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RESEARCH ARTICLE

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Differential approach to strategies of segmental stabilisation in postural control

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Abstract The present paper attempts to clarify the between-subjects variability exhibited in both segmental stabilisation strategies and their subordinated or associated sensory contribution. Previous data have emphasised close relationships between the interindividual variability in both the visual control of posture and the spatial visual perception. In this study, we focused on the possible relationships that might link perceptual visual field dependence–independence and the visual contribution to segmental stabilisation strategies. Visual field dependent (FD) and field independent (FI) subjects were selected on the basis of their extreme score in a static rod and frame test where an estimation of the subjective vertical was required. In the postural test, the subjects stood in the sharpened Romberg position in darkness or under normal or stroboscopic illumination, in front of either a vertical or a tilted frame. Strategies of segmental stabilisation of the head, shoulders and hip in the roll plane were analysed by means of their anchoring index (AI). Our hypothesis was that FD subjects might use mainly visual cues for calibrating not only their spatial perception but also their strategies of segmental stabilisation. In the case of visual cue disturbances, a greater visual dependency to the strategies of segmental stabilisation in FD subjects should be validated by observing more systematic "en bloc" functioning (i.e. negative AI) between two adjacent segments. The main results are the following:

1. Strategies of segmental stabilisation differed between both groups and differences were amplified with the deprivation of either total vision and/or static visual cues.
2. In the absence of total vision and/or static visual cues, FD subjects have shown an increased efficiency of the hip stabilisation in space strategy and an "en bloc" operation of the shoulder–hip unit (whole trunk). The last "en bloc" operation was extended to the whole head–trunk unit in darkness, associated with a hip stabilisation in space.
3. The FI subjects have adopted neither a strategy of segmental stabilisation in space nor on the underlying segment, whatever the body segment considered and the visual condition. Thus, in this group, head, shoulder and hip moved independently from each other during stance control, roughly without taking into account the visual condition.

The results, emphasising a differential weighting of sensory input involved in both perceptual and postural control, are discussed in terms of the differential choice and/or ability to select the adequate frame of reference common to both cognitive and motor spatial activities. We assumed that a motor-somesthetics "neglect" or a lack of mastering of these inputs/outputs rather than a mere visual dependence in FD subjects would generate these interindividual differences in both spatial perception and postural balance. This proprioceptive "neglect" is assumed to lead FD subjects to sensory reweighting, whereas proprioceptive dominance would lead FI subjects to a greater ability in selecting the adequate frame of reference in the case of intersensory disturbances. Finally, this study also provides evidence for a new interpretation of the visual field dependence–independence dimension in both spatial perception and postural control.

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Introduction

Postural regulation is a complex skill that raises the problem of the many degrees of freedom (*df*) to be controlled. Regulating postural equilibrium requires to coordinate and control rotational movements around hundreds of joints by means of several hundreds of muscles. The dynamics of postural balance, i.e. the variations of the kinematics and kinetic patterns of postural movements, would be informative of the direction of balance (DOB; Riccio et al. 1992) and of the time-to-contact to stability boundaries (van Wegen et al. 2002). These dynamics of postural balance would be redundantly specified through the many sensory systems (for the sensorial component of the DOB). The assembly of these many *df* into an adaptive and proficiency coordinative structure (Turvey 1990) should make it possible to reduce the immensity of implied dimensions. We claimed that achieving the compression of *df* could be linked to or constrained by the frame of reference "selected" by the subject. Depending on the selected frame of reference should emerge original modes of sensory weighting (Isableu et al. 1997) allowing or facilitating a stable control mode of intersegmental coordination and segmental stabilisation. Reciprocally, the optimised control of segmental coordination and stabilisation modes constrains the individual to adopt the more adapted reference frame (*RF*). Removing or decreasing the possibility for the subject to rely on its usual frame of reference (in daily low constraints tasks; see Ohlmann 2002) would conduct to postural disturbances. This paper addresses specifically the question of the interindividual variability as a key issue that should express a differential choice of the *RF* to postural control depending on perceptivo-motor preferences. More precisely, it was expected that manipulating the visual frame of reference (in direction and availability of visual cues) should organise the classic intersubject variability by assembling different subjects according to their (similar) sensibility to visual perturbations. The adopted segmental stabilisation and coordination strategies could be seen as a kind of preferred dialogue that the actor kept up with the task demands and the surrounding constraints. The structure of the interindividual variability should be revealed through strategies of segmental stabilisation adopted, which upstream were themselves structured by the frame of reference chosen.

During postural tasks, the orientation and stability of the head with respect to space may have to be maintained in order to serve as an egocentric reference value for maintaining balance (Berthoz and Pozzo 1988; Grossmann et al. 1988; Amblard et al. 1997). This is especially true with increasing equilibrium constraints (Assaiante and Amblard 1993). Minimising the head movements induced by body oscillations may thus improve the processing of the sensory feedback from the head (visual and/or vestibular) required for balance to be maintained. The head stabilisation in space strategy (HSSS), mainly observed under dynamic conditions, has been shown to be mainly of vestibular origin (Bronstein 1988; Pozzo et al. 1991; Assaiante and Amblard 1993). A visual contribution to HSSS, however, has been demonstrated in sitting adults during "white noise" chair rotation around the vertical axis (Guitton et al. 1986). It has also been observed in adult subjects during unpredictable tilts of the seated, restrained trunk from earth upright around the anterior or lateral axes (Gresty and Bronstein 1992; Kanaya et al. 1995), and in adults sitting on a seesaw inducing lateral destabilisation (Pérennou et al. 1997).

The present paper attempts to clarify the between-subjects variability exhibited in postural stability. Recent studies have demonstrated that interindividual differences in postural performances (body orientation and stabilisation) were strongly linked to the visual field dependence–independence (Isableu et al. 1997, 1998). These authors have shown that visual field dependent (FD) subjects were largely less stable and more dependent on the orientation of the visual field than visual field independent (FI) subjects were. Moreover, FD subjects were found to be more dependent than FI ones on dynamic visual cues to improve their postural stability. These results have put forward the close relationships between perceptive visual dependence as tested by an estimation of the subjective vertical on the one hand and on the other hand by the visual contribution to postural control. Similar variability in the use of visual cues in posture have been described by Lacour et al. (1997), who have reported that in a healthy population, almost half of the subjects significantly increased their body sway upon eye closure, whereas the other half exhibited no change or significantly swayed less without vision. Similar variability was also found by several other authors (Amblard and Crémieux 1976; Dichgans et al. 1976; Mauritz et al. 1977; Crémieux and Mesure 1994; Collins and De Luca 1995; Rougier and Caron 1997). These visual and non-visual styles seemed consistent over time in adult individual subjects. Interestingly, Lacour et al. (1997) have also mentioned that the same split was observed in a homogeneous population of unilateral vestibular-deficient patients (Ménière's disease patients).

Analyses conducted on strategies of segmental stabilisation could provide insight to understand how sensorimotor styles (non-disoriented–stable versus disoriented–unstable subjects) in postural regulation emerge and need to be addressed in relation with the question of the physical spatial frame of reference selected (visual versus non-visual) by subjects.

The visual sensitivity to the frame effect in estimating the subjective vertical is classically evaluated by means of the rod and frame test (RFT), when the size of the tilted frame is greater than about 15°. This visual sensitivity to the frame effect has been shown to be a good indicator of the use of either a visual or a non-visual frame of reference for spatial processing (Rock 1990; Zoccolotti et al. 1997). A corresponding visual dependence–independence has been found in postural control (Isableu et al. 1997). Taken together, these results are coherent with the idea that both perceptual orientation and postural control share some common processes (as the same *RF*) for calibrating spatial relationships (Paillard 1974, 1987, 1991; Ohlmann 1988; Berthoz 1991). In perceptual processing, moreover, it has been reported that an increase in the angular size of the display implies a corresponding increase in the visuo-vestibular interactions, themselves connected to postural activities (Spinelli et al. 1995). We may thus suggest that FD subjects could rely on a visual frame of reference both for perception and postural control, whereas FI subjects would rather rely on gravitoinertial frames of reference specified by vestibular information and/or motor–proprioceptive loops.

