The functional role of central and peripheral vision in the control of posture

Andrea Berencsi a,c, Masami Ishihara b, Kuniyasu Imanaka a,*

a Department of Kinesiology, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan
b Unit 534, INSERM, Unité 534 Espace et Action, 16 avenue du Doyen Lépine, Bron 69500, France
c National Institute for Medical Rehabilitation, Budapest, Hungary

Abstract

Three experiments were conducted to investigate the role of central and peripheral vision (CV and PV) in postural control. In Experiment 1, either the central or peripheral visual field were selectively stimulated using a circular random dot pattern that was either static or alternated at 5 Hz. Center of foot pressure (CoP) was used to examine postural sway during quiet standing under both CV and PV conditions. The results showed that, when the visual stimulus was presented in the periphery, the CoP area decreased and more so in the anterior–posterior (AP) than in the medio-lateral (ML) direction, indicating a characteristic directional specificity. There was no significant difference between the static and dynamic (alternating) conditions. Experiment 2 investigated the directional specificity of body sway found in Experiment 1 by having the trunk either be faced toward the stimulus display or perpendicularly to it, with the head always facing the display. The results showed that the stabilizing effect of peripheral vision was present in the direction of stimulus observation (i.e., the head/gaze direction), irrespective of trunk orientation. This suggested that head/gaze direction toward the stimulus presentation, rather than a biomechanical factor like greater mobility of the ankle joint in AP direction than in ML direction, was essential to postural stability. Experiment 3 further examined whether the stabilizing effect of peripheral vision found in Experiments 1 and 2 was caused because more dots (500) were presented as visual cues to the peripheral visual field than to the central visual field (20 dots) by presenting the same number of dots (20) in both conditions. It was found that, in spite of the equal number of dots, the postural sway amplitudes were larger for the central vision conditions than for the peripheral vision conditions. In conclusion, the present study showed that peripheral rather than central vision contributes to maintaining a stable standing posture, with postural

* Corresponding author. Tel.: +81 426 77 2972; fax: +81 426 77 2961.
E-mail address: imanaka-kuniyasu@c.metro-u.ac.jp (K. Imanaka).

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sway being influenced more in the direction of stimulus observation, or head/gaze direction, than in the direction of trunk orientation, which suggests that peripheral vision operates primarily in a viewer-centered frame of reference characterized by the head/gaze direction rather than in a body-centered frame of reference characterized by the anatomical planes of the body.

Keywords: Central vision; Peripheral vision; Postural control; Center of pressure

1. Introduction

Vision provides rich information for self-motion in the environment and is therefore of overarching importance in motor control, often overriding other sources of information (Schmidt & Lee, 1999). In motor control, two kinds of vision, focal and ambient, are distinguishable that have different functional and information processing characteristics. Focal vision is assumed to be responsible for detecting the physical characteristics of environmental objects, while ambient vision is concerned with detecting the spatial characteristics of the surrounding visual world (Schmidt & Lee, 1999; Sekuler & Blake, 2000). Focal vision is mediated by visual information from the central retinal field, while ambient vision is mediated primarily by peripheral vision. These different features of focal and peripheral vision have previously been examined in various motor actions, such as hand movements (Sivak & MacKenzie, 1990), long jumping (Eves, 1995) and postural control (Amblard & Carblanc, 1980).

Using different methodologies, a number of studies have examined various aspects of motor and postural control in relation to central and peripheral vision. On the basis of these studies, Bardy, Warren, and Kay (1999) distinguished three different theories regarding the role of central and peripheral vision in the control of posture. One is the peripheral dominance hypothesis, which emphasizes the superiority of peripheral vision for the control of posture and self-motion (Amblard & Carblanc, 1980; Brandt, Dichgans, & Koenig, 1973; Lestienne, Soechting, & Berthoz, 1977). A second is the retinal invariance hypothesis, which holds that central and peripheral vision have the same functional role in the control of posture (Bardy et al., 1999; Straube, Krafczyk, Paulus, & Brandt, 1994). The third is the functional sensitivity hypothesis, which suggests that there are functional differences and complementary roles for central and peripheral vision in the control of posture (Nougier, Bard, Fleury, & Teasdale, 1997, 1998; Stoffregen, 1985; Stoffregen, Schmuckler, & Gibson, 1987).

A likely reason for these contradictory notions is that peripheral and central vision have received a broad range of operational definitions in investigations of their respective roles in postural control. For example, in the studies by Stoffregen (1985) and Stoffregen et al. (1987), central vision was manipulated by presenting visual stimulation in front of the participants (i.e., visual stimuli were projected on both central and peripheral visual fields), while peripheral vision was manipulated by presenting visual stimulation to the sides of the participants (in this case the stimuli only reached the peripheral visual field). This kind of visual stimulation may be inadequate in examining the respective functional roles of central and peripheral vision in postural control. Nougier et al. (1997) defined central vision as the central 10° of the visual field, whereas Brandt et al. (1973) defined central vision up to the central 60° of the visual field. Although these definitions of central vision may be formulated
on the basis of behavioral viewpoints, a neuroanatomical definition indicates that central vision should refer to either the central 2° to 4° of the visual field defined on the basis of the retinal distribution of the cone and rod photoreceptors (Osaka, 1994) or the central 7° of the visual field projecting to the particular area of the primary visual cortex responsible to process central vision (Daniel & Whitteridge, 1961; Mishkin & Ungerleider, 1982). The peripheral visual field is generally considered the area surrounding the central visual field.

