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Slow changing postural cues cancel visual field dependence on self-tilt detection

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ABSTRACT

Interindividual differences influence the multisensory integration process involved in spatial perception. Here, we assessed the effect of visual field dependence on self-tilt detection relative to upright, as a function of static vs. slow changing visual or postural cues. To that aim, we manipulated slow rotations (i.e., $0.05^\circ\,s^{-1}$) of the body and/or the visual scene in pitch. Participants had to indicate whether they felt being tilted forward at successive angles. Results show that thresholds for self-tilt detection substantially differed between visual field dependent/independent subjects, when only the visual scene was rotated. This difference was no longer present when the body was actually rotated, whatever the visual scene condition (i.e., absent, static or rotated relative to the observer). These results suggest that the cancellation of visual field dependence by dynamic postural cues may rely on a multisensory reweighting process, where slow changing vestibular/somatosensory inputs may prevail over visual inputs.

1. Introduction

Since observations by Aubert [1], it is well known that the perception of spatial orientation is biased by static roll body tilt yielding, for instance, a deviation of the perceived longitudinal body axis in the direction of tilt (e.g., [2]). Similar deviations induced by static body tilt appear in pitch when visually estimating the body longitudinal axis [2,3] or the egocentric eye level [4].

In parallel, static tilt of a visual scene has also been found to influence subjective visual vertical (SVV; e.g., [5]) as well as self-orientation estimates, such as adjusting the body to vertical (body adjustment test; [6,7]). In their pioneer work, Asch and Witkin conducted a set of experiments in which they showed that SVV deviates in the same direction as the static roll tilt of the visual scene [8,9]. Strikingly, they observed large interindividual differences, which were interpreted as reflecting that some individuals may rely more on vision than others, namely visual field dependent ('FD') or independent ('FI') subjects.

Available data regarding the influence of combined changes in body and visual scene orientation were rarely issued from dynamic rotations (e.g., [10]), and rather concerned static tilts with a variable time delay between the end of body tilt and the task onset [4,11–13]. In this context, while some studies showed that errors during combined head and visual scene static tilts appeared as an additive combination of the errors observed for each single tilt [4,11], other studies revealed that these errors were mainly induced by the visual tilt [12,13]. Although the influence of visual field dependence on spatial perception has been investigated during static tilt of the body/head and a visual scene [14], it has never been studied during very slow rotations, where cues were continuously – although slowly – refreshed.

Here, we assessed visual field dependence on self-tilt detection relative to upright, during slow continuous rotations of the body and/or the visual scene (i.e., $0.05^\circ\,s^{-1}$) performed below semicircular canals stimulation [15]. Slow rotation profiles were previously shown to impair self-tilt detection in subjects who were not a priori selected on the basis of their degree of field dependence [16]. We expected that FD would be more sensitive to slow visual rotation alone compared to FI. However, we hypothesized that these interindividual differences would disappear during actual slow body rotation, whatever the presence and the orientation of the visual background. This second hypothesis

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was supported by recent data suggesting a 'vestibular/somatosensory capture' relative to visual cues as soon as the body is not upright anymore [17].

2. Methods

2.1. Participants

In order to drastically select subjects relative to their visual field dependence, 100 participants (55 males; 45 females; mean age ± SD: 20.6 ± 2.3 years) were recruited among the students of Aix-Marseille University, and were submitted to a portable rod-and-frame test (RFT). Subjects reported having normal or corrected-to-normal vision and no neurological or sensorimotor disorders. All participants gave written informed consent prior to the experiment, in accordance with the 1964 Declaration of Helsinki.

The RFT consisted in setting a tilted visual rod along the gravitational vertical when facing a tilted visual frame (i.e., SVV task). Three roll frame tilts (0 and ±18°) and random initial rod orientations of ±18° were manipulated. According to Nyborg and Isaksen's method [18], we computed the 'frame effect' (tendency to align the visual rod towards the frame) at 18°. The magnitude of the 'frame effect' determined the degree of visual field dependence, with high scores for visually-dependent subjects and low scores for visually-independent subjects [8]. Extreme scores (i.e., highest and lowest scores) were identified and enabled us to define two groups of eight subjects being either highly visually-dependent (8 females; 19.6 ± 1.3 years; mean 'frame effect': 8.6 ± 1.3°) or visually-independent (3 females and 5 males; 20.1 ± 1.1 years; mean 'frame effect': 1.0 ± 0.3°). Strikingly, the sample size of both groups was in the range of those manipulated in [18,19]. Furthermore, we considered that the strict selection process, leading to a marked differentiation between groups, increased the chance of finding a significant difference, if it actually existed.

Finally, prior to the experiment, stereoscopic vision acuity was checked for each selected subject using the Randot Stereotest® with all individual scores greater than 70 s of arc.