According to this fact, our *main hypothesis* was that FD subjects might use mainly visual cues for calibrating not only their spatial perception but also their strategies of segmental stabilisation. In particular, we have assumed that FD subjects might largely use vision to stabilise their heads in space and shoulder–hip unit. Conversely, FI subjects could either adopt HSSS of vestibular origin (no effect of vision) or even stabilise another segment, such as the pelvis, on the basis of proprioceptive cues.

Even when vision intervenes for controlling body balance, however, it is not systematically through HSSS. Stabilisation of the head with respect to gravity during movement has been mainly described, up to now, under dynamic conditions (Nashner et al. 1988), when subjects either sit on a seesaw (Pérennou et al. 1997), walk or move in place (Berthoz and Pozzo 1988; Grossmann et al. 1988; Amblard et al. 1997), or on compliant, unstable or unpredictable surfaces (Assaiante and Amblard 1993; Thomachot et al. 1995), or during hops (Grossmann et al. 1988; Assaiante et al. 1997). When standing on solid ground, even in the sharpened Romberg posture as in the present study, the head movements of small amplitudes and low frequencies can be well compensated for by vestibulo-ocular and cervico-ocular reflexes (Grossmann et al. 1989), which efficiently stabilise the gaze in space. In this case, an *alternative hypothesis* of the HSSS could be that subjects rather stabilise their trunk in space (Horak and MacPherson 1996). This could be done either by means of visual cues in FD subjects or on the basis of proprioception and/or vestibular cues in FI subjects, since adequate somatosensory information concerning the relationship between body and the gravity vertical are available from the supporting surface. It is also likely that visual disturbance or deprivations may have more effects on the trunk stabilisation in FD than FI subjects.

The aim of this study was to search for the factor contributing to the interindividual differences observed in the sensory inputs weighting for controlling both postural orientation and stabilisation. This article was aimed at examining the strategies of segmental stabilisation, which could be linked with or could traduce the way the physical frames of reference are selected and/or the sensory inputs are weighted. In other words, is it the preferential mode of SSS that constrains the weighting sensory inputs mechanism or are the functional sensory weighting habits that constrain the emerging of a preferential mode of SSS? For this purpose, we have analysed the strategies of segmental stabilisation and their associated sensory contribution.

Materials and methods

Subjects

With a view to selecting subjects on the basis of their dependence–independence with respect to static visual field, 97 healthy young men (mean age 23±3 years) have been subjected to the RFT apparatus (Oltman 1968). In this test, the observer has to estimate the subjective vertical by means of a little bar enclosed within a square frame, which may be either tilted to the right or to the left. In these conditions, an error in setting the rod to the subjective vertical generally occurs in the direction of the frame tilt. In fact, clear and stable differences have been found among subjects' scores and have led to establish the well-known dimension of "field dependence–independence" (Witkin and Asch 1948; Witkin and Wapner 1950; Asch and Witkin 1992). Thus, an observer standing on this dimension is indexed by the degree to which his settings of the rod correspond either to the gravitational axes of space (field independent) or to the geometrical visual vertical axes of the laterally tilted frame (field dependent).

Each of the tested 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 this 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 subjective vertical due to the tilted frame, was calculated according to Nyborg and Isaken's method (1974).

Usually, the observed population is simply divided into visual field independent (error below the median) or dependent subjects (error above the median). However, in order to obtain two clear-cut groups of subjects in a previous experiment (Isableu et al. 1997), we have eliminated the intermediate population. Our subjects were then selected a priori among the initial population, on the basis of their extreme scores: eight dependent (FD) and ten independent (FI) subjects with respect to static visual field, who had the highest and lowest errors in their subjective vertical, respectively. The remaining subjects were kept for the postural experiment provided that they presented no history of any known vestibular, ocular and otoneurological disorders. The corresponding mean errors in FD and FI groups were, respectively, 7.4° (SD 1.3°) and 1.7° (SD 0.8°).

Postural task

Subjects stood barefoot in a sharpened Romberg position (heel-to-toe) on solid ground in front of a visual scene, which was structured by a fluorescent square frame covering 50° of visual field (1×1 m, borders thick: 2 cm). This frame, with its centre situated at 0.7 m in front of the subject's eyes, was presented either vertically (V) or tilted (T; 18° to the left). The distance of 0.7 m for the frame from the subject's eyes was decided firstly because it has been shown that visual objects must be <2.5 m in order to stabilise stance (Bles et al. 1980; Paulus et al. 1984, 1989). The visual locking to the environment is easier when the scene is close to the subject (Dijkstra et al. 1992). Secondly, the visual pattern of the RFT was situated at 0.65 m in front of the subject's eyes, which makes both perceptual test and postural task comparable as regards visual processing. The frame 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 (Amblard and Crémieux 1976), and was

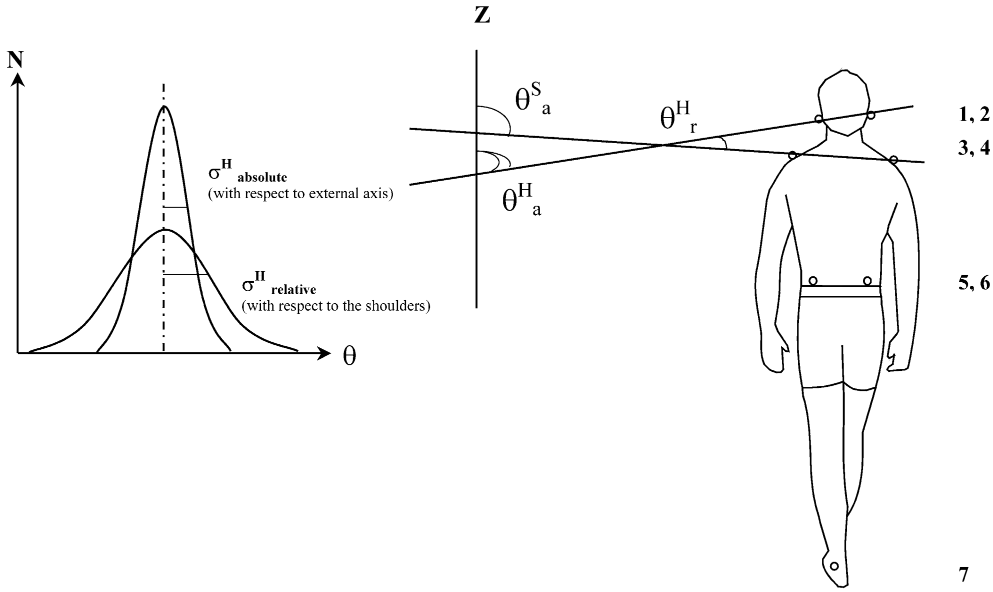

Fig. 1 *Right* Definition of *head roll* with respect to external axis ($\theta^{H}{}_{a}$) and with respect to shoulder axis ($\theta^{H}{}_{r}$) and of *shoulder roll* with respect to external axis ($\theta^{s}{}_{a}$). *Left* Ideal absolute (with respect to space) and relative (with respect to shoulder) distributions of the head roll with the corresponding standard deviations ($\sigma^{H}{}_{a}$) and ($\sigma^{H}{}_{r}$) from which were obtained the *anchoring index* (AI). *Numbers* indicate markers positions

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 14 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, observers 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 10 s of the trial, except during the control trials in darkness (14 s). 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, VC, VS, TC and TS) was presented in a different random order for each subject.