The methodological differences between previous studies regarding the size of the central and peripheral visual fields, as well as the methods of presenting visual stimuli to those fields, may have resulted in contradictory findings concerning the respective contributions of the two visual systems in postural control. It has long been believed that central and peripheral vision have different functional characteristics and thus play different roles in postural control. Nevertheless, because of inadequate methodologies, it is still unclear whether the functional roles of the central and peripheral vision in postural control are indeed different from one another.

The goal of the present study was to examine the effects of central and peripheral vision on postural control, using a restricted visual stimulation applied to either the central or peripheral visual field alone, in keeping with their neuroanatomical definitions. The postural responses to those restricted visual stimulations were examined by measuring several characteristics of the center of foot pressure (CoP). The CoP refers to the mean point of the vertical ground reaction force vectors, representing the weighted average of all the pressures over the surface of the area in contact with the ground (Winter, 1995). CoP measurements have been applied extensively in studies on postural control (Buchanan & Horak, 2001; Kitabayashi, Demura, & Noda, 2003; Teasdale, Stelmach, & Breunig, 1991), and have provided important insights into balance control because they can be related to the motion of the center of body mass or the center of gravity (Chiari, Rocchi, & Cappello, 2002; Morasso & Schieppati, 1999; Winter, 1995). In the present study, several characteristics of the CoP excursions during quiet standing under various visual stimulation conditions were examined.

2. Experiment 1

The aim of Experiment 1 was to examine the contributions of central and peripheral vision to the control of posture by selectively stimulating either the central or peripheral visual field. The central visual field was defined neuroanatomically as either the central 4° (cf. Osaka, 1994) or the central 7° (cf. Daniel & Whitteridge, 1961; Mishkin & Ungerleider, 1982) retinal areas, while the peripheral visual field was defined as the retinal area surrounding the central visual field. The restricted stimulation of the central and peripheral visual fields used in Experiment 1 (and Experiments 2 and 3 as well) was applied according to those two definitions (i.e., the central 4° and 7° areas) of the central visual field and thus, by implication, the peripheral visual field.

The visual stimulus presented to either the central or peripheral visual field consisted of a random dot pattern, which was either static or dynamic in the sense that it was replaced alternately by another random dot pattern every 200 ms, inducing a spatial/temporal change at a frequency of 5 Hz. It is well known that peripheral vision is generally more sensitive to temporal changes in stimulation (Kelly, 1984) because retinal ganglion cells in the peripheral retina are transient in nature (Nelson, 1974; Paillard & Amblard, 1985). Paillard and Amblard (1985) reported that stroboscopic illumination of either 6 or 3 Hz
affected motor behaviors and deteriorated postural stability. Such a stroboscopic stimulation should not elicit directional postural responses because it contains no directional components. Similar to the stroboscopic stimulation as a non-directional spatial/temporal stimulus change, we used the static condition and the 5 Hz non-directional spatial/temporal perturbation conditions in presenting the random dot pattern. It was predicted that such a perturbation affects postural control, especially when applied to the peripheral visual field.

2.1. Methods

2.1.1. Participants
Seven healthy university students, three males and four females, participated in Experiment 1. They all had normal or corrected-to-normal vision, with no evidence or known history of postural or skeletal disorders. They were informed of the experimental procedures prior to participation and consented to take part in the experiment. Their mean height was 167.9 (SD = 6.4) cm, and their mean weight was 63.8 (SD = 12.0) kg.

2.1.2. Apparatus and stimuli
The apparatus used to measure the CoP excursions consisted of a force platform (KISTLER, 9281B), an amplifier (KISTLER, 3863A), and a data acquisition card (NI-DAQ 6.9), through which CoP data were obtained and then processed by software run on a personal computer (SONY VAIO PCG-FR). CoP data during quiet standing were sampled at a frequency of 1 kHz and filtered by a 20 Hz low-pass filter to eliminate high-frequency artifacts. An electro-oculogram (EOG) was also measured through an amplifier (NIHON KHODEN, Nistagmograph Amplifier, 601G) to monitor fixation compliance at the fixation point throughout the experimental trials. EOG data were visually evaluated by the experimenter during each trial. Trials in which the fixation was lost, amounting to a total of 2.7% of all trials in Experiments 1–3, were repeated and the data of the trials in question were excluded from subsequent analyses.

A 17-inch personal computer display (Compaq V7550, resolution 1024 × 768 pixels, refresh rate 75 Hz) was used to present visual stimuli at a viewing distance of 35 cm from the participant’s eyes. A cave-like black cover was placed in front of the participant to occlude the far peripheral visual fields (i.e., 180° in the horizontal axis and 90° in the vertical axis). At the center of this cover was a circular window, where the computer display was placed. The diameter of the circular window was 32.8° in visual angle; in it, 500 white random dots were presented on a black background. The size of each dot was eight pixels. The luminance of the dots and the screen was 72 cd/m² and 6 cd/m², respectively. A luminous red fixation point was presented in the middle of the computer display throughout the experiments.

2.1.3. Stimulation conditions
There were six visual field conditions: central vision 4° (CV4), central vision 7° (CV7), peripheral vision 4° (PV4), peripheral vision 7° (PV7), full vision (FV), and a no dots conditions. In the CV4 and CV7 conditions, the central 4° and 7° of the stimulus were visible, while, in the PV4 and PV7 conditions, the central 4° and 7° of the stimulus were masked. In the FV condition, the entire stimulus area was visible, whereas in the no dots condition only a fixation point was presented on the display. Within each visual field condition,
except the no dots condition, there were two conditions, perturbation and control (i.e., no perturbation). For the perturbation condition, the random dot pattern was replaced alternately by another random dot pattern every 200 ms (i.e., 5 Hz), while, in the control condition, the original random dot pattern was stationary during visual stimulation.

