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RESEARCH NOTE

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Selection of spatial frame of reference and postural control variability

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Abstract The present paper addresses the question of the possible links between perceptive visual field dependence-independence and the visual contribution to postural control. In our differential approach, visual field dependent (FD) and independent (FI) subjects were selected on the basis of their score in the Rod and Frame Test (subjective vertical). The hypothesis that we have tested is that the FD subjects use mainly visual cues for estimating not only their subjective vertical but also their body orientation and stability. Moreover, we have postulated that these subjects use mainly dynamic visual cues to control their postural stability. In the postural test, the selected subjects were instructed to stand in the sharpened Romberg position in darkness and under normal or stroboscopic illumination, in front of either a vertical or a tilted frame. Lateral head and body orientation and stability were measured. We found that: (1) all subjects leaned slightly towards the tilted frame (postural frame effect), and this was obtained on the basis of the static visual cues alone; (2) FD subjects were less stable than FI subjects, and their stability required the use of dynamic visual cues, mainly extracted from the vertical frame. In FI subjects, static visual cues may act as a complementary regulation, enhancing stability even with a strobe tilted frame. We thus demonstrate that visual field dependence interacts with the visual contribution to postural control.

Introduction

Postural control involves multiple sensory inputs, in which there is some redundancy. Despite their specificity, spatial information encoded by visual, vestibular as well as proprioceptive inputs may be used with almost an equivalent efficiency to ensure equilibrium under natural unperturbed conditions (Amblard et al. 1990). Nevertheless, in healthy subjects, striking intra- and interindividual differences have been observed. These differences were evident at both the sensorimotor and the perceptual levels. Various authors have reported that some subjects used visual cues to improve their balance, while other did not (Crémieux and Mesure 1994; Collins and De Luca 1995). We have assumed here that these differences may be due to processes involved in spatial orientation and more specifically in those selecting and/or controlling the spatial frame of reference. The well-known interindividual differences described in the perception of verticality, and particularly in the perceived orientation of the body in space, could explain the postural variability.

Independence versus dependence with respect to visual field have been classically distinguished in spatial orientation tasks (subjective vertical) using the Rod and Frame Test (RFT). It has been hypothesised that field dependent (FD) subjects use mainly visual cues for estimating not only their subjective vertical but also their body orientation, whereas field independent (FI) subjects rely rather on gravitational or/and egocentric cues (Luyat et al. 1997). The present study has addressed precisely this question, since little attention has been paid to the possible links between subjective and postural vertical.

In the control of stance, orientational and stabilising functions have been usefully distinguished (Nashner and Cordo 1981). Concerning this distinction, a rule has been proposed by Amblard et al. (1985), namely that positional inputs could govern changes in position while dynamic inputs could govern stabilisation. In particular, a clear distinction between the respective contributions of static and dynamic visual cues has been put forward by these authors. They have suggested that static visual cues contribute primarily to the slow reorientation of the upper part of the body, whereas dynamic visual cues serve for rapid stabilisation of the whole body.

Given these multiple sources of variability, complex relationships should be expected between subjective and

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postural verticals on the one hand, and between field dependence-independence and postural stability on the other. In the present experiment, our first hypothesis was that the FD subjects would also be FD in the control of their direction of balance (Riccio et al. 1992) – namely, they could be influenced by the orientation of the visual frame, and lean themselves laterally towards a tilted one. This postural tilt, however, could either be limited to the head or extended to the whole-body. Conversely, the FI subjects would be more insensitive to the orientation of the visual field. The second aim of the present study was to analyse the subjects' ability to use static (under stroboscopic illumination) and/or dynamic visual cues in postural control, depending on their perceptual weighting. The FD subjects may be destabilised under stroboscopic illumination or in darkness, while the FI subjects may be more insensitive to visual modification or suppression.

Materials and methods

Subjects and experimental paradigm

With a view to selecting subjects on the basis of their dependence-independence with respect to visual field, we tested 97 healthy young men (mean age 23 years±3 years) by means of the RFT apparatus (Oltman 1968). In this classical test the subject has to adjust a small bar about the subjective vertical. This bar is placed in the centre of a square frame, which may be tilted to the right or to the left. In the tilted condition, the subjects may make an error towards the side to which the frame leans. In fact, clear and stable differences have been found among subjects' scores.