2.2. Apparatus

Subjects were seated in a tilting chair, firmly maintained by a six-point seatbelt. The chair could be rotated in the pitch dimension, around an axis positioned under the seat (see Fig. 1a). The rotation was produced by lengthening/shortening an electric jack (Phoenix Mecano®, thrust: 3 kN, clearance: 0.6 m, precision 0.12 mm) attached to the back of the seat. The angular profile of the tilt was servo-assisted using an inclinometer fixed to the chair (AccuStar®; resolution: 0.1°; range: ±60°). The rotation velocity was set at $0.05^\circ\ \mathrm{s}^{-1}$ following an acceleration phase at $0.005^\circ\ \mathrm{s}^{-2}$, below the threshold for semicircular canals stimulation [15]. During the experimental trials, earphones provided white noise to mask any auditory cues. Two push buttons held by subjects in both hands were used to sample the digital response for judgement settings.

A 3D head-mounted display (HMD, 3D Cybermind hi-Res900®, Cybermind Interactive Nederland, The Netherlands; resolution: 800 × 600 pixels; field of view: 31.2° diagonal for each eye) was fixed horizontally onto a headrest attached to the seat. This headrest was adjustable in elevation to the subject size. As illustrated in Fig. 1, the HMD was used to display a stereoscopic 3D visual background, composed of a full furnished and polarized room. The room was 3 m width × 2.25 m height, which corresponded to a relative standard room size, and was 6 m length. The distance of the virtual scene front was set at 1.7 m from subjects' eye in the transverse plane, in order that the front wall could be fully visible according to the HMD field of view. The virtual room displayed in the HMD could rotate in the pitch dimension around the same axis as the rotating chair. Overall, the HMD device prevented subjects from having visual feedback from the experimental setup and about their current body location.

A real-time acquisition system (ADwin-Pro®, Jäger, Lorsch, Germany) running at 10 kHz was driven by a customized software (Docometre) to synchronously control visual background and/or chair rotations. The lag measured between visual and chair stimulus was negligible (<55 ms, that is, less than 0.003°).

2.3. Procedure

During the experiment, subjects, seating in the rotating chair, were asked to indicate whether they felt being tilted forward, i.e., away from vertical [16,21,22]. To that aim, subjects were required to respond to a binary choice via the push buttons, thus indicating 'Yes, I feel being tilted forward' by pressing the right hand-held button or 'No, I do not feel being tilted forward' by pressing the left hand-held button.

For each condition, the chair and the visual background were initially set at 0° (i.e., at vertical). Subjects gave their subjective response when prompted by an auditory tone every 1°, from 0° to 18° of body and/or visual scene rotations. Once the body and/or the visual scene was rotated by 18°, the visual scene disappeared. If the body was actually rotated, the chair was rotated back to 0° with a profile in which we varied the magnitude and duration of the acceleration and deceleration phases. This pseudo-random profile was chosen such that the subjects did not infer the angle of tilt they previously reached. Between trials, the HMD was removed and a period of rest in full ambient light, during at least 1 min, was consistently provided before the next condition started. This resting period was used to suppress post-rotational effects due to semicircular canal stimulation [15] and to limit possible fatigue. The subsequent body and/or visual scene rotations condition began only when subjects did not feel tilted anymore.

During the experiment, we manipulated tilts of the body and/or the visual scene in the pitch dimension with forward body rotation and backward visual scene rotation up to 18°. The same velocity profile was used to reach 18° as subjects were asked to perform the task during the continuous rotation(s), so that these rotations were comparable. Overall, 4 experimental conditions were presented: S_{bwd}: backward visual scene rotation (top towards the observer) without body rotation; B_{fwd}: forward body rotation without scene (no visual background); $B_{\mathrm{fwd}}S$: forward body rotation with a visual **s**cene remaining static relative to the subject; $B_{\mathrm{fwd}}S_{\mathrm{bwd}}$: forward body rotation with backward visual scene rotation relative to the observer.

All 16 subjects performed 3 repetitions in each of the 4 aforementioned conditions, which were presented in a pseudo-random, counterbalanced order, to avoid any potential learning effect. A training session without body and/or visual scene rotations was provided before data collection actually started, to familiarize subjects with the task. The whole experimental session lasted about 2 h.

