. However, one may assume that when precise gaze shifts have to be performed while maintaining upright standing, there is a need to coordinate or link oculomotor and postural behaviors. Indeed, the best programmed saccade alone may not allow the eyes to precisely reach a target because of inherent postural sway. Also, the best postural stability is useless alone as it does not move the eyes to reach the target. For these reasons, when precise gaze shifts have to be performed upright, the CNS may need to link oculomotor and postural behaviors to succeed. To go even further, negative relationships between oculomotor and

postural behaviors could be expected in precise visual tasks to show a reduction in postural sway when individuals need to explore further away. This main hypothesis comes from the consensus that a decrease in postural sway is assumed as a sign of better postural stability (Mitra et al., 2013). Indeed, better stability may be required to succeed in the coordination of visual and postural behaviors. If our main hypothesis were correct, the synergy between visual and postural processes may be associated with higher cognitive workload in precise visual tasks. Indeed, synchronous integration of visual and postural information in a goal-directed manner may require higher cognitive workload than simply performing visual or postural controls in isolated manners.

The objective of this study was to explore relationships between postural and oculomotor behaviors and related subtended changes in cognitive workload. To this end, a free-viewing task (looking freely at a picture; control task) and a searching task (trying to localize a target in a picture; e.g., Kowler, 2011) were performed in this study. The free-viewing task was considered as a control task because saccades could run randomly on the image. Supposedly, in the searching task, precise saccades and therefore precise postural control were required. We expected the participants to be more stable in the searching task than in the free-viewing task (Rougier & Garin, 2007; Stoffregen et al., 2007; Uchida et al., 1979; White et al., 1980), even though the cognitive workload should be greater in the first task. Moreover, we expected to find significant negative relationships between visual and postural behaviors in the searching task, supporting the rationale that postural sway should be more constrained in precise visual tasks to allow precise oculomotor behaviors in a larger visual field. The expected negative relationships should involve higher attentional resources of the CNS, meaning that they would not be significant anymore if the cognitive workload was controlled. Instead, in the control free-viewing task, significant relationships between visual and postural behaviors may be mostly positive, showing that larger visual explorations would lead to larger postural sway, first because there would be no need to over restrain postural sway to succeed in random exploration and second because larger saccades could induce longer time with no visual information. Indeed, during saccades, the visual system does not pick up any visual information (this is usually called the saccadic suppression; Rey, Lê, Bertin, & Kapoula, 2008). Hence, larger saccades in the free-viewing task may destabilize postural control more than shorter saccades. These findings would emphasize the need of an alternative model to explain postural control in precise visual tasks.

2. Methods

2.1. The participants

A total of 16 students (4 males, 12 females) from the University of Lille participated to this study. The mean age, body weight, and height were 21.13 years ± 1.31, 60.75 kg ± 7.90, and 167.83 m ± 6.80, respectively. To be included, the participants' visual acuity and visual contrast sensitivity had to be high (Armagnac: ≥8.2; Pelli-

Robson: ≤1.80), either naturally or corrected. The participants were excluded if they had a history of neurological or musculoskeletal disease, known vestibular problems, recurrent dizziness, or visual impairment (epilepsy, strabismus, nystagmus, and amblyopia). They were also excluded if they had a known pathology or a recent surgery (<1 year). The study was approved by the local ethical committee of our University.

2.2. Apparatus

A dual-top force platform (AMTI, Watertown, MA) was used to record the COP displacement with a sampling frequency of 120 Hz. Two white papers with printed lines were taped to the platform to mark the normative stance width and angle recommended by McIlroy and Maki (1997; 17 cm and 14°).

A magnetic tracking system (Polhemus Liberty 240/8-8 System, Colchester, VT) was used to record head, neck, and lower-back markers with a sampling frequency of 120 Hz. The markers were positioned at the occiput (head marker, on the headset), at the seventh cervical vertebra (neck marker), and at the fifth lumbar vertebra (lower-back marker, on a chest belt).

A head-mounted eye tracker (SensoMotoric Instruments, Teltow, Germany) was used to record eye motions. The iViewX system recorded the pupil position at a sampling rate of 50 Hz. The video showed the visual environment and (as a cross) what the right eye was looking.

All apparatus (platform, magnetic tracking system, and eye tracker) were triggered at the same time as the image was projected on the display.

To quantify the cognitive workload in each visual task, we used a validated French version (Cegarra & Morgado, 2009) of the National Aeronotics and Space Administration Task Load Index (NASA-TLX; Hart & Staveland, 1988) for different reasons. First, this NASA-TLX has been used in more than 550 studies already in 2006 (Hart, 2006) and has shown excellent reliability, sensitivity, and utility (Hart, 2006). Second, the cognitive workload depends on many dimensions (mental demand, physical demand, temporal demand, own performance, effort, and frustration) and the NASA-TLX is a multidimensional questionnaire owing these dimensions (Hart & Staveland, 1988). Third, Cegarra and Morgado (2009) explained that the NASA-TLX was more sensitive than other questionnaires (e.g., Subjective Workload Assessment Technique) to fine variations between tasks, which is what we needed in our study. Fourth, the NASA-TLX was already used in the postural control study by Stoffregen et al. (2007).

2.3. Tasks

In all trials, the participants stood at 3.11 m from a display on which the image was projected during 35 s. We specifically chose to place the participants further than 1.50 m from the display to avoid the participants to control their posture by use of optic flow, that is, visible motion of the environment engendered by their own postural sway (Bonnet, Temprado, & Berton, 2010). Four tasks were assessed: the searching task, the

free-viewing task, and two additional stationary-gaze tasks (black dot and structured dot tasks).