Data collection

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 kinematics measurements of seven spherical retroflective markers (15 mm in diameter) were obtained by means of two video cameras placed at 4 m from the subject frontal plane, 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 of the head (1, 2), acromion (3, 4), posterior iliac spine (5, 6) and lateral malleolus of the left back foot (7) (Fig. 1). With this particular arrangement of the markers, we measured lateral angular rotations of the head (1, 2), shoulder (3, 4), hip (5, 6) and leg (5–7) around the anterior–posterior axis (i.e. in the roll plane), at a sampling frequency of 100 Hz. Digital filtering for noise reduction was performed by means of a Finite Impulse Response filter (D'Amico and Ferrigno 1990). System accuracy was assessed to be 1/3,000 of the maximal dimension of the useful acquisition volume. This meant an error of less than 2 mm on the marker two-dimensional position.

Data analysis

The *anchoring index* (AI; Assaiante and Amblard 1993; Amblard et al. 1997) of any body segment measured (head, shoulder and hip) was taken into account to evaluate the subject's strategies of segmental stabilisation in any given experimental condition. This normalised AI was used to compare the stabilisation of a given segment with respect both to external space and to underlying anatomical segment (Assaiante and Amblard 1993; Amblard et al. 1997; Pérennou et al. 1997). With regard to the head AI for example, the angular orientation (around the roll axis) of the head relative to the shoulder was first calculated each 10 ms during a trial using the formula:

$$\theta_{r}^{H} = \theta_{a}^{H} - \theta_{a}^{S} \qquad (1)$$

In this formula, $\theta^{H}{}_{r}$ is the angular orientation of the head relative to the shoulder, and $\theta^{H}{}_{a}$ and $\theta^{S}{}_{a}$ are the absolute head and shoulder angular orientations, respectively. At a given trial, the standard deviation of the relative angular distribution σ ($\theta^{H}{}_{r}$) was then calculated. The normalised AI of the head was then calculated by means of the simple formula:

$$\mathrm{AI(H)} = \left[\sigma^{2}\left(\theta_{r}^{H}\right) - \sigma^{2}\left(\theta_{a}^{H}\right)\right] / \left[\sigma^{2}\left(\theta_{r}^{H}\right) - \sigma^{2}\left(\theta_{a}^{H}\right)\right] \qquad (2)$$

Similarly, the shoulder AI was calculated by comparing angular orientations of the shoulder and hip, and the hip AI by comparing angular orientations of the hip and left leg (see Fig. 1). The AI is thus a description of the degree of dependency between two consecutive segmental movements. Values of AI may vary between −1 and +1. For any given experimental condition, a positive value of AI for a given segment would indicate a better stabilisation in space than on the inferior supporting segment, whereas a negative value would indicate a better stabilisation on the inferior segment than in space.

Normalised *cross-correlation functions* (CCFs) were also calculated between head and shoulder, shoulder and hip and between hip and left leg angular movements about the roll axis (Amblard et al. 1994; Lekhel et al. 1994). This is usually done to evaluate quantitatively the *time lag* (abscissa of the CCF peak) between the co-ordinated movements of each pair of segments and the *coefficients of correlation* at the abscissa zero, to validate the AI calculations (Assaiante and Amblard 1993). Averages of the CCFs from three to four trials in similar conditions were calculated in each subject.

Statistics

The design included three factors with two levels: one between-subject factor, field dependence–independence (FD versus FI) and two within-subject factors. The first within-subject factor was the type of vision, either continuous or strobe. The second was the orientation of the frame, either vertical or tilted. Three anatomical levels were considered: head, shoulder and hip.

The AIs were subjected to Z transform before conducting statistical analyses. The AIs of the hip, shoulder and head were tested for significance using a one-sample analysis (*t*-test) against the null hypothesis. This was done in order to identify the intersegmental strategies (Assaiante and Amblard 1993; Amblard et al. 1997). The AIs 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 was adopted throughout data analysis and the *P* value that we actually obtained was indicated.

In order to test the significance of the coefficient of correlation (also subjected to Z transform) at the abscissa zero in each experimental condition and group of subjects, the corresponding values of the averaged individual CCFs were used for Student's *t*-test across subjects (Amblard et al. 1994). A significance level of 0.05 was imposed, which is indicated in Table 4. Given the low size of the sample, *b* risk (acceptance of H_o while it is false) is increased. Consequently, statistical trends ($0.05<P\leq 0.10$) are completed with effect size (Cohen 1977, 1992; Chow 1988; Corroyer and Rouanet 1994). In the case of within-subject differences (correlated *t*), the benchmark values for effect size (d statistic) are: $D\leq 0.20$: weak effect; $0.20<D\leq 0.50$: moderate effect; $0.50<D\leq 1.00$: important effect. In the case of between-subject differences, the f^2 statistic is used, and the benchmark values for this effect size are: $0.06\geq f^2>0.01$: weak effect; $0.20\geq f^2>0.06$: moderate effect; $f^2\geq 0.20$: important effect.

Results

Anchoring indexes

The averaged head, shoulder and hip AIs about the roll axis, in each group of subjects, are shown in Fig. 2, as a function of the experimental conditions.

Before analysing each anatomical level independently, data were subjected to a three-way ANOVA with fixed effects combining FDI (FD versus FI) × anatomical levels (head, shoulder and hip) × visual conditions (VC, IC, VS, IS and D). Results revealed significant main effects of perceptual styles [$F(1,16)=6.39$; $P<0.02$] and anatomical levels [$F(2,32)=3.57$; $P<0.04$]. Two-order interactions also appeared significant between FDI and anatomical levels [$F(2,32)=3.53$; $P<0.04$] and between anatomical levels and visual conditions [$F(8,128)=3.94$; $P<0.0003$]. The three-way FDI × anatomical level × visual conditions was also significant [$F(8,128)=2.40$; $P<0.02$].

These results indicated firstly, concerning the main effect of perceptual style, that globally the strategies of segmental stabilisation adopted in FD subjects throughout anatomical levels evolved rather towards an "en bloc" functioning between two adjacent segments considered. Secondly, the strategies of segmental stabilisation significantly evolved throughout anatomical levels (i.e. head–trunk and shoulder–hip stiffening and hip stabilised in space) but significantly differed according to perceptual styles. Thirdly, visual disturbances (frame tilt and selective suppression of visual cues) affected strategies of segmental stabilisation depending on the subject's perceptual style.