2.1.4. Procedures

Participants were asked to stand still on the force platform with their arms comfortably placed downward at either side of the body. Their bare feet were placed parallel to each other in line with marks drawn, separated by 2 cm, on the force platform. Participants were asked to relax and to keep looking at the red fixation point presented at about eye height during the experimental trials. Data acquisition on a given trial started when the participant verbally signed that he/she was ready to start. A quiet standing trial lasted 60 s, with a 1-min rest between trials. Data from the last 30 s were analyzed. In each visual and stimulus motion conditions three trials were conducted for a total of 33 trials.

2.1.5. Dependent variables

Three CoP variables were measured to examine the influence of the applied visual stimulation on postural sway: (1) sway area (cm²), calculated as the smallest area enclosing the area traveled by the CoP, (2) maximum displacement of the CoP in the anterior–posterior (AP) direction (cm), and (3) maximum displacement of the CoP in the medio-lateral (ML) direction (cm).

2.1.6. Data analyses

Two-way (visual fields and perturbation/control factors) repeated measures ANOVAs were performed on the means of each dependent variable. Because the no dots condition only consisted of a control condition (and hence involved no perturbation of the stimulation pattern), one-way (i.e., visual field factor) repeated measures ANOVAs were also performed on the averaged values of the perturbation and control conditions for CV4, CV7, PV4, PV7, and FV conditions as well as the no dots condition. In case of a significant interaction, simple main effect tests were subsequently performed; in addition, if significant main effects appeared, then multiple comparisons by LSD were performed. Statistical significance was set at p < .05.

2.2. Results

2.2.1. Sway area

The two-way repeated measures ANOVA (Perturbation/Control × Visual Field) performed on the sway area (Fig. 1) revealed a significant main effect for visual field \((F(4,24) = 4.41, p < .01)\) in the absence of a significant main effect for motion \((F(1,6) = 0.02, p > .05)\) and a significant Perturbation/Control × Visual Field interaction \((F(4,24) = 0.27, p > .05)\). Multiple comparisons of the significant main effect for visual field showed significant differences between CV4 and each PV4, PV7, and FV and between CV7 and each PV4, PV7, and FV. There was no significant difference between the CV4 and CV7 conditions, nor between the PV4, PV7, and FV conditions.

To compare these five visual field conditions with the no dots condition, a one-way repeated measures (visual field) ANOVA was performed on the sway area, which revealed a significant main effect for visual field \((F(5,30) = 2.68, p < .05)\). Multiple comparisons
showed that sway areas of both the CV7 and no dots conditions were significantly larger than those in the PV7 and FV conditions \((p < .05)\).

### 2.2.2. Maximum displacements in the AP and ML directions

A two-way repeated measures ANOVA (Perturbation/Control \(\times\) Visual Field) performed on maximum displacement in the AP direction (Fig. 2A) showed a significant main effect for visual field \((F(4, 24) = 7.1, p < .01)\) and no significant effects for perturbation/control \((F(1, 6) = 1.07, p > .05)\) and the Perturbation/Control \(\times\) Visual Field interaction \((F(4, 24) = 0.54, p > .05)\). Multiple comparisons by LSD showed significant differences between the CV4 condition and each of the PV4, PV7, and FV conditions and between the CV7 condition and each of the PV4, PV7, and FV conditions. There was no significant difference between the CV4 and CV7 conditions or between the PV4, PV7, and FV conditions. A further one-way repeated measures ANOVA (visual field, including the no dots condition) showed a significant main effect for visual field \((F(5, 30) = 4.51, p < .05)\). Multiple comparisons showed that the maximum displacement in AP was significantly increased in the CV4, CV7, and no dots conditions compared to that in the PV4, PV7, and FV conditions.

In the maximum displacement in the ML direction (Fig. 2B), no significant main effect for either visual field \((F(4, 24) = 1.94, p > .05)\) or perturbation/control \((F(1, 6) = 1.41, p > .05)\) was found. Furthermore, there was no significant Perturbation/Control \(\times\) Visual Field interaction \((F(4, 24) = 0.32, p > .05)\). A one-way repeated measures ANOVA (visual field including the no dots condition) showed no significant main effect for visual field \((F(5, 30) = 1.76, p > .05)\).

### 2.3. Discussion

The results of Experiment 1 showed that sway area decreased in the PV4, PV7, and FV conditions compared to the CV4, CV7, and no dots conditions. In the PV4, PV7, and FV conditions, the visual stimulus was presented to the peripheral visual field. Therefore, the presence of the visual stimulus in the periphery decreased the postural sway, thus resulting in a more stable stance, in contrast with the result obtained in the central vision conditions.
Results further showed that this was mediated by the decrease of the sway amplitude in the AP, rather than the ML, direction.

Compared to static visual stimulation, alternating between two random dot patterns at 5 Hz did not significantly affect extent postural sway for either peripheral or central vision. This is inconsistent with the finding of Paillard and Amblard (1985), who showed that 3 and 6 Hz stroboscopic lighting perturbed postural control. Although the experimental manipulation in Experiment 1 differed from that of Paillard and Amblard (1985), the results of Experiment 1 suggest that perturbation by an alternating random dot pattern may not provide meaningful visual/motion information for the postural control of quiet standing. In summary, the main finding of Experiment 1 was that postural sway decreased when the peripheral visual field was visually stimulated, particularly in the AP direction.