In both free-viewing and searching tasks, the participants first had to stare at a black dot (1° of visual angle) surrounded by an image (Fig. 1B). Once the black dot had disappeared (after 5 s), they were invited to freely look anywhere they want on the image (Fig. 1C). In the searching task, the participants had to specifically locate—that is, search and find—a target after the black dot had disappeared. Once found, they had to stare at it for 5 s and then look outside of the image. The structured dot task used the same images as in the free-viewing task, but the participants had to stare at the black dot during the full trial (Fig. 1B). In the black dot task, the black dot was surrounded by a white background (Fig. 1A). The two stationary-gaze tasks were performed to control whether the structure of the visual layout (black dot vs. structured dot tasks) and the free-viewing oculomotor behavior (structured dot vs. free-viewing tasks) could alter postural control and cognitive workload. To better understand the relation between oculomotor and postural behaviors, task difficulty had to range from very easy to very difficult. For this purpose, we decided to use a game for children called "où est Charlie?" in France or "where is Waldo" in the United States of America or "where is Wally" in the United Kingdom (published in a cartoon book; collection: Charlie; Author: Martin Handford) as the difficult task. The game consists of trying to locate where the little personage "Charlie" in the image is.

Four images were used in the free-viewing task and four other images were used in the searching task to avoid the participants using the same visual scan path from one trial to another (Norton & Stark, 1971). Using different images in the free-viewing and
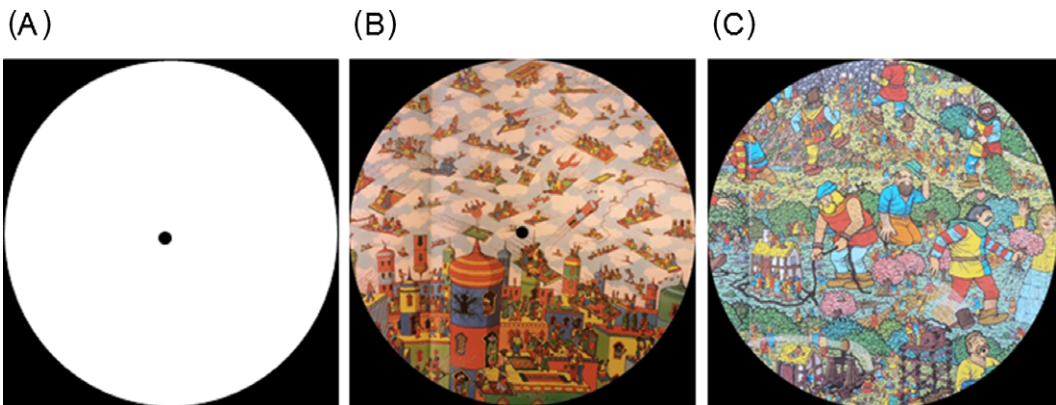

Fig. 1. (A) Representation of the black dot task in which the participants looked at the dot (1°) surrounded by a white circle (22°) during the trial. (B) This image can represent the structured dot, free-viewing, or searching tasks. The participants had to look at the dot either during the full trial in the structured dot task, or only for the 5 initial seconds in the free-viewing and searching tasks. When the dot disappeared in the free-viewing and searching tasks, the participants could freely look at the picture for the 30 last seconds of the trial when the dot had disappeared. They had to search where the personage Charlie was located in that image only in the searching task. (C) This is another image showed to the participants, but this time during the last 30 s of a trial (in the free-viewing or searching tasks).

searching tasks, however, may influence postural and oculomotor behaviors due to image characteristics. To control and avoid this spurious main effect of image, we run the participants per couple (participants a and b). The participant (a) watched images 1–4 in the free-viewing task and images 5–8 in the searching task, and the participant (b) watched images 5–8 in the free-viewing task and images 1–4 in the searching task. Consequently, the eight images were watched both in the searching and free-viewing tasks by participants (a) and (b). Furthermore, Charlie was present in the image only half the time (twice in images 1–4 and twice in images 5–8). Such a procedure allowed for recording 35 s of data in half trials in the searching task.

One methodological constraint was that the participants should not move any part of their body to perform any task. Otherwise, showing greater COP and/or markers of body segment displacements in one task relative to the other task(s) may simply be due to body motion to perform the task. If, for example, the participants had to look at a big panel (e.g., 90° horizontally and 90° vertically) in a precise visual task versus at a black dot, the participants would surely move their head and body segments in the precise visual task but not in the stationary-gaze task, hence creating a confounding variable. An ideal paradigm would have used images projected within 15° because they only require eye motion (Hallett, 1986). However, we decided to use a visual angle of 22° because we were unable to find any image sufficiently furnished to create a difficult searching task with a visual angle below 15°. Below 15°, the searched target was too quickly and easily found, whatever the chosen image. To insure that the participants did not turn or move their head, we requested them to be as steady as possible during trials. In all trials, the participants were told to hold the hands by their side of the body.

2.4. Procedure

Once they had signed the information and consent forms, the participants were invited to read and understand the French version of the NASA-TLX (Cegarra & Morgado, 2009). After calibration of the devices, the participants took their shoes off and put their feet at the standardized locations on the platform. The light of the experimental room was turned off during all recorded trials so that the participants could clearly see the image. The four tasks were run one after another, by block of four trials. This procedure was necessary to fill the NASA-TLX after each task, as recommended by Hart (2006). The four trials in the free-viewing task were performed before the four trials in the searching task to avoid the participants to search for Charlie—even unconsciously—in the free-viewing task (cf., Norton & Stark, 1971). The two control stationary-gaze tasks were randomly assigned, before, between, or after the free-viewing and searching tasks.