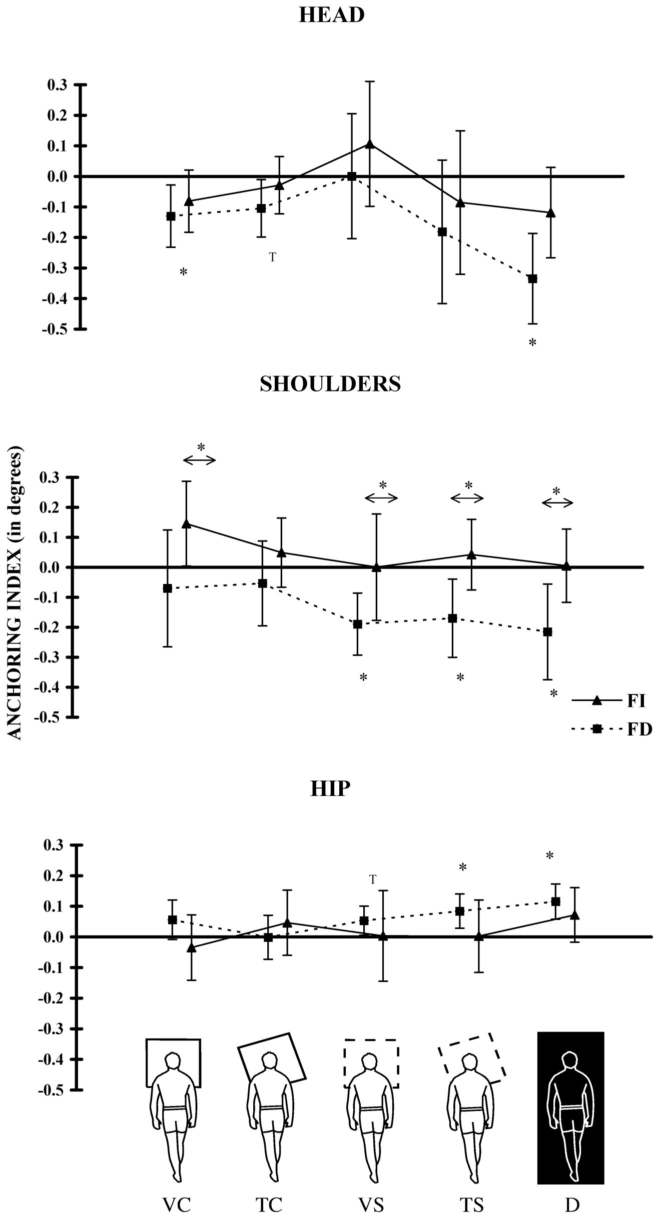

Fig. 2 Averaged *head*, *shoulder* and *hip* AI about the roll axis in each group of subjects for each experimental condition [vertical continuous vision (VC), tilted continuous vision (TC), vertical stroboscopic vision (VS), tilted stroboscopic vision (TS) and darkness (D); see *bottom of figure*]. Standard errors indicate between-subjects variability in each group. A positive AI indicates a stabilisation in space of the considered segment, whereas a negative AI indicates its stabilisation on the underlying segment ("en bloc" operation). *FD* Field dependent, *FI* field independent, *asterisk* AI significantly different from zero. *Asterisk placed on the top of a horizontal arrow* points out significant differences between groups

Head AI

The hypothesis of a greater visual dependency of the strategy of head stabilisation in FD subjects should be validated by observing more systematic "en bloc" head–trunk functioning (i.e. negative AI), especially in the case

Table 1 *t*-test of the averaged values of head anchoring index (AI) in each group and experimental condition. The confidence level adopted was 0.05. A positive AI indicates a better head stabilisation in space whereas a negative AI indicates a stabilisation of the head on shoulders. (*FD* Field dependent, *FI* field independent, *VC* vertical continuous vision, *VS* vertical stroboscopic vision, *TC* tilted continuous vision, *TS* tilted stroboscopic vision, *D* darkness, *NS* not significant, *T* trend)

Head	VC	VS	TC	TS	D
FD					
Mean AI	−0.304	0.061	−0.222	−0.181	−0.499
t df (7)	*t*=−2.536	*t*=−0.667	*t*=−1.749	*t*=−1.431	*t*=−6.295
	P<0.02	NS	*P*<0.06 T	NS	*P*<0.0002
FI					
Mean AI	0.153	0.02	0.121	−0.072	−0.038
t df (9)	*t*=1.141	*t*=0.239	*t*=1.353	*t*=−0.686	*t*=−0.284
	NS	NS	NS	NS	NS

Table 2 *t*-test of the averaged values of shoulder AI in each group and experimental condition. The confidence level adopted was 0.05. A positive AI indicates a better shoulder stabilisation in space whereas a negative AI indicates a stabilisation of the shoulder on hip

Shoulder	VC	VS	TC	TS	D
FD					
Mean AI	−0.091	−0.023	−0.218	−0.158	−0.240
t df (7)	*t*=−0.789	*t*=−0.330	*t*=−3.397	*t*=−2.304	*t*=−2.507
	NS	NS	*P*<0.057 T	*P*<0.03	*P*<0.02
FI					
Mean AI	−0.052	0.031	0.079	0.054	0.051
t df(9)	*t*=0.376	*t*=0.472	*t*=0.836	*t*=0.929	*t*=0.841
	NS	NS	NS	NS	NS

of visual cue disturbances (frame lean, total or selective suppression of visual cues). Thus, data were subjected to left unilateral *t*-test/0. The results showed that the head was indeed preferentially stabilised on the shoulder rather than on space in FD subjects only (Fig. 2 *upper panel*). The FD's *head AI* was significantly negative in VC and in D with a trend in the TC condition ($P<0.06$). There was no preferred stabilisation strategy of the head in the FI subjects in any experimental situation. The corresponding Student's *t*-test analysis is given in Table 1.

A two-way ANOVA with fixed effects [two FDI × five experimental conditions (VC, VS, TC, TS, D)] showed a significant main effect of experimental conditions [$F(4,64)=3.47$; $P<0.02$] and a significant (FDI × experimental conditions) two-way interaction [$F(4,64)=3.00$; $P<0.025$]. Taken together, these results showed firstly that visual manipulations led to a head on trunk stiffening. Secondly, they confirmed that visual disturbances generate significant differences between both groups in the adopted head stabilisation mode.

Further analyses were undertaken to analyse the respective contribution of complete vision, dynamic visual cues and static visual cues to head stabilisation strategies.

Complete vision tended to reduce the "en bloc" operation of the head–shoulder unit. Comparing darkness and continuous vision within a given orientation of the visual frame reveals this effect of vision. A two-way ANOVA [FDI × vision (continuous versus darkness)] with fixed effect showed that in the whole population, this main effect of complete vision was significant [$F(2,32)=4.09$; $P<0.03$] in the vertical frame condition (Tukey HSD; $P<0.04$) and was close to significance in the tilted frame condition (Tukey HSD; $P<0.056$). The suppression of vision also significantly interacted with perceptual style [$F(2,32)=4.84$; $P<0.01$] and mainly disturbed FD subjects. Indeed, the complete suppression of vision significantly increased the head–shoulder "en bloc" functioning in the FD subjects as compared to FI subjects (Tukey HSD; $P<0.01$).

A three-way ANOVA [FDI (FD versus FI) × vision (continuous versus strobe) × frame orientation (vertical versus tilted)] showed that the contribution of *dynamic visual cues* to the strategies of head stabilisation was non-significant and did not vary according to perceptual styles and frame orientation (vertical or tilted).

By contrast with what happened with dynamic visual cues, the availability of *static visual cues* allowed at reducing the "en bloc" operation of the head–shoulders unit. A two-way ANOVA [FDI × vision (strobe versus darkness)] in each condition of frame orientation showed a significant main effect of the contribution of static visual cues [$F(2,32)=5.11$; $P<0.01$] mainly significant in front of the vertical frame (Tukey HSD; $P<0.01$) in the whole population. The contribution of static visual cues significantly interacted with perceptual styles [$F(2,32)=3.71$; $P<0.03$] and was only significant in the FD subjects either when the frame was vertical (Tukey HSD; $P<0.001$) or tilted (Tukey HSD; $P<0.01$). Thus, the reliance to static visual cues to head stabilisation strategies in FD subjects is demonstrated.

Shoulder AI

The hypothesis of a greater visual dependency of the strategies of shoulder stabilisation in FD subjects should be validated by observing more systematic "en bloc" shoulder–hip functioning (i.e. negative AI), in the case of visual cue disturbances. Thus, data were also subjected to left unilateral *t*-test/0. In the FD subjects only, the shoulder was preferentially stabilised on the hip, demonstrating that the "en bloc" operation previously observed at the head level also extends to the whole trunk (Fig. 2 *middle panel*). This was true in VS, TS (i.e. when dynamic visual cues were suppressed) and D experimental conditions, where the *shoulder AI* was significantly negative. There was no preferred stabilisation strategy of the shoulder in the FI subjects in any experimental situation. The corresponding Student's *t*-test analysis is given in Table 2.

A two-way ANOVA with fixed effects including darkness [two FDI × five experimental conditions (VC, VS, TC, TS, D)] showed significant main effects of perceptual styles [$F(1,16)=8.49$; $P<0.01$] and experimental conditions [$F(4,64)=2.74$; $P<0.036$]. A one-way ANOVA, testing the perceptual styles factor (FD versus FI) in each experimental condition, pointed out that the shoulder stabilisation on trunk observed in FD subjects differed remarkably to that exhibited in FI subjects in VC [$F(1,16)=5.59$; $P<0.031$], VS [$F(1,16)=6.02$; $P<0.03$], TS [$F(1,16)=5.65$; $P<0.03$] and D conditions [$F(1,16)=7.13$; $P<0.02$].

Complementary analyses were undertaken to assess the respective contribution of complete vision, dynamic visual cues and static visual cues to shoulder stabilisation strategies.