3. Experiment 2

In Experiment 1, the reduction of sway area in conditions in which the peripheral visual field was visually stimulated (underscoring the advantageous effect of peripheral vision on the stability of postural control) was primarily due to a decrease in the maximum displacement of the CoP excursions in the AP direction. There are two possible explanations for
this. The first is that the advantageous effect of peripheral vision on postural control is less pronounced in the ML than in the AP direction because of biomechanical constraints. It is generally accepted that CoP excursions primarily reflect neuromuscular activities of the muscles of the lower leg and ankle (Winter, 1995) and that the range of motion in the ankle joint is greater in AP direction than in ML direction (Szentágothai & Réthelyi, 1994; Winter, 1995). Therefore, it is likely that the sway in the standing posture, as reflected in the CoP excursions, is more easily produced in the AP direction than in the ML direction. An alternative explanation pertains to the finding of Stoffregen, Smart, Bardy, and Pagulayan (1999) that the postural sway in the AP direction is susceptible to visual stimuli observed in front of the participant, while the sway in the ML direction is susceptible to laterally observed visual stimuli (Stoffregen et al., 1999). Similarly, Warren, Kay, and Yilmaz (1996) showed that the directional effect on postural sway of an optic flow presented as visual stimuli was enhanced in the direction of observing the optic flow rather than in the anatomical (i.e., AP and ML) direction of the body. Therefore, it is suggested that the effect of a visual stimulus may appear primarily in the direction of the observation of the visual stimulus rather than in the anatomical AP direction, although the underlying mechanisms have not yet been clarified (Stoffregen et al., 1999).

The aim of Experiment 2 was to examine these possible explanations. Participants were asked to stand on the force platform either in front of a computer display presenting visual stimuli or with their trunk oriented in a direction perpendicular (i.e., to the left or right) to the computer display with the head/face rotated toward the display. If the biomechanical/anatomical factor is crucial, then postural sway should be susceptible more in the direction of trunk (i.e., AP) orientation per se than in the direction of stimulus presentation/observation (i.e., the direction toward the computer display, defined as the “X” direction in the Methods section). If postural sway is influenced primarily by the direction of stimulus presentation/observation (X), then the stabilizing effects of peripheral vision should appear in the X direction toward the computer display alone irrespective of the direction of trunk orientation. These predictions were examined in Experiment 2.

3.1. Methods

3.1.1. Participants

Nine healthy university students, six males and three females, participated in Experiment 2. Their mean body height was 170.6 (SD = 8.2) cm, while their mean body weight was 68.4 (SD = 13.7) kg. They all had normal or corrected-to-normal vision, with no evidence or known history of neurological or skeletal disorders. Two of the nine participants also took part in Experiment 1.

3.1.2. Apparatus, stimulus, and procedures

The apparatus and stimulus were identical to those in Experiment 1. The procedures were also identical to those in Experiment 1, except for three additional conditions regarding the direction of stimulus observation (or direction of trunk orientation). In one condition, the stimulus was presented in front of the participant’s trunk (FRONT), as in Experiment 1. In the other conditions, the participants stood on the force platform with the trunk oriented toward either the left or the right side of the computer display, with the head rotated toward the computer display, namely toward either the right (RIGHT) or left (LEFT) shoulder. In the LEFT and RIGHT conditions, the participants were asked to
rotate the head slowly (taking about 5 s to complete the rotation) and to look at the fixation point over either the left or right shoulder. The slow turn of the head to the 90° (perpendicular to the trunk direction) end position was meant to eliminate undesired effects on postural responses of afferent inputs arising from the neck and vestibular apparatus as a consequence of the rotation (Imanaka, Funase, & Nishihira, 1994). Accordingly, there were three head-on-trunk direction conditions (FRONT, LEFT, RIGHT) under which the same visual conditions as those in Experiment 1 were presented. Two 60-s trials in each condition (head-on-trunk direction, visual field, and stimulus motion) were conducted for a total of 66 trials run in 2 days.

3.1.3. Dependent variables

Sway area and maximum displacement in the AP and ML directions (i.e., with respect to the anatomical directions) were used as dependent variables. More importantly, the maximum displacement along both the direction of stimulus observation (X, i.e., the head/gaze direction facing the stimulus) and the direction perpendicular to it (Y) were subsequently calculated in order to examine the directional postural sway relative to the trunk (or stimulus observation) direction (e.g., maximum displacement along the X-axis was calculated from the data of maximum displacement in the AP direction of the FRONT condition and the maximum displacement in the ML direction of both LEFT and RIGHT conditions.)

3.1.4. Data analyses

Three-way (Head-on-trunk Direction × Visual Field × Perturbation/Control) repeated measures ANOVAs were performed on the means of each dependent variable, with five levels (CV4, CV7, PV4, PV7, and FV) for the visual field factor. Because the no dots condition was only a control condition, two-way (Head-on-trunk Direction × Visual Field) repeated measures ANOVAs were also performed on the means of CoP parameters from the perturbation and control conditions of CV4, CV7, PV4, PV7, and FV conditions as well as the CoP data of the no dots condition.

3.2. Results

3.2.1. Sway area

The three-way ANOVA (Head-on-trunk Direction × Visual Field × Perturbation/Control) performed on the sway area (Fig. 3) revealed a significant main effect for visual field \(F(4,32) = 3.85, p < .054\) but not for head-on-trunk direction \(F(2,16) = 0.26, p > .05\) or perturbation/control \(F(1,8) = 0.00, p > .05\). In addition, all interaction effects were not significant \(F(2,16) = 2.23, p > .05\), for Head-on-trunk Direction × Perturbation/Control; \(F(4,32) = 0.96, p > .05\), for Visual Field × Perturbation/Control; \(F(8,64) = 0.88, p > .05\), for Head-on-trunk Direction × Visual Field; and \(F(8,64) = 0.73, p > .05\), for Head-on-trunk Direction × Visual Field × Perturbation/Control). Multiple comparisons by LSD showed significant differences between the CV4 condition and each of the PV4, PV7, and FV conditions and between the CV7 condition and each of the PV4, PV7, and FV conditions \(p < .05\). There was no significant difference between the CV4 and CV7 conditions nor between the PV4, PV7, and FV conditions.