Each of our subjects was naive to the experimental hypotheses at the time of initial testing and gave informed consent prior to participation. All had normal or corrected-to-normal vision. In our perceptive test both rod and frame were initially tilted at 18°, where the frame effect has been found to be maximal (Zoccolotti et al. 1993). The frame effect, which reveals the errors in the vertical subjective due to the tilted frame, was calculated according to Nyborg and Isaken's method (1974).

Usually, the observed population is simply divided into FI (error below the median) and FD subjects (error above the median). However, in order to obtain two clear-cut groups of subjects we eliminated the intermediate population. Our subjects were then selected a priori among the initial population for the postural experiment, on the basis of their extreme scores: 8 FD and 10 FI subjects who had the highest and lowest errors in their subjective vertical, respectively. The corresponding mean errors in FD and FI groups were respectively 7.4° (SD 1.3°) and 1.7° (SD 0.8°). This selection of only 18.6% of the initial 97 subjects was aimed at obtaining reliable differences between the two groups in the postural test.

Subjects stood barefoot in a sharpened Romberg position (heel-to-toe) in front of a visual scene which was structured by a fluorescent square frame covering 50° of visual field. This frame, with its centre situated 0.7 m in front of the subject's eyes, was presented either vertically (V) or tilted (T) (18° to the left). It was illuminated by means of either an ultraviolet continuous bulb or a stroboscopic one. Stroboscopic vision (S) (about 2.8 flashes/s) was used to selectively suppress dynamic visual cues, and was compared with continuous vision (C). Darkness (D) was also used as a control condition.

Under the experimental conditions of a trial at an oral signal from the experimenter the subject released a manual support and was requested to remain in equilibrium for at least 24 s. During this period he would look straight ahead, with his arms relaxed along the trunk. The instructions were to stand upright keeping optimal balance. Moreover, subjects were subjected to darkness during the first 4 s of each trial by means of liquid-crystal spectacles (Translucent Technologies, Plato spectacle) which are computer controlled and go from opaque to clear in 2 ms (Milgram 1987). This shutter was then open during the last 20 s of the trial, except during the control trials in darkness. Trials where the subject lost his balance were repeated. For each experimental condition and subject, four successful trials were run for averaging. Each of the five experimental situations (D, CV, CT, SV and ST) was presented in a different random order for each subject.

Recording and data analysis

The kinematics of lateral body oscillations were measured by means of an automatic optical TV-image processor called the ELITE system (Ferrigno and Pedotti 1985). Three-dimensional kinematic measurements of four spherical retroflective markers (15 mm in diameter) were obtained by means of two video cameras, the optical axes of which formed a 40° angle. The markers were glued onto the skin on the subject's back and placed at the following sites: mastoid bone (1, 2), vertex of the head (3) and lateral malleolus of the left back foot (4). With this particular arrangement of the markers, we measured lateral rotations of the head (1, 2) and body (3, 4) around the antero-posterior axis, at a sampling frequency of 100 frames/s. Digital filtering for noise reduction was performed by means of a Finite Impulse Response filter (FIR) (D'Amico and Ferrigno 1990).

Both orientation relative to darkness and angular stabilisation of the head, as well as of the whole-body (including the head), were the dependent variables analysed, in order to estimate the subject's postural frame effect and postural stability, respectively. Given the difficulty of placing the markers at exactly the same site in each subject, the individual head and whole-body absolute orientations in each trial were corrected by subtracting from the whole signal its mean value over the first 4 s (corresponding to initial darkness) (Fig. 1A). This corrected signal was called the head (or whole-body) "orientation relative to darkness".