After the free-viewing task was performed, the participants were asked whether they knew and recognized the Charlie game and, if yes, whether they had searched for Charlie during one or several trials in that task. If they knew the game but had not searched for Charlie, the trials were considered for analyses.

Before beginning the first trial in the searching task, the experimenter showed to the participants what the personage (Charlie) looked like (a printed image with the entire personage). Also, two pretrials were run in which Charlie was (a) easy to find and (b) hard to find, to check if the participants were able to comply with instructions. After finishing each trial in the searching task, the experimenter asked the participant the yes/no question of whether they had found Charlie. If yes, then they were asked the confidence score they had about their performance (from 1 to 5; 1 being the lower score).

2.5. Dependent variables and analyses

2.5.1. NASA-TLX
After each task, the subjective cognitive workload was assessed with the global measure of workload in the NASA-TLX (Cegarra & Morgado, 2009; Hart & Staveland, 1988).

2.5.2. Visual performance and oculomotor behavior
To describe the visual performance in the searching task, we analyzed failure/success at the task, the time spent to find the target, and the confidence score. A failure was counted when the participants did not find Charlie when it was present in the image, whereas a wrong finding was counted when the participants considered that they found Charlie but were wrong. The characteristics of saccades and fixations were analyzed in both free-viewing and searching tasks. We analyzed the number per trial and the mean time per trial for both saccades and fixations. For saccades, we also calculated the mean amplitude of eye motion per trial, the standard deviation (*SD*) amplitude of eye motion per trial, and the distance travelled per trial (scan path) in both left-right and up-down directions. For fixations, we also calculated the *SD* location, that is, whether the fixations were close to each other or spread out. These variables are classically used in the science of vision (e.g., Castelhano, Mack, & Henderson, 2009; Kowler, 2011).

2.5.3. Postural behavior
The linear displacement of the postural control system was analyzed in both antero-posterior (AP) and mediolateral (ML) axes with the maximum excursion or range (*R*), *SD*, and mean velocity (*V*) of the COP, head, neck, and lower-back displacements. *R*, *SD,* and *V* are classical linear variables often used in the postural control literature (Bonnet & Despretz, 2012; Era et al., 2006; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). Noticeably, COP, head, neck, and lower-back linear variables described COP and body sway in the tasks. The angular displacement (yaw, pitch) of the head, neck, and lower back was analyzed to verify that the participants did not rotate their body segments to perform the tasks. Hence, our hypothesis of negative relationships between postural/COP displacement and eyes displacement in the searching task was concerned with linear postural/COP displacement variables only.

2.5.4. Preparation of the behavioral data

The first 5 s of data during which the participants looked at the black dot in the four tasks was not considered for analyses. Behavioral data after Charlie was found in the searching task were not considered for analyses as well. For adequate comparison between tasks, the length of the corresponding trials in the three other tasks was adjusted accordingly (same trial duration analyzed in the four trials). If, for example, Charlie was found after 20 s in the first trial of the searching task, data from 20 to 35 s in this trial were deleted and data from 20 to 35 s in the first trial of the three other tasks were also deleted. Thirdly, trials during which the personage was searched in the free viewing were not considered for analyses. In fact, three of the sixteen participants searched for the personage in the four free-viewing trials. The behavioral data in all trials were detrended (cf., Bonnet, Cherraf, Szaffarczyk, & Rougier, 2014). This procedure (MLsway = detrend (MLsway); APsway = detrend(APSway)) led the principal component of displacement to be flat in each trial, reducing thereby the influence of change in body orientation on the characteristics of COP and head, neck, and lower-back body displacement. For control purposes, the mean position of the COP and markers (not detrended this time) was analyzed to check any change in body orientation between tasks (cf., Bonnet, Morio, Szaffarczyk, & Rougier, 2014; Tarantola, Nardone, Tacclini, & Schieppati, 1997).

2.6. Statistical analysis

The mean of the four trials per task for each postural behavior variable was used for analysis. All variables for the postural behavior, the oculomotor behavior, and the cognitive workload exhibited normal distribution, homogeneity of variance, and no outlier. Therefore, repeated measure ANOVAs and post hoc Newman–Keuls tests were used to compare these dependent variables. These analyses were performed at $p < .05$. Pearson's correlations were used to study significant relationships between postural and oculomotor behaviors in the free-viewing and searching tasks separately. We tested all combinations of postural and oculomotor variables in these correlations because our analyses were mostly exploratory. Partial correlations were also used to control the effect of the cognitive workload on the significant relationships. To be clear, these partial correlations were performed on all significant relations between visual and postural variables to control—or withdraw—the contribution that the cognitive workload could have on these relations. All these correlations were performed on the average amount of variability of both behaviors throughout each trial (Pearson's correlations, partial correlations) and not on the full-time series (no cross-correlation). All these correlation analyses were performed at $p < .01$ (Bonferroni correction for multiple uses of the dependent variables). Pearson's correlation (a) between oculomotor behaviors and cognitive workload and (b) between postural behaviors and cognitive workload were not investigated because our study did not test whether individual changes—either visual or postural—could be due to a change in cognitive workload. Our interest was to test relationships between oculomotor and postural behaviors that could be explained by a change in cognitive workload.

3. Results

3.1. Visual task performance

During the searching task, six participants never found Charlie and one of these participants even made one mistake in one trial (wrong finding). Eight participants found Charlie once but two of these participants performed one mistake in another trial. The last two participants found the two Charlies and performed no mistake otherwise. Overall, Charlie was accurately found 37.5% of the time (12/32) with a mean confidence score of 4.2 ± 1.3 and mistakably found 9.4% of the time (3/32) with a mean confidence score of 2.3 ± 0.6. The time spent to find the personage was on average shorter for good finding (14.3 ± 8.6 s) than for wrong finding (23.0 ± 3.0 s).