A two-way ANOVA [FDI × vision (continuous versus darkness)] in each frame condition revealed a significant main effect of *complete vision* [$F(2,32)=3.38$; $P<0.04$] in front of the vertical frame (Tukey HSD; $P<0.04$) in the whole population. The contribution of *complete vision* allowed subjects at reducing the "en bloc" operation of the shoulder–hip unit (Fig. 2 *middle panel*, the two first columns as compared to the three last columns), as was the case for the head–shoulder unit. The main effect of perceptual style was also significant [$F(1,16)=8.24$; $P<0.01$] but did not interact with complete suppression of vision in any frame orientation condition.

A three-way ANOVA with fixed effects [two FDI × two frames × two visions (continuous versus strobe)] revealed significant main effects of contribution of *dynamic visual cues* [$F(1,16)=8{,}50$; $P<0.01$] and *perceptual styles* [$F(1,16)=8{,}03$; $P<0.01$]. The previous effect of complete vision at the shoulder–hip level was mainly due to the contribution of *dynamic visual cues*. The suppression of dynamic vision induced a decrease of the AI towards the negative values in front of the vertical frame [$F(1,16)=5.93$; $P<0.03$]. The contribution of *dynamic visual cues* was significant in FD subjects mainly in front of the vertical frame [$F(1,7)=6.46$; $P<0.04$]. Given the values of their shoulder AI, this indicates that in the absence of dynamic visual cues, FD subjects adopted an "en bloc" operation of the whole trunk.

The contribution of *static visual cues* to the shoulder stabilisation mode did not reached the significant level in any group of subjects.

Hip AI

The hip was preferentially stabilised in space than on the legs in the FD subjects only (Fig. 2 *lower panel*). The *hip AI* revealing this was significantly positive in TS and D with a trend in VS, i.e. in the most difficult visual conditions. The corresponding (bilateral) Student's t-test analyses are given in Table 3.

Nevertheless, there was neither significant main effect of the *perceptual styles* nor main effect of experimental conditions at the hip level.

The presence of *complete vision* suppressed the hip stabilisation in space observed in darkness. A two-way ANOVA [FDI × vision (continuous versus darkness)] in each condition of frame orientation revealed a significant main effect of *complete vision* in front of the vertical frame [$F(1,16)=5.33$; $P<0.04$] and in front of the tilted frame [$F(1,16)=9.22$; $P<0.01$]. The FDI factor significantly interacted with the suppression of complete vision in the tilted frame condition [$F(1,16)=5.84$; $P<0.03$]. The effect of vision was significant in the FD subjects alone, in front of the vertical frame [$F(1,7)=11.68$; $P<0.011$] and the tilted frame [$F(1,7)=8.12$; $P<0.03$]. This indicates that the suppression of vision disturbs mainly FD subjects, and led them to adopt a hip stabilisation in space.

A three-way ANOVA with fixed effects [FDI × frame (vertical versus tilted) × vision (continuous versus strobe)] showed that the contribution of *dynamic visual cues* on hip stabilisation strategies was neither significant nor interacting with frame orientation and perceptual styles.

Analyses conducted on the contribution of *static visual cues* on hip stabilisation strategies showed that they intervened [$F(2,32)=3.17$; $P<0.055$] in decreasing the hip stabilisation on space observed in darkness, and mainly in front of the vertical frame [$F(1.16)=5.22$; $P<0.04$]. However, their contribution to hip stabilisation strategies did not interact with the perceptual style factor.

Table 3 t-test of the averaged values of hip AI in each group of subjects and experimental condition. The confidence level adopted was 0.05. A positive AI indicates a better hip stabilisation in space whereas a negative AI indicates a stabilisation of the hip on leg

Hip	VC	VS	TC	TS	D
FD					
Mean AI	0.040	0.052	0.091	0.091	0.088
t df (7)	t=0.516	t=2.27	t=1.31	t=2.70	t=2.51
	NS	P<0.057 T	NS	P<0.03	P<0.04
FI					
Mean AI	−0.011	−0.016	0.125	−0.007	0.058
t df (9)	t=−0.1	t=−0.197	t=1.16	t=−0.12	t=1.22
	NS	NS	NS	NS	NS

Correlation analyses between the modes of segmental stabilisation and FDI scores

These additional statistics showed that the "en bloc" functioning of the head significantly increased with increasing field dependence scores in darkness ($r=-0.52$, $P=0.03$; see Fig. 3). Moreover this correlation contains an implication: to be FD is a necessary and sufficient condition to always exhibit an "en bloc" functioning. In other words, in these conditions, an FD dependent observer never shows a space stabilisation. These results also extended to the trunk (attested by the negative shoulder AI). The "en bloc" functioning of the shoulder–hip unit significantly increased with increasing field dependence scores in almost all of the experimental conditions (VC: $r=0.53$, $P=0.03$; VS: $r=0.64$, $P=0.005$; TS: $r=0.66$, $P=0.005$; D: $r=0.79$, $P=0.000$; see Fig. 4)

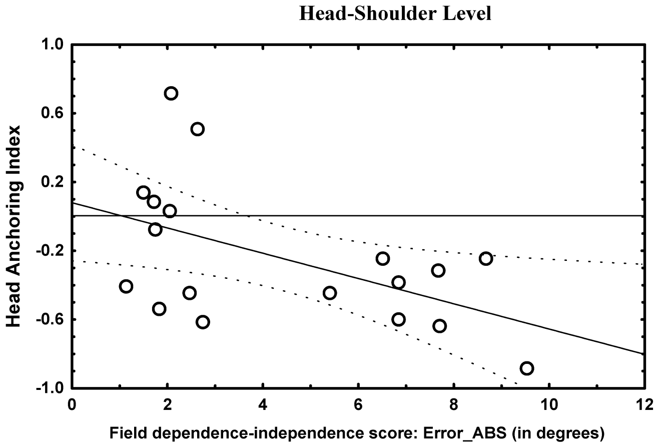

Fig. 3 Example of correlation between field dependence–independence (*FDI*) score and the corresponding AI of the head in darkness. Each point represents the averaged values for a subject in the given experimental condition. A positive AI value (above the *horizontal line*) indicates an articulated mode of functioning of the head (i.e. stabilised on space). A negative AI value (below the *horizontal line*) indicates an "en bloc" head–trunk operation

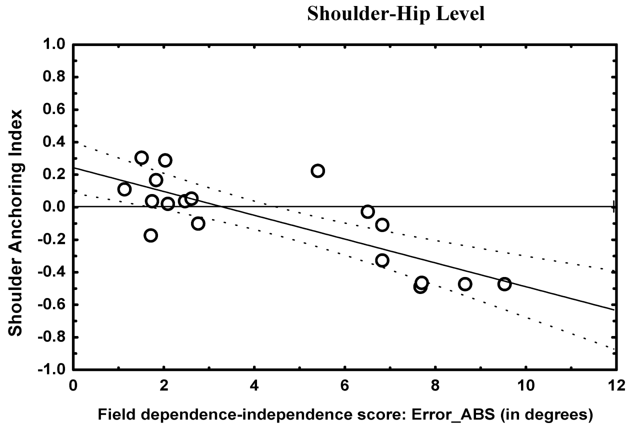

Fig. 4 Example of correlation between FDI score and the corresponding AI of the shoulder in darkness. Each point represents the averaged values for a subject in the given experimental condition. A positive AI value (above the *horizontal line*) indicates an articulated mode of functioning of the shoulder (i.e. stabilised on space). A negative AI value (below the *horizontal line*) indicates an "en bloc" head–trunk operation

except in TC (n.s.). In the darkness condition, increasing *field dependence* scores are tied to high values of shoulder on hip stabilisation (i.e. trunk stiffening). Conversely, increasing *field independence* scores are tied to high values of shoulder on space stabilisation (trunk articulated functioning). These significant relationships between field dependence and the strategies of segmental stabilisation confirm and reinforce our previous ANOVA. They show clearly that: (1) the subjects' perceptual styles allow to discriminate differential sensory-motor behaviours, relying on different frames of reference, and (2) the correspondent postural strategies co-varied with the gradient of the subjects' perceptual score.