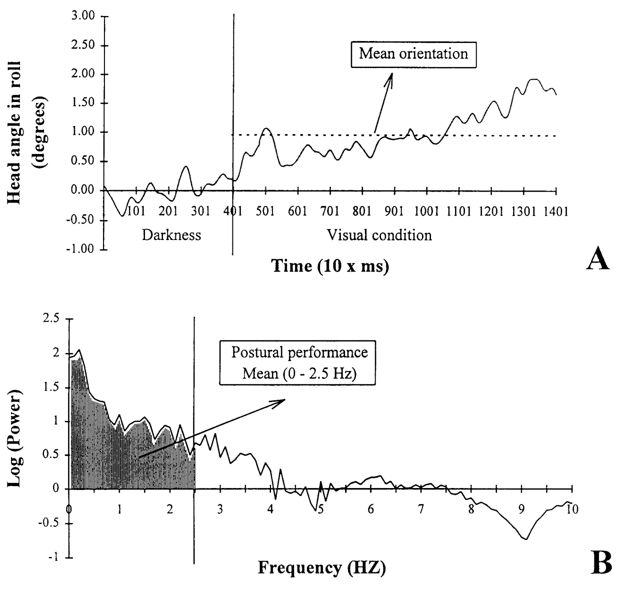

Fig. 1 Definition of the mean head (or whole-body) orientation about the roll axis (**A**) and the corresponding mean postural performance (**B**) in each trial and experimental condition. In each trial, each measured orientational signal (**A**) was corrected so as to have its mean value equal to zero in the first 4 s (corrsponding to initial darkness). The mean orientation considered during the postural trial was then the average from second 4 to second 14. This part of the signal was also subject to a fast Fourier transform (**B**). In each trial, the postural score was the average of the logarithm of the power spectrum between 0 and 2.5 Hz

For each successful trial, the mean orientation of the head (or whole-body) around the roll axis was taken as the average from second 4 to second 14 of the corresponding corrected measurements (orientation relative to darkness) (Fig. 1A). In a given experimental condition, the subject's head or whole-body orientation was then averaged over four trials. The head (or whole-body) orientation in darkness (from second 4 to second 14) was then subtracted from that of each visual condition (NV, NT, IV and IT), in order to obtain the head (or whole-body) orientation relative to darkness. In some cases there was a non-visual slight shift of the head or body orientation in darkness, after the first 4 s. The difference between the head (or whole-body) orientation relative to darkness in front of a vertical and a tilted visual frame was called the head (or whole-body) postural frame effect. The postural frame effect is thus the reorientation of the head (or whole body) induced by a visual tilted frame, by comparison with a vertical one. We have postulated that the FD subjects would lean laterally towards the tilted frame.

The head and body lateral rotation recordings (between seconds 4 and 14 of each trial) were also subjected to a spectral analysis. For each trial, the power spectrum of the component frequencies of the rotations was obtained by means of a standard fast Fourier transform program. The postural performance was calculated from the logarithm of the power spectrum between 0 and 2.5 Hz (0.01-Hz bins) (Fig. 1B). The overall measure of a subject's head (or whole-body) postural performance (or stability) was thus the average of this mean power from four trials in similar conditions (Amblard et al. 1985). A decrease in this averaged mean power expresses an increase in postural stability.

Both the orientation relative to darkness and angular stabilisation of the head, as well as of the whole-body, were subjected to an appropriate ANOVA in order to make comparisons between experimental situations and groups, which constituted the independent variables. The 0.05 level of significance (two-tailed test unless stated otherwise) was adopted throughout data analysis.