3.2. NASA-TLX score

The ANOVA showed a significant main effect of task for the global score of the NASA-TLX ($F(3, 45) = 11.87$, $p < .05$; Fig. 2), with a significantly lower score in the free-viewing task than in the three other tasks and a significantly higher score in the searching task than in the three other tasks ($p < .05$).

3.3. Difference in COP and body segment behaviors between the four visual tasks

The significant findings are presented in Table 1. The *R* and *SD* linear displacements and yaw angular displacement were significantly lower in the searching task than in the three other tasks ($p < .05$), for COP, lower-back, neck, and head variables in both the AP
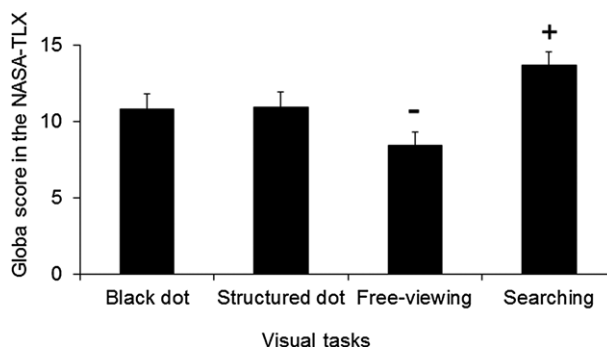

Fig. 2. A significant main effect of task for the global score in the NASA-TLX. The four tasks are the black dot stationary-gaze, the structured dot stationary-gaze, the free-viewing, and the searching tasks. The definition of these tasks is discussed in the text. The global score was significantly higher in the searching task than in the three other tasks as indicated by the "+" sign. It was also significantly lower in the free-viewing task than in the three other tasks as indicated by the "−" sign. Error bars represent the standard error of the mean. $p < .05$.

C. T. Bonnet, S. Szaffarczyk, S. Baudry / Cognitive Science 41 (2017)

Table 1
Significant main effects of task in the repeated measures ANOVA and additional post hoc Newman–Keuls analyses

	Black Dot	Structured Dot	Free Viewing	Searching	ANOVA
COP R_{AP} (cm)	1.65 ± 0.45	1.72 ± 0.59 (+)	1.66 ± 0.53 (+)	1.41 ± 0.39 (+)	$F(3, 36) = 3.03$, $\eta_p^2 = 0.17$
COP SD_{AP} (cm)	0.33 ± 0.09	0.36 ± 0.13 (+)	0.33 ± 0.10 (+)	0.28 ± 0.08 (+)	$F(3, 36) = 4.12$, $\eta_p^2 = 0.20$
COP R_{ML} (cm)	0.75 ± 0.29	0.88 ± 0.49 (+)	0.85 ± 0.45	0.62 ± 0.23 (+)	$F(3, 36) = 3.07$, $\eta_p^2 = 0.17$
Neck R_{AP} (cm)	1.93 ± 0.63 (+)	1.91 ± 0.59 (+)	1.84 ± 0.52 (+)	1.60 ± 0.47 (+)	$F(3, 36) = 3.50$, $\eta_p^2 = 0.18$
Lower-back R_{AP} (cm)	1.31 ± 0.43 (+)	1.32 ± 0.43 (+)	1.25 ± 0.38 (+)	1.03 ± 0.38 (+)	$F(3, 36) = 5.56$, $\eta_p^2 = 0.24$
Lower-back SD_{AP} (cm)	0.30 ± 0.11 (+)	0.31 ± 0.11 (+)	0.28 ± 0.09 (+)	0.24 ± 0.09 (+)	$F(3, 36) = 5.07$, $\eta_p^2 = 0.23$
Head R_{ML} (cm)	0.91 ± 0.37	1.07 ± 0.67 (+)	1.07 ± 0.48	0.77 ± 0.34 (+)	$F(3, 36) = 3.23$, $\eta_p^2 = 0.18$
Neck R_{ML} (cm)	0.79 ± 0.33	0.93 ± 0.64 (+)	0.93 ± 0.45	0.66 ± 0.30 (+)	$F(3, 36) = 2.99$, $\eta_p^2 = 0.17$
Lower-back R_{ML} (cm)	0.59 ± 0.29	0.73 ± 0.59 (+)	0.65 ± 0.36	0.44 ± 0.24 (+)	$F(3, 36) = 3.69$, $\eta_p^2 = 0.19$
Lower-back SD_{ML} (cm)	0.12 ± 0.06	0.15 ± 0.13 (+)	0.14 ± 0.08	0.09 ± 0.05 (+)	$F(3, 36) = 2.91$, $\eta_p^2 = 0.16$
Neck R_{yaw} (°)	2.07 ± 1.38 (+)	2.05 ± 1.18 (+)	1.85 ± 0.99	1.46 ± 0.66 (+)	$F(3, 36) = 4.47$, $\eta_p^2 = 0.21$