The main results to emerge from this analysis of segmental stabilisation modes were thus that both groups displayed different strategies. The FD subjects have adopted a strategy consisting of stabilising hip in space with an "en bloc" operation of the head–trunk unit, whereas in FI subjects, hip, shoulder and head moved independently from each other. As a main consequence of their chosen segmental stabilisation modes, FD subjects were less stable at any anatomical level considered than FI ones (Isableu et al. 1998).

Table 4 *t*-test and probability of the averaged coefficients of correlation at the null abscissa for the head–shoulder, shoulder–hip and hip–leg couples of measurements in each group of subjects and experimental condition. The confidence level adopted was 0.05

	FD subjects		FI subjects	
	t value	*P*	*t* value	*P*
Head–shoulder				
VC	7.75	0.00020	6.05	0.00027
VS	8.32	0.00014	9.89	0.00001
TC	11.56	0.00002	7.35	0.00008
TS	9.95	0.00006	7.39	0.00004
D	9.77	0.00007	7.02	0.00010
Shoulder–hip				
VC	3.24	0.01513	5.68	0.00040
VS	5.48	0.00109	4.30	0.00277
TC	6.58	0.00045	5.24	0.00065
TS	3.54	0.01079	5.21	0.00049
D	4.56	0.00362	4.93	0.00092
Hip–leg				
VC	1.06	NS	4.80	0.00107
VS	2.12	NS	3.01	0.01538
TC	3.09	0.01798	3.39	0.00919
TS	0.49	0.00000	3.59	0.00602
D	–0.35	0.00000	2.23	NS

Time and space relationships between segmental co-ordinated movements

Averaged cross-correlation functions between pairs of anatomical levels considered (head–shoulder, shoulder–hip and hip–leg) are shown in Fig. 5, as a function of experimental condition and group. It can be seen in this figure that CCF peaks, when they exist, are always positive, indicating co-ordinated angular movements in the same direction. Moreover, they all roughly corresponded to synchronism between pairs of co-ordinated movements, since the positive peaks were roughly situated at the null abscissa. We will therefore consider only the coefficients of correlation at the null abscissa, which are given in Table 4. They allow us firstly to confirm the validity of the AIs (none of them correspond to significantly negative correlation between pairs of segments at zero time lag; Assaiante and Amblard 1993). Secondly, we were able to compare coefficients of correlation in both groups by means of two-way ANOVAs with fixed effects [FDI x five experimental

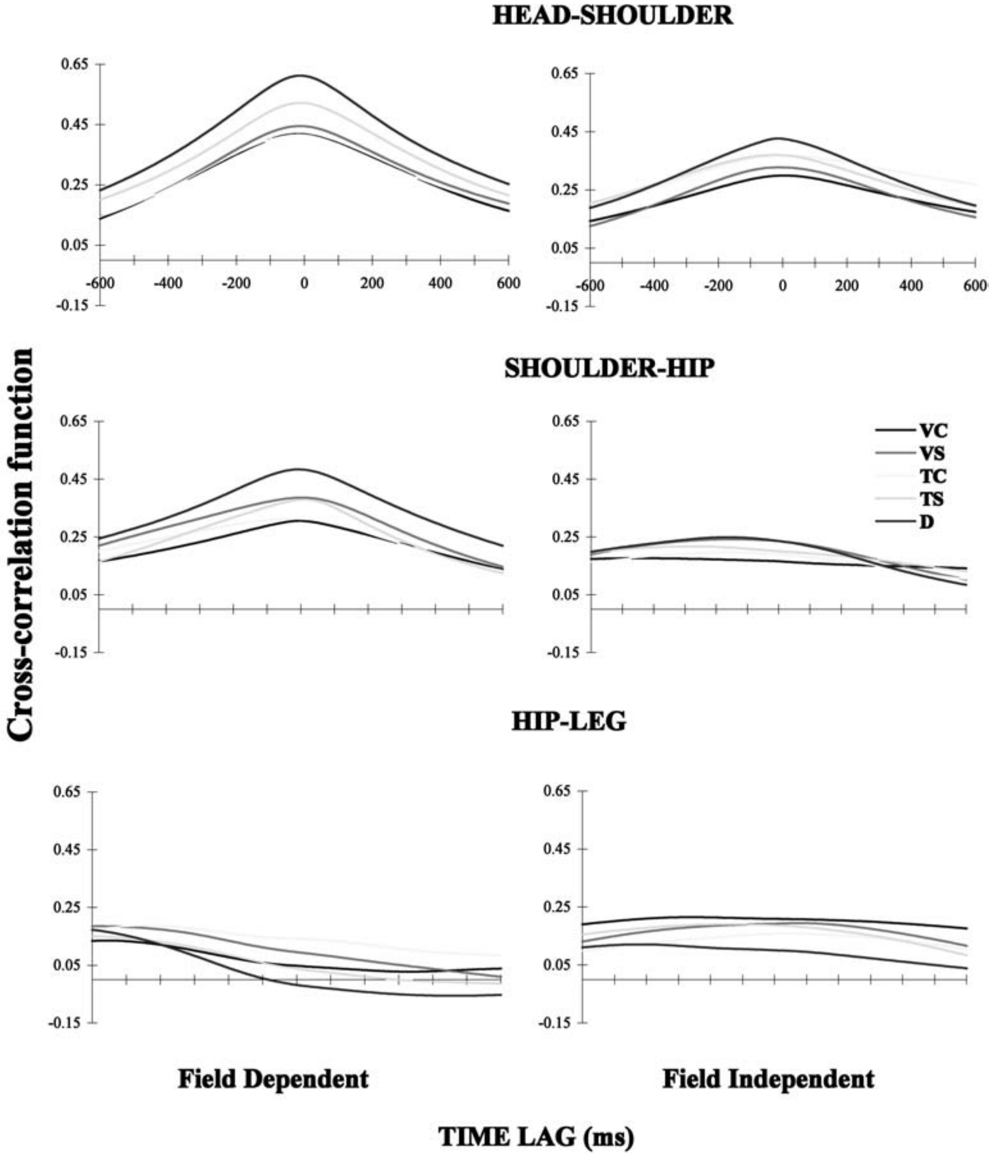

Fig. 5 Examples of cross-correlation functions between head and shoulder, shoulder and hip and hip and leg angular oscillations around the roll axis, as a function of group of subjects and experimental condition. Each curve is the averaged value over the subjects of the corresponding group. It can be seen that there are only positive peaks, when they do exist, roughly centred at zero abscissa, indicating co-ordinated movements in the same direction of the considered segments with a good synchronism

conditions (VC, VS, TC, TS and D)]. This last analysis has completed our previous findings concerning the modes of segmental stabilisation adopted in each group.

The "en bloc" operation of the head–trunk unit observed by means of the AIs in the FD subjects (see above) was confirmed by their head, shoulder and hip significantly co-ordinated movements. If we take into account all experimental situations, including darkness, two-way ANOVA analyses showed that the main effect of perceptual styles was significant for the head–shoulder [$F(1,16)=8.51$; $P<0.01$] and the shoulder–hip coefficients of correlation [$F(1,16)=6.32$; $P<0.02$]. The coefficients of correlation between head and shoulder on the one hand, and on the other hand between shoulder and hip angular movements were thus higher in FD than in FI subjects, confirming that the first adopted an "en bloc" operation of the head–trunk unit, whereas FI subjects did not. Moreover, the hip stabilisation in space demonstrated in the FD subjects by their hip AI was confirmed by their hip–leg correlations. The coefficients of correlation between hip and leg tended to be higher in FI than FD subjects [$F(1,16)=3.50$; $P<0.08$; $f^2=0.21$].