A two-way ANOVA (Head-on-trunk Direction × Visual Field) showed a significant main effect for visual field \(F(5,40) = 3.42, p < .05\) but not for head-on-trunk direction \(F(2,16) = 0.37, p > .05\) and the Head-on-trunk direction × Visual Field interaction
Multiple comparisons showed that the sway area of both the CV4 and no dots conditions differed significantly from that of either the PV7 or FV condition \((p < .05)\), with the CV7 condition differing significantly from each of the PV4, PV7, and FV conditions.

3.2.2. Maximum displacement along the X-axis

A three-way ANOVA (Head-on-trunk Direction × Visual Field × Perturbation/Control) performed on the maximum displacement along the X-axis (i.e., the direction of stimulus observation; Fig. 4A) showed a significant main effect for visual field \((F(4, 32) = 8.53, p < .05)\) but not for head-on-trunk direction \((F(2, 16) = 0.49, p > .05)\) and perturbation/control \((F(1, 8) = 0.05, p > .05)\). The two-way interactions were also not significant \((F(2, 16) = 1.02, p > .05)\) for Head-on-trunk Direction × Perturbation/Control; \(F(4, 32) = 0.68, p > .05\) for Visual Field × Perturbation/Control; \(F(8, 64) = 1.01, p > .05\), for Head-on-trunk Direction × Visual Field), as was the three-way interaction \((F(8, 64) = 0.71, p > .05)\). Multiple comparisons showed that the maximum displacements in both the CV4 and CV7 conditions were significantly larger than those in the PV4, PV7, or FV condition \((p < .05)\). There was no significant difference between the CV4 and CV7 conditions, nor between the PV4, PV7, and FV conditions.

A two-way ANOVA (Head-on-trunk Direction × Visual Field) showed a significant main effect for visual field \((F(5, 40) = 6.48, p < .01)\) but not for head-on-trunk direction \((F(2, 16) = 0.49, p > .05)\). The interaction between the two factors was not significant \((F(10, 80) = 0.69, p > .05)\). Multiple comparisons revealed that the maximum displacement along the X-axis was significantly larger in the CV4, CV7, and no dots conditions than in the PV4, PV7, and FV conditions \((p < .05)\). There were no significant differences between the CV4, CV7, and no dots conditions, nor between the PV4, PV7, and FV conditions.

3.2.3. Maximum displacement along the Y-axis

A three-way ANOVA (Head-on-trunk Direction × Visual Field × Perturbation/Control) performed on the maximum displacement along the Y-axis (Fig. 4B) showed that there were no main effects for visual field \((F(4, 32) = 2.25, p > .05)\), head-on-trunk direction

\((F(10, 80) = 0.65, p > .05)\). Multiple comparisons showed that the sway area of both the CV4 and no dots conditions differed significantly from that of either the PV7 or FV condition \((p < .05)\), with the CV7 condition differing significantly from each of the PV4, PV7, and FV conditions.

![Fig. 3. Mean sway areas for motion and control in each visual field condition. The vertical bars indicate the standard error. Asterisks indicate a significance level lower than .05.](image)
(F(2, 16) = 1.20, p > .05) and perturbation/control (F(1, 8) = 0.02, p > .05). There were also no significant interactions (F(2, 16) = 0.26, p > .05, for Head-on-trunk Direction × Perturbation/Control; F(4, 32) = 0.87, p > .05, for Visual Field × Perturbation/Control; F(8, 64) = 0.99, p > .05, for Head-on-trunk Direction × Visual Field; and F(8, 64) = 0.72, p > .05, Head-on-trunk Direction × Visual Field × Perturbation/Control).

A two-way ANOVA (Head-on-trunk Direction × Visual Field) showed a significant main effect for visual field (F(5, 40) = 2.46, p < .05) but not for head-on-trunk direction (F(2, 16) = 1.03, p > .05), with no significant interaction (F(10, 80) = 0.87, p > .05). Multiple comparisons showed that the maximum displacement along the Y-axis was larger in both the CV4 and no dots conditions than in the FV condition (p < .05), with all other combinations for the factors indicating no significant differences.

3.2.4. Maximum displacement in the AP direction

A three-way ANOVA (Head-on-trunk Direction × Visual Field × Perturbation/Control) on the maximum displacement in the AP direction (Fig. 5A) showed a significant main effect for visual field (F(4, 32) = 3.02, p < .05), but not for head-on-trunk direction (F(2, 16) = 1.91, p > .05) and perturbation/control (F(1, 8) = 0.13, p > .05). In addition, all interaction effects were not significant (F(2, 16) = 1.11, p > .05, for Head-on-trunk...
Direction & Perturbation/Control; $F(4,32) = 1.52, p > .05$, for Visual Field & Perturbation/Control; $F(8,64) = 1.39, p > .05$, for Head-on-trunk Direction & Visual Field; and $F(8,64) = 0.65, p > .05$, for Head-on-trunk Direction & Visual Field & Perturbation/Control). Multiple comparisons performed for the significant main effect for visual field showed significant differences between the CV4 condition and each of the PV4, PV7, and FV conditions and between the CV7 and FV conditions ($p < .05$), with no significant difference either between the CV4 and CV7 conditions or between the PV4, PV7, and FV conditions.

A two-way ANOVA (Head-on-trunk Direction & Visual Field) showed a significant main effect for visual field ($F(5,40) = 2.51, p < .05$) but not for head-on-trunk direction ($F(2,16) = 2.72, p > .05$), with no significant interaction ($F(10,80) = 0.82, p > .05$). Multiple comparisons showed that the maximum displacement in the AP direction was larger in the CV4, CV7, and no dots conditions than in the FV condition and also larger in the CV4 than the PV7 condition ($p < .05$), with no other significant differences.