Note. The dependent variables were the range amplitude (R), standard deviation amplitude (SD) of the center of pressure (COP), head, neck, and lower-back linear displacements in the mediolateral (ML) and anteroposterior (AP) axes. An additional variable was the R of the yaw rotations of the neck displacements. Averages ± standard deviations are reported in the four experimental tasks (see text for the definition of these tasks). + shows a significant difference between the searching task and other marked tasks (post hoc Newman–Keuls tests). There was no significant difference between the black dot, the structured dot, and the free-viewing tasks (post hoc Newman–Keuls tests). The *p*-value was set to $p < .05$. Non-significant main effects of task are not reported in this table.
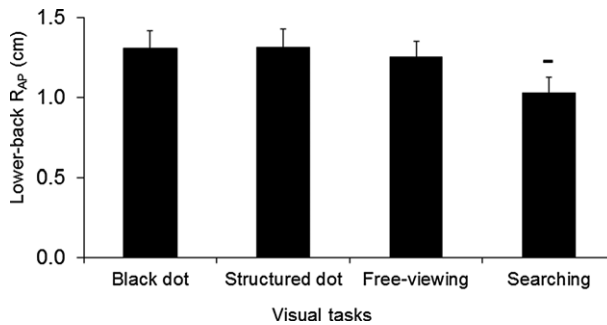
Fig. 3. A significant main effect of task in the ANOVA for the range of the lower-back displacement in the anteroposterior (R_{AP}) axis. The four tasks are the black dot stationary-gaze, the structured dot stationary-gaze, the free-viewing, and the searching tasks. The definition of these tasks is discussed in the text. The range of the lower-back displacement in the AP axis was significantly lower in the searching task than in the three other tasks as indicated by the "−" sign (post hoc Newman–Keuls tests). Error bars represent the standard error of the mean. $p < .05$.

and the ML axes. Fig. 3, for example, shows that the lower-back range of AP displacement was lower in the searching task than in the three other tasks. In contrast, analyses of the mean position of COP and body segment failed to demonstrate any significant difference between tasks ($F(3, 36) < 2.08$, $p > .05$). Hence, the participants stood upright in the same way in the four tasks.

3.4. Difference in oculomotor behavior between the four visual tasks

In the comparison between the free-viewing and searching tasks, the analyses did not show any significant difference in oculomotor behavior, both for characteristics of fixation and saccade ($F_s(1, 13) < 2.55$, $p > .05$). In both free-viewing and searching tasks, the eyes were required to move $< 22°$ and this very limited zone of exploration may have limited—eliminated—task-dependent differences in oculomotor behavior.

3.5. Correlation analyses between oculomotor and postural behaviors

The significant relationships between COP, head, neck, lower-back linear displacements and oculomotor displacements in the free-viewing and searching tasks are reported in Table 2. Significant negative relationships were only found in the searching task, whereas significant positive relationships were only found in the free-viewing task. In the four negative relationships, lower mean variability of head and neck AP displacements was significantly associated with more expended mean variability of visual exploration in the left-right direction. In contrast, in the four positive relationships, higher R and SD of ML COP displacements were significantly associated with greater path length of successive saccades in the left-right direction.

When controlling for the influence of the cognitive workload on the significant relationships between visual and postural behaviors (partial correlations), none of the

Table 2
Significant relationships (Pearson's correlations) between oculomotor behaviors and linear displacement of the center of pressure (COP), head, neck, and lower back

	Saccades	Fixations
Searching and head displacement		SD left-right of fixation and R_{AP} ($r = -.80$) and SD_{AP} ($r = -.79$)
Searching and neck displacement		SD left-right of fixation and R_{AP} ($r = -.76$) and SD_{AP} ($r = -.75$)
Free-viewing and COP displacement	Scan path of saccades left-right and R_{ML} ($r = .80$), SD_{ML} ($r = .82$)	
Free-viewing and back displacement	Scan path of saccades left-right and R_{ML} ($r = .69$), SD_{ML} ($r = .72$)	

Note. For the oculomotor behavior, the dependent variables were related to saccades (number, path) and to fixations (path, mean, and standard deviation amplitude (SD)) in the left-right and up-down directions. For the body displacement, the dependent variables were the range amplitude (R), SD, and mean velocity (V) in the mediolateral (ML) and anteroposterior (AP) axes. The relationships were all significant at $p < .01$. Non-significant relationships are not reported in this table.

relationships remained significant for the searching task. In contrast, for the free-viewing task, taking into account the cognitive workload did not influence the relationships between vision and posture (they were still significant).

3.6. Control analyses

In the searching task, the trial was finished once Charlie was found and not at the end of the 35 s. Although the length of time series was equivalent in the four tasks (see Section 2), the trials in each task did not always have the same length of data. In the postural control literature, we are not aware of any study that used such a procedure to compute the dependent variables. This is one methodological issue of performing the searching task because the trial stopped once the target was found. In our method, two of the four trials in the searching task did not display the little personage. These trials lasted as long as the trials in the three other tasks (35 s). For control purposes, ANOVAs of COP, head, neck, and lower back were performed again, but the means of the searching task were calculated only based on these two trials. Overall, seven of the eleven significant findings in Table 1 were still significant ($p < .05$). The ANOVA for the four other relationships (COP R_{AP}, head R_{ML}, neck R_{ML}, and lower-back SD_{ML}) was only marginally significant ($.05 < p < .08$). In conclusion, our way to prepare the dependent variables allowed to have more power (four trials instead of only two) but did not bias the trends of the result.

4. Discussion

In this study, we introduced the possibility that oculomotor and postural control may be functionally related in a challenging precise visual task but not in a control free-

viewing task. The results showed significantly lower COP and body displacements in the searching task than in the three other tasks and significantly greater cognitive workload. Most important, our exploration of data showed negative vision–posture linear relationships between visual and postural behaviors only in the searching task, suggesting that postural stability was improved to perform precise gaze shifts in this challenging precise visual task. The functional nature of these vision–posture synergies in precise visual tasks and the greater implication of the CNS to facilitate these synergies are discussed below.