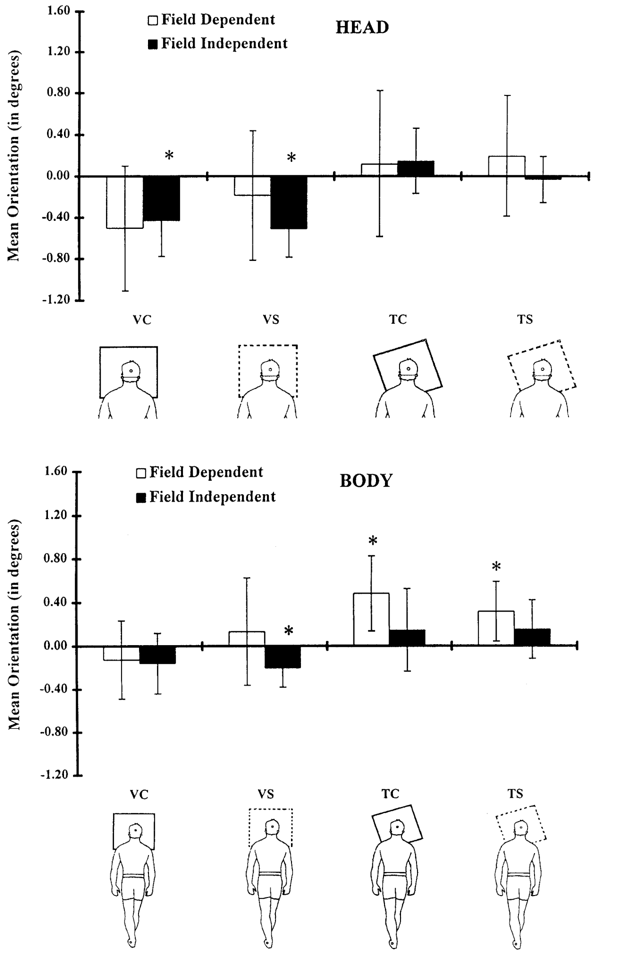

Fig. 2 Head and whole-body orientation aorund the roll axis relative to that observed in darkness, with respect to lighting condition (*S* strobe, *C* continuous light) and frame orientation (*V* vertical, *T* tilted). *Open bars* represent the field dependent (FD) subjects and *black bars* the field independent (FI) subjects. * Mean orientations significantly different from zero (a positive value means a counterclockwise tilt with respect to darkness; see the text)

Results

The *mean orientation* in roll of the head and whole-body relative to darkness with respect to lighting condition and frame orientation are shown in Fig. 2 for both groups. The vertical frame induced a clockwise change (negative value of the mean orientation with respect to darkness) of the head (t=–2.43 and t=–3.63 with continuous and stroboscopic vision respectively) and the whole-body (t=–2.30 with stroboscopic vision) orientation in the FI subjects only. Because of the measured variability, there were no such significant changes in orientation with respect to darkness in the FD subjects, although the mean values were similar in the two groups. This observed reorientation of the head and/or whole-body of FI subjects in front of the vertical frame with respect to darkness was presumably due to biomechanical constraints in the sharpened Romberg position (with the left foot behind). During our control condition in darkness, we have systematically observed a slight postural shift to the left. This initial lateral shift (during the first 4 s in darkness) was then visually corrected by the vertical frame. The tilted frame induced a counterclockwise change (positive value of the mean orientation with respect to darkness), namely a reorientation towards the frame, of the whole body orientation in the FD subjects only (t=2.71 and t=2.86 with continuous and stroboscopic vision, respectively). By contrast, the same tilted frame did not induce any significant change with respect to darkness in the FI subjects. However, there was no significant difference between the two groups.

According to the ANOVA, there was a *postural frame effect* for the head whatever the group and the lighting condition [F(1,16)=16.51] and with both continuous [F(1,16]=21.36] and stroboscopic vision [F(1,16)=5.18]. There was no difference between the two visual conditions. There was also a postural frame effect for the whole body in all groups and lighting conditions [F(1,16)=25.62], and with both continuous [F(1,16)= 10.59] and stroboscopic vision [F(1,16)=6.84]. Here again there was no difference between the two visual conditions, indicating that this postural frame effect did not depend crucially on dynamic visual cues either at the head or for the whole-body, for the whole population of subjects. Moreover, there was neither a difference between FD and FI subjects nor an interaction between the postural frame effect and the perceptual weighting, indi-