3.2.5. Maximum displacement in the ML direction
A three-way ANOVA (Head-on-trunk Direction & Visual Field & Perturbation/Control) performed on the maximum displacement data showed significant main effects for

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Fig. 5. Mean displacements in the AP (A) and ML (B) directions for motion and control in each visual field condition. The vertical bars indicate the standard error. Asterisks indicate a significance level lower than .05.
both head-on-trunk direction ($F(2, 16) = 4.54, p < .05$) and visual field ($F(4, 32) = 6.2, p < .01$), but not for perturbation/control ($F(1, 8) = 1.93, p > .05$). In addition, all interactions were not significant ($F(2, 16) = 0.12, p > .05$, for Head-on-trunk Direction × Perturbation/Control; $F(4, 32) = 0.78, p > .05$, for Visual Field × Perturbation/Control; $F(8, 64) = 1.45, p > .05$, for Head-on-trunk Direction × Visual Field; and $F(8, 64) = 0.57, p > .05$, for Head-on-trunk Direction × Visual Field × Perturbation/Control). Multiple comparisons on the significant main effect for visual field (Fig. 5B) showed that the maximum displacement in the CV4 condition was significantly larger than in the PV4, PV7, and FV conditions, while the maximum displacement in the CV7 condition was significantly larger than in the PV7 and FV conditions ($p < .05$), with no significant difference either between the CV4 and CV7 conditions nor between the PV4, PV7, and FV conditions. Furthermore, multiple comparisons for the significant main effect for head-on-trunk direction (Fig. 6) showed that the maximum displacement was larger ($p < .05$) in both the LEFT and RIGHT conditions (i.e., when the visual stimulus was observed laterally) than in the FRONT conditions (i.e., when the visual stimulus was observed in front of the participants).

A two-way ANOVA (Head-on-trunk Direction × Visual Field) showed significant main effects for both visual field ($F(5, 40) = 7.52, p < .01$) and head-on-trunk direction ($F(2, 16) = 10.71, p < .01$), with no significant interaction ($F(10, 80) = 1.21, p > .05$). Multiple comparisons showed that the maximum displacement in the ML direction was larger in the CV4, CV7, and no dots conditions than in the PV7 and FV conditions ($p < .05$), with larger maximum displacements in the CV4 and no dots conditions than in the PV4 condition as well. Furthermore, multiple comparisons for the significant main effect for head-on-trunk direction showed that the maximum displacement was larger ($p < .05$) in both the LEFT and RIGHT conditions than in the FRONT condition.

3.3. Discussion

The results of Experiment 2 showed that the sway area (see Fig. 3) significantly decreased when the visual stimulus was presented to the peripheral visual field (i.e., PV4, PV7, and FV conditions), consistent with the findings of Experiment 1. Furthermore, such visual-field effects (i.e., stable postural sways evident for the PV4, PV7, and FV conditions
compared to the CV4, CV7, and no dots conditions) for postural sway clearly appeared in the maximum displacement along the X-axis (see Fig. 4A) but not along the Y-axis (Fig. 4B). Although such visual-field effects also appeared in both the AP (Fig. 5A) and ML (Fig. 5B) directions, the displacement data for the AP and ML conditions contained both the X- and Y-directions; namely, the maximum displacement data for the ML direction contained those in the X-direction in the LEFT and RIGHT head-on-trunk conditions, and the data for the AP direction contained those in the X-direction only in the FRONT head-on-trunk condition but in the Y-direction in the LEFT and RIGHT conditions. This may probably have caused similar visual-field patterns for both the AP and ML directions. These results therefore suggest that biomechanical/anatomical factors may not give rise to the visual-field effects on postural sway which were evident in both the sway area and maximum displacement of the CoP excursions. Rather, the visual-field effects (i.e., the stabilizing effect of peripheral vision) on the postural sway may well be mediated by the direction of stimulus observation.

4. Experiment 3

In Experiments 1 and 2, stimuli presented to the peripheral rather than the central visual field stabilized postural sway. However, in these experiments, the number of dots presented in the central and peripheral visual fields differed from each other in that more dots (visual cues) were presented in the peripheral visual field than the central visual field. The spatial structure of the visual environment has previously been shown to affect postural control (Amblard & Carblanc, 1980; Lestienne et al., 1977; Paillard & Amblard, 1985), with higher spatial frequencies being more influential in the control of posture (Lestienne et al., 1977). Therefore, it was supposed that the number of dots presented in the visual field could have affected the nature of the postural control. The aim of Experiment 3 was to examine the stabilizing effect of peripheral and central vision with an equal number of dots (visual cues) being presented in the central and peripheral visual fields. In Experiments 1 and 2, the number of dots presented in the CV7 condition was approximately 20; thus, in Experiment 3, the stabilizing effect of peripheral vision was examined by applying the number (i.e., 20) of dots to be presented in both the central and peripheral visual fields. In addition, a large number of dots, namely 500, was also presented in order to compare the peripheral vision condition of 20 dots with that of a large number of dots (visual cues) available.

4.1. Methods

4.1.1. Participants

Eight healthy university students, three males and five females, participated in Experiment 3. Their mean height was 166.6 (SD = 6.8) cm, while their mean weight was 58.1 (SD = 9.9) kg. All participants had either normal or corrected-to-normal vision and had neither vestibular nor movement disorders.