4.1. Basis of the results

Our results demonstrated that the participants exhibited lower amplitude of COP, head, neck, and lower-back sway in the AP and the ML axes in the searching task compared with the three other tasks (Table 1). These results confirmed previous work reporting reduction of COP and/or body motions in a precise visual task compared to a control task (Bonnet et al., 2010; Giveans, Yoshida, Bardy, Riley, & Stoffregen, 2011; Legrand et al., 2013; Rodrigues et al., 2013; Rougier & Garin, 2007; Stoffregen et al., 2007; White et al., 1980). Our results even extend the literature reports because we used a very difficult precise visual task with free oculomotor behaviors. The difficulty of the precise visual task was confirmed by the fact that Charlie was found only 37.5% of the time and the participants were even not entirely sure of their accuracy (4.17 ± 1.34). In the literature, the most difficult precise visual tasks published were easier, with 87% and 75–83% of good performance in Stoffregen et al. (2007) and in Mitra et al. (2013), respectively.

Our paradigm controlled the role of optic flow (structured dot vs. black dot) and eye motions (free viewing vs. structured dot) as potential causes of changes in postural control. Overall, the study clearly showed that the reduction in postural sway in the searching task was related to the task of actively moving the eyes on the image and was not caused by any other reason. Indeed, there was no significant difference in COP and head, neck, and lower-back displacements between the free-viewing and both stationary-gaze tasks.

4.2. A functional synergy between visual and postural processes in precise visual tasks

Original relationships between visual and postural variables were observed in both free-viewing and searching tasks. The results showed significant negative relationships only in the searching task for AP displacements of the head and neck (Table 2). These negative relationships seemed functional as individuals swayed less to explore further, and still accurately. Individuals even swayed significantly less in the precise visual task than in the free-viewing task (Table 1) and lower postural/COP displacement is generally assumed as a sign of better postural stability (Mitra et al., 2013). Remarkably, significant relationships between oculomotor and postural variables only involved characteristics of fixation in the precise visual task, and fixations usually serve to improve encoding of different objects/personages (Castelhano et al., 2009), which is relevant in the searching task. The significant negative relationships between oculomotor and postural variables were consistent with the idea that when stable fixation takes high priority, participants

make slower and smaller amplitude of head movements during a sequential gaze-shift task (Epelboim, 1998). These relationships also logically involved even more the CNS because they required an increased in cognitive workload to exist. Indeed, the same negative relationships were not significant anymore when the cognitive workload was controlled (partial correlations). In other words, if the CNS had not increased its cognitive workload (Fig. 2), there may not have been any significant relationships between oculomotor and postural behaviors. In the free-viewing task, the positive relationships seemed more instability related as individuals exhibited more ML COP and ML lower-back sway when they performed saccades—not fixations—further away (Table 2). On one hand, saccades are not known to encode or facilitate the identification of objects or personages, but they serve to displace the eyes on region of interest before identification can take place. No visual information is picked up during saccades (Rey et al., 2008), and this argument may explain why larger saccades led to larger COP displacements during the free-viewing task (Table 2). We need to add that the participants did not need to overconstrain their postural stability in the free-viewing task because their eyes did not have to reach any specific target. Their postural control system could be relaxed and therefore more easily affected by any kind of perturbation (the saccadic suppression being one of them). On the other hand, greater postural/COP displacement is generally assumed as a sign of postural instability (Mitra et al., 2013). Moreover, these positive relationships did not involve greater implication of the CNS (see partial correlations). Overall, the results confirmed our main hypothesis.

4.3. Insufficiency of the existing models to explain our results

The basis of the existing cognitive models (limited attentional resources and U-shaped nonlinear interaction models) is that the CNS is limited in attentional resources. Therefore, the simple act of performing a secondary task may lead to postural instability if that secondary task is sufficiently hard (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002). A secondary task may be expected to improve postural stability only if the task is very easy in the U-shaped nonlinear interaction model. In our study, the precise visual task was very hard, as shown by the visual task performance and the cognitive workload (Fig. 2), and it led to better postural stability (Table 1). Hence, these two cognitive models may not explain our results in COP and body (head, neck, and lower back) linear displacements. In other words, the concept of division of attention or duality of tasks may not be appropriate in the context of precise visual tasks.

In contrast, the ecological model of postural control claims that postural control should facilitate the performance of other goals, that is, visual performance (e.g., Stoffregen et al., 2007). The results of our ANOVAs with COP, head, neck, and lower-back displacements could thus validate this model. Indeed, they showed that the participants oscillated and rotated their body significantly less in the searching task than in the free-viewing task (Fig. 3, Table 1). However, the ecological model may be insufficient to explain our results. Indeed, it would have predicted only our results in postural control. This model is not concerned with relationships between oculomotor and postural variables as it does not

suggest hypotheses on characteristics of oculomotor behavior (saccades, fixations). Also, it would not have predicted that greater cognitive workload is associated with lesser body sway. Exactly as the ecological or cognitive existing models, Mitra's model (2004), combining both ecological and cognitive arguments, may also be insufficient to explain our results. Indeed, Mitra's model (2004) is concerned with postural control as such and not with visual control (saccades, fixations) or relationships between postural and visual variables. It would not have predicted any change in vision–posture relationships between the free-viewing and searching tasks.

4.4. Proposition of a new model to explain postural control in precise visual tasks

The present results suggest that the CNS needs to create a synergy between visual and postural variables, that is, a vision-posture link, to succeed in precise visual tasks. The CNS would not decrease COP and body displacements as a main goal, but it would adjust postural behaviors in relation to oculomotor behaviors. It could be assumed that lower COP and body displacements are mostly a facilitatory aspect of the vision–posture synergy, not a goal by itself.