Discussion

In the present study, we have assumed that the perceptual visual field dependence–independence might be upstream a predictor of the *RF* used and downstream of the appropriate strategy of segmental stabilisation adopted. Experimental conditions were expected to force subjects to rely on their usual *RF* and a difficult balancing posture was thus chosen, the sharpened Romberg. In those conditions, we have assumed that FD subjects would adopt an HSSS of visual origin, and also predicted a regression of the strategies of segmental stabilisation toward a more "en bloc" functioning between two adjacent segments in the case of visual disturbances

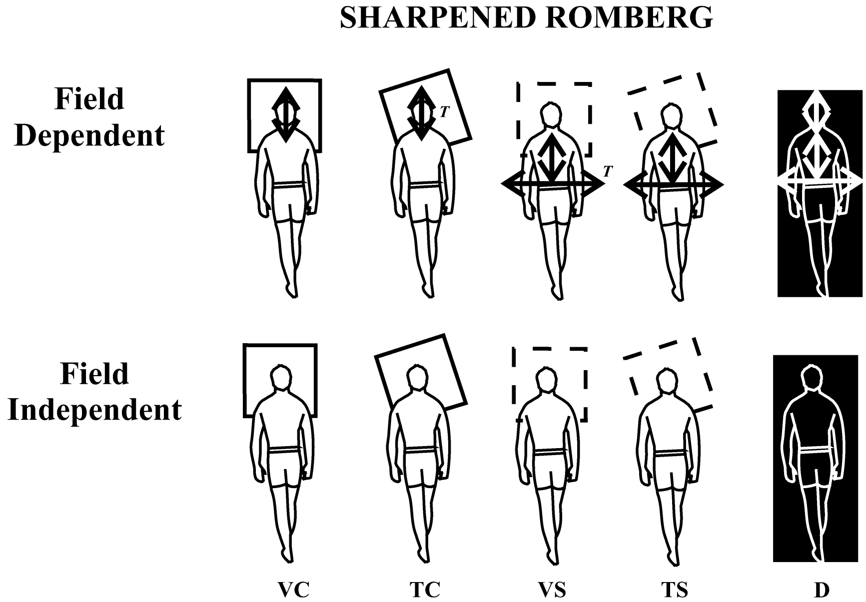

Fig. 6 Schematic representation of the strategies of segmental stabilisation in both groups of subjects as a function of experimental condition. The three segments considered are the head, the shoulder and the hip. *Vertical arrows* at the head level indicate an "en bloc" operation of the head–shoulder unit. *Vertical arrows* at the trunk level indicate an "en bloc" operation of the shoulder–hip unit. *Horizontal arrows* indicate hip stabilisation in space of the hip only

(frame tilted and total or selective suppression of visual cues). By contrast, FI subjects have been suspected to rely mainly on non-visual references for strategies of segmental stabilisation. Our results, showed that FD subjects never adopted a preferred HSSS of visual origin, but rather adopted an "en bloc" operation of the head–shoulder unit likely of visual origin. This intersegmental functioning also extended to the whole trunk (i.e. shoulder–hip stiffening) and was subjected to the same regression towards increasing intersegmental stiffening due to visual disturbances. On the other hand, FI subjects were almost independent of visual cues, and have adopted on average neither HSSS nor head stabilisation on the trunk strategy. However, correlation analyses have showed that HSSS was significantly present in the most FI subjects.

Before discussing strategies, we will first refer to the *postural performances* in the frontal plane already studied elsewhere (Isableu et al. 1997, 1998). The FI subjects were found significantly more stable than FD subjects in any experimental condition, even in the easiest one, i.e. vertical frame and continuous vision. Correlations have also been observed between the scores of visual field dependence and body stability. The degree of instability correlated well with increasing field dependence. The visual field dependence–independence thus appears to be a good predictor of the subject's ability to stabilise their posture efficiently. As regards the *visual contribution* to body balance, FD subjects were found to be clearly dependent on visual proprioception for improving balance, whereas FI subjects were much less so. This was confirmed by correlation analyses, showing positive correlation between the scores of visual field dependence and the visual gain. The postural visual dependence of FD subjects was evident at any anatomical level when comparing full vision and darkness. This was especially clear for improving head stability. We may assume that FI subjects, by contrast, may be posturally more dependent on either static and/or dynamic vestibular or somatosensory cues. Their almost non-visual contribution to postural control could thus be either head (vestibular) or feet (somatosensory) dependent, implying that either the head or the support were their stabilised *RF* (Assaiante and Amblard 1995).

These results clearly raise the question of the efficiency for postural control of the use of visual and non-visual frames of reference, respectively. In other words, we may wonder whether FD subjects were less stable because they relied on visual *RF*, the efficiency of which being perhaps lower than that of non-visual ones, or they needed visual assistance because they were less stable (Isableu et al. 1997, 1998). In this view, we must also keep in mind that visual cues provided by the horizontal or tilted frame in our experiment are potential but not exclusive candidates to improve stance in more ecological situations. As suggested by Bronstein and Buckwell (1997), motion parallax may also be used to improve body stability, and it was not available here with our 2D visual frame. This could partly explain the lower efficiency of visual contribution and have enhanced the differences between FD and FI subjects. These differences in postural performances could be also attributable to the use of different postural strategies in both groups, the efficiency of which being possibly different (see below). Thus, analyses of strategies of segmental stabilisation could provide insight to understand how sensorimotor styles (non-disoriented–stable versus disoriented–unstable subjects) in postural regulation emerge and need to be addressed in relation to the question of the physical spatial *RF* selected (visual versus non-visual) by subjects.

Concerning the *strategies of segmental stabilisation*, a schematic view of the main results is given in Fig. 6. This figure clearly shows that different sensorimotor strategies of segmental stabilisation were used, depending on both the perceptual style and the visual cues available. The main features are the following:

1. In the absence of total and static visual cues, FD subjects have shown an increased efficiency of the hip stabilisation in space strategy and an “en bloc” operation of the shoulder–hip unit (whole trunk). The last “en bloc” operation was extended to the whole head–trunk unit in darkness, associated with a hip stabilisation in space. Contrary to that found in postural performances, dynamic visual cues have played a marginal role in the adopted strategies of segmental stabilisation.
2. On average, FI subjects have adopted neither a strategy of segmental stabilisation in space nor on the underlying segment, whatever the body segment considered. Thus, in this group, head, shoulder and hip moved independently from each other (articulated functioning of the whole body), roughly without taking into account the visual condition. However, correlation analyses showed that head in space and shoulder in space strategies were adopted in most of our FI subjects, indicating a greater reliance on vestibular cues for stabilising their heads in space and on proprioceptive cues for stabilising their shoulders in space.
3. Consequently, higher head–shoulder and shoulder–hip coefficients of correlation were found in FD than FI subjects.

In FD subjects, the stabilisation of the hip in space, associated with an “en bloc” operation of the head–shoulder and/or shoulder/hip unit, which induced a corresponding stability of the whole trunk and head, was the primary response to postural constraints, at least in the poorest visual conditions. Similar trunk stabilisation in space has been postulated to be the main variable controlled in a postural task by Gurfinkel et al. (1995). Given the better postural performances in the FI than in the FD subjects, it can thus be concluded that the “en bloc” operation of the head–shoulder and/or shoulder–hip unit of FD subjects were less efficient strategies than the articulated operation of the studied joints in FI subjects. This was true even when the “en bloc” operation of the trunk was associated with hip stabilisation in space. The FI subjects have thus demonstrated a good mastering of the corresponding proprioceptive cues on which they rely. By contrast, FD subjects, in the absence of adequate visual cues (see below), may be suspected to have blocked most of their joints due to their difficulty in interpreting and using corresponding proprioceptive cues.