4.1.2. Apparatus and stimulus

The apparatus was the same as that used in Experiments 1 and 2. The visual stimulus consisted of a random dot pattern identical to that used in Experiments 1 and 2, except that 20 white dots were presented in the three visual conditions. In the central vision condition (CV7), 20 dots were presented within the central 7° of the visual field, while in the
peripheral vision condition (PV7_20) 20 dots were presented outside the central 7°. In the full vision condition (FV_20) 20 dots were presented in the whole stimulus area, covering both central and peripheral visual fields. Furthermore, additional peripheral and full vision conditions (PV7_500 and FV_500) were examined by applying the same random dot pattern (which consisted of about 500 dots) as that used in the PV7 and FV conditions in Experiments 1 and 2.

4.1.3. Procedures

Procedures were generally identical to those described in Experiment 1 except for the six visual conditions, i.e., the CV7, PV7_20, PV7_500, FV_20, FV_500, and the no dots condition. Three trials were conducted in each condition for a total of 18 trials. These trials were presented in random order. The duration of a trial (i.e., quiet standing) was 60 s.

4.1.4. Dependent variables and data analyses

The sway area and maximum displacement in the AP and ML directions were examined as dependent variables. One-way repeated measures ANOVAs (visual condition) were performed on the means of each dependent variable.

4.2. Results

An ANOVA on the sway area data (Fig. 7) revealed a significant main effect for visual condition ($F(5, 35) = 5.19, p < .01$). Subsequent multiple comparisons showed that the sway areas in the CV7 and no dots conditions were significantly larger than those in the PV7_20, PV7_500, FV_20, and FV_500 conditions ($p < .05$), with no significant differences between the PV7_20, PV7_500, FV_20, and FV_500 conditions ($p > .05$). Analysis of the length of the CoP path showed no significant main effect for the visual field condition ($F(5, 35) = 0.98, p > .05$).

Analysis of the maximum displacement in the AP direction (Fig. 8A) by one-way repeated measures ANOVA showed a significant main effect for visual field condition ($F(5, 35) = 5.5, p < .01$). Multiple comparisons showed that the maximum displacement in the AP direction was larger in the CV7 condition than in all other conditions ($p < .05$), with

![Fig. 7. Mean sway area in each visual condition. The vertical bars indicate the standard error. Asterisks indicate a significance level lower than .05.](image-url)
no significant differences between the PV7_20, PV7_500, FV_20, FV_500, and no dots conditions \((p > .05)\). In contrast, an ANOVA on maximum displacement in the ML direction (Fig. 8B) showed a non-significant effect for visual field condition \((F(5, 35) = 2.22, p > .05)\).

4.3. Discussion

The results showed that, when a visual stimulus was presented to the central visual field (CV7 and no dots conditions), the sway area increased significantly in comparison to conditions in which a stimulus was presented in the periphery (PV7_20, PV7_500, FV_20, and FV_500 conditions). This effect was manifest regardless of the number of dots presented in the visual field. Furthermore, there was no significant difference between the peripheral vision (PV7_20 and PV7_500) and full vision (FV_20 and FV_500) conditions even when different numbers of dots (i.e., 20 and 500 dots) were presented in the visual fields.

The visual field conditions affected the maximum displacement in the AP direction (i.e., the direction of stimulus observation) rather than the ML direction. The maximum displacement in the AP direction increased in the CV7 condition compared to all other conditions, while the peripheral and full vision conditions did not differ from each other irrespective of the number of dots presented. This indicated that, as in Experiments 1

![Fig. 8. Mean maximum displacements in the AP (A) and ML (B) directions in each visual condition. The vertical bars indicate the standard error. Asterisks indicate a significance level lower than .05.](image)
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and 2, the decrease in the sway area under the presence of peripheral visual stimulation may have been mediated by the decreased sway amplitude in the AP (i.e., stimulus observation) direction. It is therefore concluded that peripheral vision is more effective in stabilizing standing posture than central vision and that this difference is not only caused by the amount of visual information (i.e., the number of dots/visual cues) available in the peripheral visual field.

5. General discussion

5.1. Decreased body sway in the presence of peripheral visual information

The present study was conducted to investigate whether central and peripheral vision contribute differently to the control of posture. CoP characteristics were measured to examine postural responses to visual stimulation of either central or peripheral vision during quiet standing. Stimuli were either static or dynamic (i.e., alternating at a frequency of 5 Hz). In general, the results of Experiments 1, 2, and 3 showed that, in conditions in which peripheral visual information was present (i.e., PV4, PV7, and FV), body sway (sway area and maximum displacement of the CoP excursions) was less than that in the conditions in which only central visual information was available (i.e., CV4 and CV7). Furthermore, the results of Experiments 1 and 2 did not show any significant differences between perturbed and static (control) conditions.

The present finding that peripheral vision results in smaller postural sway than central vision probably indicates a greater contribution of peripheral vision to the control of quiet standing than central vision. This is consistent with the findings of Amblard and Carblanc (1980), who studied the postural control of quiet standing using static environmental visual stimuli. It is generally suggested that, during unperturbed (i.e., quiet) standing, the postural control system may well use visual information to minimize body sway (Dijkstra, Schöner, & Gielen, 1994a; Mitra, 2004), and that the visual system (either central or peripheral vision) that provides the highest postural stability also contributes more to the control of posture than the other visual system (Straube et al., 1994).