Our results suggest that the posture–vision synergy involved greater implication of the CNS for two reasons. First, the cognitive workload was significantly greater in the searching task than in the three other tasks (Fig. 2). Second, negative vision–posture relationships were significant in the searching task but not in the free-viewing task. Our analyses with partial correlations showed that without an increase in cognitive workload, that is, without a greater implication of the CNS, there would not have been any significant vision–posture synergy in the searching task. Indeed, when the role of the CNS was kept constant, there was no significant negative relationship between oculomotor and postural behaviors in precise visual tasks anymore. Instead, in the free-viewing task, there was no need for the participants to link oculomotor and postural behaviors because gaze shifts could be performed randomly on the pictures. For this reason, only positive relationships were found significant between visual and postural behaviors, potentially showing a sign of postural destabilization. This is the basis of a cognitive functional synergetic model of postural control. Further investigations are required to assess the strengths and weaknesses of this new model.

The frontal cortex may play an important role in the emergence of functional synergies between visual and postural systems in precise visual tasks. Indeed, the frontal cortex is known to perform attentional modulations of brain activation (Milham, Banich, Claus, & Cohen, 2003), and it is involved in the control of higher-order oculomotor (voluntary intentional saccades; Goldberg, Bisley, Powell, & Gottlieb, 2006) and postural behaviors (postural control in challenging tasks; Mihara, Miyai, Hatakenaka, Kubota, & Sakoda, 2008). Remarkably, the frontal cortex is strongly connected to the parietal cortex because both structures share similar properties and work together through their association pathways (Andersen & Cui, 2009) in the so-called fronto-parietal circuit (Milham et al., 2003). Supposedly, in the free-viewing task, there would be no need for the prefrontal cortex to be more activated than usual and therefore to functionally link the visual and postural systems. Conversely in the searching task, and through the fronto-parietal circuit,

the frontal cortex could (a) perform goal-directed voluntary saccades, (b) modulate the activation of reflexive saccades as it is strongly connected to the parietal eye-field (Gaymard, Lynch, Ploner, Condy, & Rivaud-Péchoux, 2003), and (c) modulate the activation of area 5, which is an association area (Cui, 2014) integrating signals from the somatosensory system and involved in posture (Sakata, Takaoka, Kawarasaki, & Shibutani, 1973). In the searching task, the visual and postural systems may be linked to each other in both parietal eye field and area 5 because area 5 is known to integrate the visual goals in the specific task of reaching (Cui, 2014; Shi, Apker, & Buneo, 2013). All these ideas are inferences for a potential neuroscientific circuit specific to the searching task and to the vision–posture synergy. Future studies will need to verify these inferences.

4.5. Limitations and conclusion

We need to mention that our results are limited to healthy, young adults and cannot be generalized to other individuals yet. Another limitation is that images showed to the participants were not representative of everyday activities. Future studies with images of the real world should be conducted. Also, future studies should examine the unexpected finding that the cognitive workload was significantly lower in the free-viewing task than in the two stationary-gaze tasks. Figure 2 indeed showed that the task of looking at a black dot was actually cognitively demanding, although it is usually assumed, as a control task, to be the simplest task (Wulf, 2007).

In conclusion, visual and postural behaviors seemed to be functionally and cognitively linked in the challenging searching task. The visual–postural synergy was not functionally and cognitively linked in the easy free-viewing task. We conclude that the CNS may be more engaged to perform a goal-directed visual–postural control in precise visual tasks than in the control free-viewing task. In future studies, new relationships between visual and postural variables should be investigated to better build the functional synergistic model of postural control. Some other analyses could be tested to validate the existence of these synergies. Instead of testing linear variables describing the variability of body and eye motions, future studies could investigate nonlinear variables. They could use the Recurrence Quantification Analysis with variables such as percent recur, percent determinism, entropy, trend, or use the Detrended Fluctuation Analysis and Fractal Analysis to study the stochastic versus deterministic structures of the time series and/or the behavioral flexibility versus rigidity of the system. Instead of testing relationships on summary statistics for both visual and postural variables, future studies could also use cross-correlations to test relationships between both visual and postural time-dependent structures (they could even use the Cross Recurrence Quantification Analysis). Another way to test synergies between visual and postural variables may be to analyze dimensional compression and reciprocal compensation, by means of the Principal Component Analysis and Uncontrolled Manifold Approach, as suggested by Riley, Richardson, Shockley, and Ramenzoni (2011). In brief, there are many ways to discover vision–posture synergies in precise visual tasks in this new—exploratory—field of research.

Conflict of interest

The authors have no conflicts of interest to declare.

Acknowledgments

References

Andersen, R. A., & Cui, H. (2009). Intention, action planning, and decision making in parietal-frontal circuits. *Neuron*, *63*, 568–583.

Bonnet, C. T., Cherraf, S., Szaffarczyk, S., & Rougier, P. (2014). The contribution of body weight distribution and center of pressure location in the control of mediolateral stance. *Journal of Biomechanics*, *47*, 1603–1608.

Bonnet, C. T., & Despretz, P. (2012). Large lateral head movements and postural control. *Human Movement Science*, *31*, 1541–1551.

Bonnet, C. T., Kinsella-Shaw, J. M., Frank, T. D., Bubela, D., Harrison, S. J., & Turvey, M. T. (2010). Deterministic and stochastic postural processes: Effects of task, environment, and age. *Journal of Motor Behavior*, *42*(1), 85–97.

Bonnet, C. T., Morio, C., Szaffarczyk, S., & Rougier, P. R. (2014). Postural mechanisms to control body displacements in the performance of lateral gaze shifts. *Journal of Motor Behavior*, *46*, 397–405.

Bonnet, C. T., Temprado, J.-J., & Berton, E. (2010). The effects of the proximity of an object on human stance. *Gait & Posture*, *32*, 124–128.

Castelhano, M. S., Mack, M. L., & Henderson, J. M. (2009). Viewing task influences eye movement control during active scene perception. *Journal of Vision*, *9*, 1–15.