Concerning the modulation of postural strategies by vision, we have shown that it was almost not present in FI subjects. The FD ones, by contrast, were shown to rely massively on vision for segmental strategies. This was confirmed by the correlation analysis, showing positive correlation between the scores of visual field dependence and the AIs. Full vision allowed FD subjects to reduce their shoulder–hip (trunk) “en bloc” functioning and even to give up stabilising their hip in space. The last was typically chosen as soon as static visual cues or total vision were withdrawn. Impoverished or total suppression of vision thus seems to be a key factor in the onset of intersegmental stiffening strategies adopted by FD subjects. However, our hypothesis of an HSSS of visual origin in FD subjects has not been confirmed, these subjects rather choosing an “en bloc” operation of the head on the shoulder.

The “en bloc” operation of the head–trunk unit (head stabilisation on the trunk strategy, HSTS; Assaiante and Amblard 1993), which was observed in FD subjects in darkness but also paradoxically under full vision, may have induced in the last condition some visual blurring which could have impaired visual processing and thus induced a corresponding impairment of the visual contribution to postural stability. Nevertheless, a reason why the HSTS may have been chosen under full vision could be that FD subjects needed to enhance visual feedback to improve the visual contribution to postural control. Another interpretation, which does not exclude the previous one, could be that the “en bloc” functioning of the head–trunk unit may directly provide the subject with visual (and vestibular) information concerning the trunk imbalance, without having to take into account the head-on-the-trunk signal. A similar HSTS has been shown to be adopted in Parkinson’s disease during locomotion under full vision as well as in stroboscopic illumination (Mesure et al. 1999), these patients being also visually dependent as regards this task (Azulay et al. 1999). The equivalent HSTS of our FD subjects in darkness may have rather corresponded to a simplifying strategy aimed firstly at minimising the number of *df* to be controlled simultaneously in the absence of any visual cues. Secondly, it may have been aimed at providing the subject with vestibular cues concerning the trunk imbalance, also without having to take into account the head-on-the-trunk signal. It could be also argued that intersegmental stiffening may be understood as a sensorimotor strategy that could potentially lead FD Ss towards a better use of proprioceptive cues provided that intersegmental interactions (like head-on-the-trunk signal) were withdrawn (i.e. reducing the processing complexity). However, their usefulness required that sufficient motions were produced to be sufficiently informative. In other words, increasing motions (instability) of an assembly of many *df* could be seen as a good mean for increasing the weight of proprioceptive cues over visual ones.

The hip stabilisation in space of the FD subjects deprived from visual cues may be interpreted as an indication that they have shifted from a usual visual *RF* to a non-visual one linked to the hip level. This could be a gravito-inertial *RF* based on motor-proprioceptive loops, similar to that adopted by toddlers at the very beginning of their walking experience, as suggested by Assaiante and Amblard (1995).

Should the better postural control observed in FI subjects, despite visual perturbations, be explained by a better control of non-visual inputs? A heuristic assumption has been put forward by Ohlmann and Luyat (2001). According to these authors, the perception and the control of spatial orientation could be based either on static and kinetic cues about forces (i.e. linked to inertial, frictional, gravitational forces, motor commands) or on geometric (static surrounding) or kinematic (optical flow) cues. Consequently we may assume that spatial perception and motor control in FI subjects could be based on force cues and particularly on inertia momentum (Pagano and Turvey 1995; Pagano 2000) while FD subjects should rely on the visual array.

In other words, our data suggest that relying on visual proprioception (FD subjects, i.e. a kinematic mode of spatial control) to control upright posture or to set a rod to the gravitational vertical surrounded by large tilted frame seems to preclude the use of kinetic cues. The following elements seem to fund our assumption. The IRMf studies carried out by Brandt et al. (1998), Dieterich and Brandt (2000) and Deutschlander et al. (2002) shed light on the central mechanism subserving the multisensory integration for self-motion perception. Their findings showed that stimulation of one sensory system affects other sensory systems. They have proposed a new functional interpretation for self-motion perception via an inhibitory reciprocal mode of interaction as a multisensory mechanism. Indeed, vestibular stimulation deactivates the visual cortex and visual stimulation deactivates the vestibular cortex. This mechanism of an inhibitory interaction allows a shift of the dominant sensorial weight during self-motion perception from one sensory modality (visual, vestibular or somatosensory; Bense et al. 2001) to the other, depending on which mode of stimulation prevails: body acceleration (vestibular input) or constant velocity motion (visual input).

This experiment was designed to verify whether the ability to coordinate intersegmental movements for stabilising and orienting the body or some parts of the body relative to the variety of physical *RF* can produce differences between subjects. We can reasonably advance the idea that spatial referencing habits can emerge, leading subjects towards the use of only some *RF* (subset) among their variety (guided by simple economic samples law) and perhaps in a hierarchical manner (see Ohlmann 2002). A simple control law could guide the perception and control of spatial orientation to the more usual *RF* towards the less usual, and this driven by the difficulties of task demands and environmental constraints (see Ohlmann 2002). Modifying the hierarchy in using our usual–non-usual *RF* would have a cost. Many reasons exist. One reason, that fits well with our data, is that hierarchy and the strength of *RF* habits could lead to less flexibility and less adaptation in the case of sudden, unusual and/or changing situations. This spatial habits reinforcement should lead thus to forsake the use of some spatial relationships between us and some *RF* and to neglect sensory channels with which they are tied. Neglecting some sensory channels would have cortical, perceptive and behavioural consequences. Cortical consequences of this neglect would shape cortical motor-somesthetics map atrophy (i.e. less developed and less detailed sensory maps). Recent studies provide evidence supporting this hypothesis (Elbert et al. 1998; Coq and Xerri 2001; Pantev et al. 2001). In the case of visual disturbances like that in our study, the best way to resist or to reduce sensory conflict would consist in establishing new relationships with other available physical *RF* (like the supporting ground or GIF) via motor-somesthetic cues. Two alternative interpretations could be put forward to explain our data. Either FD subjects have difficulty to shift to their best usual *RF* towards the adequate ones (ground or GIF) in the case of visual perturbations or they met difficulties relying on motor-somesthetic cues. This "neglect" or a lack of mastering of these motor-somesthetic cues should originate in the reinforcement of other preferred visual spatial relationships. This "neglect" should be linked to less structured cortical maps, consecutively to lesser proprioceptive tuning experiences. Thus, to resist to visual disturbances FD subjects cannot use alternative solutions than weighted visual cues with weaker structuring of proprioceptive cues. Consequently, that proprioceptive deficit would reduce the possibility to select ground or GIF references and or to use them in the most efficient manner, i.e. to a lesser extent than FI Ss.

This allows us to assume that a motor-somesthetic "neglect" or a lack of mastering of these sensory inputs rather than a greater visual field dependence in FD subjects would generate these interindividual differences in both spatial perception and postural balance. This proprioceptive "neglect" is assumed to lead FD subjects to sensory weighting and towards a difficulty to differentiate the *RF* and thus establishing relationships with non-visual *RF*, whereas proprioceptive dominance would lead FI subjects to a greater ability in selecting the adequate *RF* in the case of intersensory disturbances. A recent study seems to validate that interindividual differences in the perception of egocentric spatial orientation would originate in a motor-somesthetic "neglect" or a lack of mastering of these inputs in some subjects (and mainly in FD subjects) (Isableu et al. submitted for publication). Indeed, FD subjects met difficulties to perceive the direction of their Z body egocentric reference in the supine position, while subjected to rotation of visual displays. Even when proprioceptive cues were continuously added, providing a continuous updating of the direction of the Z body axis, FD subjects never reached the body egocentric perception accuracy observed in FI subjects.

This hypothesis provides insight and a new interpretation of the visual field dependence–independence dimension in spatial perception and in postural control.

In conclusion, we have demonstrated close relationships between subjective vertical and postural control as regards the typology of dependence–independence with respect to visual field. This was due to the fact that these spatial activities clearly require the choice of an adequate spatial *RF*, which appeared to be the same in both cases in a given subject. Whether the individual choice of a single *RF* could be generalised to any other activity requiring spatial processing and whether this would be the case for simplifying the CNS control remain, however, open questions for further investigations. Finally, this study also provides evidence for a new interpretation of the visual field dependence–independence reliance in both spatial perception and postural control.

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