In contrast, other studies on postural control using either optic flow stimulation (Andersen & Dyre, 1989; Bardy et al., 1999; Habak, Casanova, & Faubert, 2002; Lestienne et al., 1977; Schmuckler, 1997; Warren et al., 1996) or a moving room paradigm (Lee & Aronson, 1974; Stoffregen, 1985; Stoffregen et al., 1987; Warren & Kurtz, 1992) have identified features of postural responses to visual stimuli that are completely opposite to the present findings, like the findings of several studies using static environmental visual stimuli (Amblard and Carblanc, 1980; Nougier et al., 1997, 1998; Straube et al., 1994). Optic flow generally induces an illusory motion of the body, which is, in turn, compensated by directionally specific postural adjustments. Therefore, when using optic flow stimuli or a moving room, the contribution of the visual system to postural control is characterized by synchronization of postural responses with the visual stimulus, with greater sway indicating a greater contribution of the visual system (Bardy et al., 1999; Lestienne et al., 1977; Stoffregen, 1985; Stoffregen et al., 1987; Warren et al., 1996). Although the apparent features of postural responses to a given visual stimulus (i.e., either optic flow or static visual stimuli) are rather different in nature, both the large postural sway for the optic flow and the stable postural sway for the static visual stimuli may well indicate a large contribution of, or a high sensitivity to, the given visual stimulus. Accordingly, the present finding of greater...
postural stability under peripheral compared to central visual stimulation suggests a greater contribution of peripheral vision to the control of posture than central vision, which is consistent with the peripheral dominance hypothesis.

In the present study, the stabilizing effect of peripheral vision on quiet standing was shown not only when the number of dots (i.e., the number of visual cues) was higher in the peripheral than in the central visual field (Experiments 1 and 2), but also when the number of presented dots was equal in the two fields (Experiment 3). The spatial structure of the visual environment has long been known to influence postural behavior in general (Amblard & Carblanc, 1980; Lestienne et al., 1977; Paillard & Amblard, 1985), with higher spatial frequencies being more effective for the visual control of posture (Lestienne et al., 1977). Therefore, it was predicted in Experiment 3 that decreasing the number of dots in the peripheral visual field would result in a deterioration of postural performance. However, the smaller number of dots of a random dot display presented in the peripheral visual field did not result in decreased performance. This suggests that the role of peripheral vision in postural control does not (simply) depend on the function of the number (or density) of dots, that is, the amount of visual information, available in the visual field. This theme should be examined further in future studies by manipulating the number of dots or the physical characteristics of visual stimuli.

5.2. Directional specificity of postural sway

In the present study, the stabilizing effect of peripheral vision was manifest in the direction of stimulus observation (Experiment 2), rather than in the anatomical AP and/or ML directions of the body. That is, the stabilizing effect clearly appeared both in the AP direction when the stimulus was observed in front of the participant and in the ML direction when the stimulus was observed laterally by the participants. These results suggest that the function of peripheral vision is more likely related to the direction of the head and/or gaze orientation than to either the AP or ML plane relative to the body.

Directionally specific postural responses to head and gaze orientations during standing and locomotion have previously been shown by Ivanenko, Grasso, and Lacquaniti (1999, 2000). In these studies, the head and/or eyes were turned by specific angles in the horizontal plane during neck muscle vibration, while the direction of spontaneous postural sway and the direction of acceleration during walking were measured as dependent variables. The results showed that directional postural responses occur in the direction of either head or gaze orientation during standing and walking. This suggests that the position of the head and eyes provides a viewer-centered frame of reference for the control of posture and locomotion (Ivanenko et al., 1999, 2000).

Based on the present results showing directional specificity of postural sway, it is plausible that, in the control of posture, peripheral vision operates in a viewer-centered frame of reference defined by head and gaze positions rather than in a body-centered frame of reference defined by the anatomical planes of the body. During stance and locomotion in everyday life, head and gaze are usually oriented in the direction of heading or forward locomotion, suggesting that peripheral vision plays a role in the control of such forward motion during standing and locomotion. This is consistent with the findings of Stoffregen and colleagues (1985, 1987), who showed that peripheral vision was more sensitive to stimulation corresponding to forward–backward motion of the participants than to stimulation corresponding to left–right motion during either quiet standing or locomotion.
5.3. Lacking the effect of 5-Hz visual perturbation

In Experiments 1 and 2, the random dot pattern was replaced alternately at 5 Hz by another random dot pattern. It was assumed that such a perturbation would affect postural behavior, especially when presented to the peripheral visual field because peripheral vision is known to be more sensitive to temporal changes in both visual stimuli (Kelly, 1984) and visual motion. The reason for this higher sensitivity is that ganglion cells in the peripheral retina are transient in nature, thus responding to temporal changes in stimulation (Paillard & Amblard, 1985). Furthermore, Paillard and Amblard (1985) also showed that stroboscopic illumination at either 6 or 3 Hz deteriorated postural stability. However, the spatial/temporal perturbation used in the present study did not affect postural control, neither with central or peripheral vision nor in general. It is likely that temporal changes of a visual pattern without any directional component (such as multiple directions) may not elicit different postural responses. This may be because information about the direction of motion of visual stimuli rather than the temporal change per se is crucial in controlling posture during quiet standing. To further examine this issue in future studies, the optic flow patterns, which involve a directional component (Andersen & Dyre, 1989; Bardy et al., 1999; Dijkstra et al., 1994a; Dijkstra, Schöner, Giese, & Gielen, 1994b; Habak et al., 2002), should be used as alternative visual stimuli in attempting to elicit different postural responses to a visual motion stimulus.

6. Conclusions

The present study suggests that peripheral rather than central vision plays an essential role in maintaining stable quiet standing. Because visual stimulation of the peripheral visual field was found to decrease postural sway in the direction of observing the visual stimulus to which head and gaze were oriented rather than in the direction of the trunk (i.e., the AP and ML), it seems reasonable to conclude that peripheral vision operates in a viewer-centered frame of reference characterized by the position of the head and gaze rather than in a body-centered frame of reference characterized by the anatomical planes of the body and may contribute to the control of posture in the direction of heading.

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