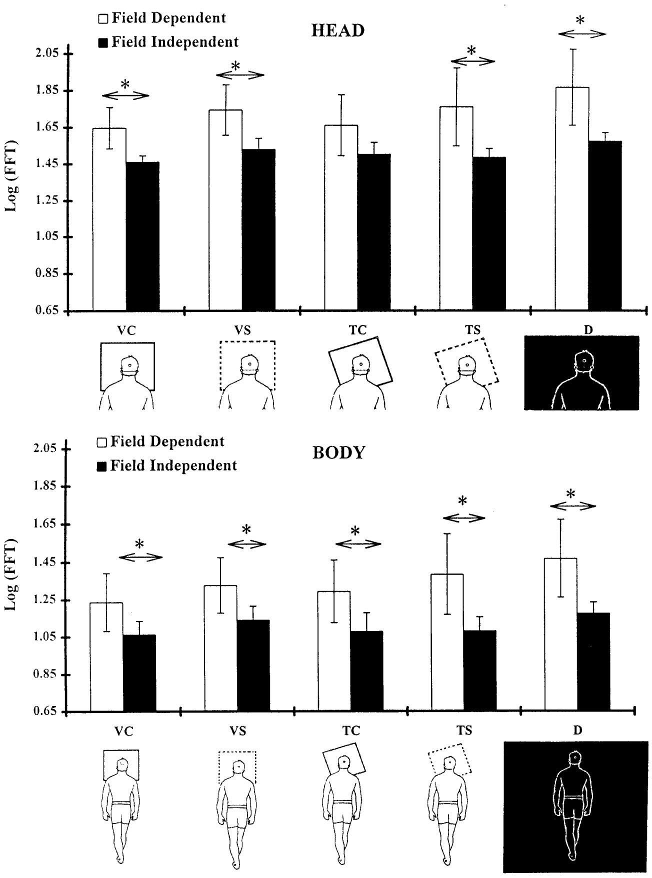

Fig. 3 Head and whole-body postural performances (mean log of the frequency power spectrum; see the text) around the roll axis, with respect to lighting condition and frame orientation (same symbols as in Fig. 1). A lower values means a higher stabiliy. * Significant difference between the two groups in a given experimental condition

cating that the postural frame effect was almost the same in both groups.

The *postural performance* in roll of the head and whole body with respect to lighting condition and frame orientation is shown in Fig. 3 for both groups. The first result to be noted is a global significant difference between the performances of the FD and FI subjects [F(1,16)=8.98], the latter group being more stable. This effect of the perceptual weighting was also significant at the head level [F(1,16)=8.92] as well as for the body [F(1,16)=8.50], whatever the frame and visual condition. FI subjects were also more stable than FD ones in each experimental condition (P<0.04 in all cases).

The contribution of *dynamic visual cues* may be revealed by comparing stroboscopic vision and continuous vision. There was a global significant difference between the performances in continuous and stroboscopic vision [F(1,16)=5.96], whatever the frame orientation, anatomical level and perceptual weighting. This difference was also significant at the head level [F(1,16)=8.05], with a trend for the whole-body [F(1,16)=3.50]. Since we have hypothesised that stroboscopic vision would globally increase the subjects' instability, it was possible to apply a one-tailed ANOVA analysis, so that this trend became a significant effect (with P<0.04). Concerning the ability to use dynamic visual cues for improving postural stability in the case of a given perceptual weighting, there was a significant difference between continuous and stroboscopic vision at the head level in the FD subjects only [F(1,7)=5.75]. The improvement in postural performance by means of dynamic visual cues, however, was dependent on the *frame orientation.* This improvement was significant at the head [F(1,16)=10.98] and for the whole-body [F(1,16)=5.56] in front of the vertical frame only, whatever the perceptual weighting. It was also significant at the head level in the FD subjects alone in front of a vertical frame (F(1,7)=9.07], with a trend for the whole-body in the same group [F(1,7)=4.62; one-tailed-test]. Moreover, there was a significant interaction between the visual condition (continuous or strobe) and the perceptual weighting, for the head and in the tilted frame condition [F(1,16)=3.81, significant with one-tailed test]. The use of the one-tailed test is justified by our hypothesis of a visual dependence for postural control in FD and not in FI subjects. This interaction suggests that FD subjects use also dynamic visual cues in front of the tilted frame. There was only a trend at the head level in the FI subjects alone in front of the vertidal frame [F(1,9)=3.69].

The contribution of *static visual cues* to postural performance may be attested by the comparison between darkness and stroboscopic vision within a given orientation of the visual frame. The difference between postural performances in darkness and under stroboscopic vision was significant in front of both the vertical [F(1,16)= 5.99] and the tilted frame [F(1,16)=13.14], whatever the perceptual weighting and the anatomical level. This was also true at the head level in the case of the vertical [F(1,16)=5.87], and the tilted frame [F(1,16)=12.13] and for the whole-body in front of a tilted frame [F(1,16)=8.65], with a trend for the vertical frame [F81,16)=4.26]. Concerning this ability to use static visual cues for improving stability, it was also dependent on the perceptual weighting. The difference between stroboscopic light and darkness was significant in the FI subjects at the head level [F(1,9)=23.29] and for the whole-body [F(1,9)=6.84] in front of the tilted frame. There was only a trend in the FD subjects at the head level [F(1,7)=4.48, P<0.07] and for the whole-body (F(1,7)=3.63, P<0.10] in front of the vertical frame.

There was no significant effect of frame orientation on postural performance, either globally or in any visual condition, anatomical level or perceptual weighting.