Cegarra, J., & Morgado, N. (2009). Étude des propriétés de la version francophone du NASA-TLX. In B. Cahour, F. Anceaux, & A. Giboins (Eds.), *EPIQUE 2009: 5ème Colloque de Psychologie Ergonomique* (pp. 233–239). Nice, France.

Cui, H. (2014). From intention to action: Hierarchical sensorimotor transformation in the posterior parietal cortex. *eNeuron*, *1*, 1–6. doi: 10.1523/ENEURO.0017-14.2014

Epelboim, J. (1998). Gaze and retinal-image stability in two kinds of sequential looking tasks. *Vision Research*, *38*, 3773–3784.

Era, P., Sainio, P., Koskinen, S., Haavisto, P., Vaara, M., & Aromaa, A. (2006). Postural balance in a random sample of 7,979 subjects aged 30 years and over. *Gerontologty*, *52*, 204–213.

Gaymard, B., Lynch, J., Ploner, C. J., Condy, C., & Rivaud-Péchoux, S. (2003). The parieto-collicular pathway: Anatomical location and contribution to saccade generation. *European Journal of Neuroscience*, *17*, 1518–1526.

Giveans, M. R., Yoshida, K., Bardy, B., Riley, M., & Stoffregen, T. A. (2011). Postural sway and the amplitude of horizontal eye movements. *Ecological Psychology*, *23*, 247–266.

Goldberg, M. E., Bisley, J. W., Powell, K. D., & Gottlieb, J. (2006). Saccades, salience and attention: The role of the lateral intraparietal area in visual behavior. *Progress in Brain Research*, *155*, 157–175.

Hallett, P. E. (1986). Eye movements. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of human perception and performance* (Vol. 1, pp. 10-1–10-112) New York: Wiley.

Hart, S. G. (2006). NASA-TLX index (NASA-TLX); 20 years later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*, 904–908.

Hart, S. G., & Staveland, L. (1988). Development of the NASA task load index (TLX): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). Amsterdam: North-Holland.

Kowler, E. (2011). Eye movements: The past 25 years. *Vision Research*, *51*, 1457–1483.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: Models and posture-analysis methods. *Clinical Neurophysiology*, *38*, 411–421.

Legrand, A., Mazars, K. D., Lazzareschi, J., Lemoine, C., Olivier, I., Barra, J., & Bucci, M. P. (2013). Differing effects of prosaccades and antisaccades on postural stability. *Experimental Brain Research*, *227*, 397–405. doi:10.1007/s00221-013-3519-z

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.

Mihara, M., Miyai, I., Hatakenaka, M., Kubota, K., & Sakoda, S. (2008). Role of the prefrontal cortex in human balance control. *NeuroImage*, *43*, 329–336.

Milham, M., Banich, M., Claus, E., & Cohen, N. (2003). Practice-related effects demonstrate complementary roles of anterior cingulated and prefrontal cortices in attentional control. *NeuroImage*, *18*, 483–493.

Mitra, S. (2004). Adaptive utilization of optical variables during postural and suprapostural dyal-task performance: Comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 28–38.

Mitra, S., Knight, A., & Munn, A. (2013). Divergent effects of cognitive load on quiet stance and task-linked postural coordination. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 323–328.

Norton, D., & Stark, I. (1971). Eye movements and visual perception. *Scientific American*, *224*, 35–43.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering*, *43*(9), 956–966.

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.

Reynolds, R. F. (2010). The ability to voluntarily control sway reflects the difficulty of the standing task. *Gait & Posture*, *31*, 78–81.

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

Riley, M. A., Richardson, M. J., Shockley, K., & Ramenzoni, V. C. (2011). Interpersonal synergies. *Frontiers in Psychology*, *2*, 38. doi:10.3389/fpsyg.2011.00038.

Rodrigues, S. T., Aguiar, S. A., Polastri, P. F., Godoi, D., Moraes, R., & Barela, J. A. (2013). Effects of saccadic eye movements on postural control stabilization. *Motriz Rio Claro*, *19*, 614–619.

Rougier, P., & Garin, M. (2007). Performing saccadic eye movements or blinking improves postural control. *Motor Control*, *11*, 213–223.

Sakata, H., Takaoka, Y., Kawarasaki, A., & Shibutani, H. (1973). Somatosensory properties of neurons in the superior parietal cortex (area 5) of the rhesus monkey. *Brain Research*, *64*, 85–102.

Shi, Y., Apker, G., & Buneo, C. A. (2013). Multimodal representation of limb endpoint position in the posterior parietal cortex. *Journal of Neurophysiology*, *109*, 2097–2107.

Stoffregen, T. A., Hove, P., Bardy, B. G., Riley, M. A., & Bonnet, C. T. (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior*, *39*, 126–138.

Swan, L., Otani, H., Loubert, P. V., Sheffert, S. M., & Dunbar, G. L. (2004). Improving balance by performing a secondary cognitive task. *British Journal of Psychology*, *95*, 31–40.

Tarantola, J., Nardone, A., Tacclini, E., & Schieppati, M. (1997). Human stance stability improves with the repetition of the task: Effect of foot position and visual condition. *Neurosciences Letters*, *228*, 75–78.

Uchida, T., Hashimoto, M., Suzuki, N., Takegami, T., & Iwase, Y. (1979). Effects of periodic saccades on the body sway in human subjects. *Neuroscience Letters*, *13*, 252–258.

Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological Research*, *71*, 192–200.

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 & Posture*, *16*, 1–14.

Wulf, G. (2007). Attentional focus and motor learning: A review of 10 years of research. *Bewegung and Training*, *1*, 4–14.

Zok, M., Mazzà, C., & Cappozzo, A. (2008). Should the instructions issued to the subject in traditional static posturography be standardized? *Medical Engineering & Physics*, *30*, 913–916.