Discussion

In this study, our first hypothesis was the existence of a differential postural response to a tilted environment in the FD and FI subjects (Luyat et al. 1997). Although we have postulated a postural frame effect (orientation toward the tilted frame) in the FD subjects only, this effect has been shown to exist at the head level as well as for the whole-body in both groups of subjects. Moreover, since it is even observed under stroboscopic illumination, this postural frame effect involves static visual cues on orientation (Amblard et al. 1985). This postural frame effect was much lower than or similar to (within a degree) the error in the adjustment of the subjective vertical in the RFT (about 7.4° and 1.7° in FD and FI subjects, respectively). Nevertheless, real but complex links between perceptual weightings and sensory control of body orientation must be underlined. The FD subjects were influenced by a tilted visual frame at both the perceptual and postural levels, whereas the FI subjects displayed only a postural frame effect.

It could be argued that the sharpened Romberg position results in an exaggerated lateral body sway, which imposes obvious biomechanical limitations on the body orientation with respect to the vertical. In this posture, indeed, sustained lateral deviation of the body would inevitably result in a loss of equilibrium. This could be a reason why the postural frame effect was found to be smaller than the perceptual one in the FD subjects. However, we have also shown that this effect was small in the FI subjects, despite their greater stability (see below). Moreover, we have also used the normal Romberg position, as well as the monopodal position, in similar experimental conditions. The results were that the postural frame effects was even smaller and greater in the normal Romberg position and in the monopodal position, respectively, than in the sharpened Romberg position (unpublished results). In other words, the postural frame effect was found to increase with increasing postural instability, rather than the contrary. The sharpened Romberg position therefore does not exert opposite effects on the subjects' performances in orientation and stabilisation, presumably because of the very low amplitude of the postural frame effect.

The second result was that FD and FI subjects displayed very different efficiencies in their postural performance, at least in the sharpened Romberg task: FI subjects performed significantly better than FD subjects whatever the visual condition. Differences were so striking that even with normal vision and the vertical frame, FD subjects were not more stable than FI subjects in darkness. The visual field dependence-independence thus appears to be a good predictor of the subject's global ability to stabilise both the head and whole body efficiently. Similar but smaller differences between FD and FI subjects were previously found in women standing with the feet together, suggesting that these differences may be task- and/or sex-dependent (Kitamura and Matsunaga 1990).

Concerning the kind of sensory contribution brought into play to control balance, contrary to our second hypothesis the stability of the head and whole body depends on visual reafferents in both groups of subjects, although in a very different way. The differential use of visual orientational cues in perception and motor control does not fit with our initial assumption, according to which perceptive visual dependence could be predictive of an equivalent visual dependence for postural control (Luyat et al. 1997). Nevertheless, the unpredictable strong intergroup differences in postural performance prompt us to reanalyse the links between perception and posture. According to their postural performances in darkness, FI subjects are clearly able to stabilise their posture without vision. Their stabilisation accuracy is sufficient to slow down postural oscillations to such a level that static visual cues may act as a complementary regulation, enhancing stability even with a strobe tilted frame. This complementary role of vision in FI subjects, in whom postural regulation seems to be based mainly on gravity and proprioceptive information, shows that they did not experience the visual "capture" that FD subjects did. By contrast, the visual scene must provide the latter subjects with appropriate dynamic reafferences (from the vertical frame) in order to stabilise their posture by means of visual proprioception (Amblard et al. 1985). The tilted frame, indeed, seems to impair the use of dynamic visual cues by FD subjects in their stance regulation.

These results also confirm that head and whole-body orientation and their stabilisation may be controlled by different mechanisms, as previously suggested by Nashner and Cordo (1981). Moreover, we have shown in the present paper that there was a differential use of visual feedback in these mechanisms. Namely, body orientation would be mainly built up on the basis of static visual cues in every subject, whereas body stabilisation would rely mainly on different sensory feedback, depending on the subject's perceptual style.

We have thus demonstrated the existence of a complex interaction between visual field dependence and the visual contribution to postural control, which partly fits our basic differential hypothesis. Further analyses will be necessary to determine more precisely the differential role of visual cues in postural strategies such as segmental stabilisation strategies (Assaiante and Amblard 1993) or inter-segmental coordination (Amblard et al. 1994) adopted by the two groups of subjects. Moreover, visual field dependence will be also examined by means of a dynamic RFT in further studies, to try to dissociate static and dynamic visual dependence and their relationships with postural control.

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