2.4. Data processing

We first determined the threshold for body tilt detection in each condition. Responses were converted into binary values, with '1' corresponding to the response 'Yes, I feel being tilted forward' and '0' to the response 'No, I do not feel being tilted forward'. A Probit model, using a non-linear regression analysis for binomial values

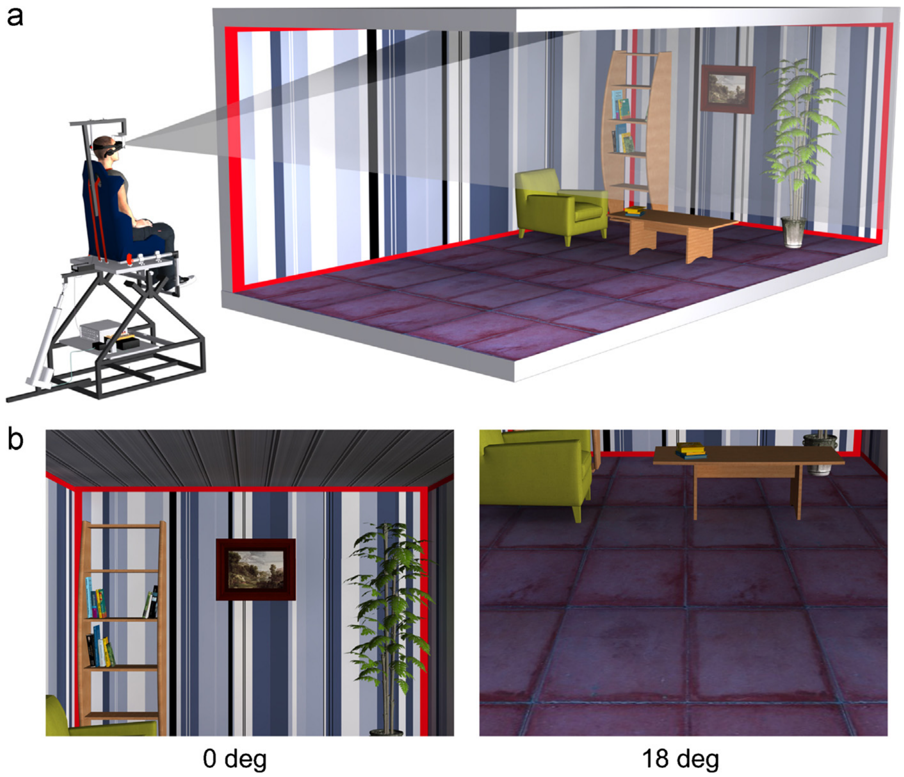

Fig. 1. Experimental setup. (a) Global view of the apparatus including the tilting chair, the HMD and the 3D visual scene at virtual scale. (b) Visual scene actually viewed by a subject at the beginning of the trial (0°) and the end of the visual scene rotation (18°) when provided (i.e., S_{bwd} and $B_{\mathrm{fwd}}S_{\mathrm{bwd}}$).

was adjusted to the data, to determine the tilt detection threshold corresponding to 50% of probability of the feeling of being tilted (0.5 value). Probit function was defined as follows:

$$Pi = \frac{1}{1+(At/T)^{b}}$$

'*P*' is the confidence probability in the feeling of being tilted for a given condition '*i*'. '*At*' corresponds to the *Angle of Tilt* during this condition and '*T*' to the tilt *Threshold* for this condition (i.e., angle of tilt for $P = 0.5$). '*b*' is the slope of the tangent at the inflection point of the curve and constitutes an estimation of the discrimination sensitivity relative to the chosen increments. A prior analysis of the consistency of the threshold detection sensitivity over conditions was performed, using a 4 condition repeated-measures ANOVA applied on '*b*' values. This analysis did not reveal any significant difference between discrimination sensitivity across conditions.

Noticeably for some subjects, we could not determine any tilt detection threshold for visual scene rotation (S_{bwd}) as they never reported a feeling of being tilted in this condition. In such cases (5/8 FI subjects and 1/8 FD subjects), a threshold was arbitrary set to 20°, that is, just over the largest magnitude of tilt presented in the experiment. We then compared the mean thresholds of body tilt using a 2 group (FD, FI) × 4 condition (S_{bwd}, B_{fwd}, $B_{\mathrm{fwd}}S$, $B_{\mathrm{fwd}}S_{\mathrm{bwd}}$) repeated-measures ANOVA. As we wanted to avoid any potential effect of the arbitrary threshold set when subjects never felt tilted in the S_{bwd} condition, we repeated the same analysis on the mean percentage of positive responses (i.e., 'Yes, I feel being tilted') for a given condition.

Overall, post hoc tests (Newman–Keuls) were performed when necessary and the level of significance was set at .05 for all statistical analyses. The effect size ($\eta^2 p$) and the power ($1-\beta$) of each test were computed.

3. Results

Statistical differences between groups and conditions were first investigated by comparing body tilt thresholds obtained from the fitted Probit function (Fig. 2). The ANOVA failed to reach significance for group ($F_{(1,14)} = 2.9$; $p = .11$; $\eta^2 p = .17$;

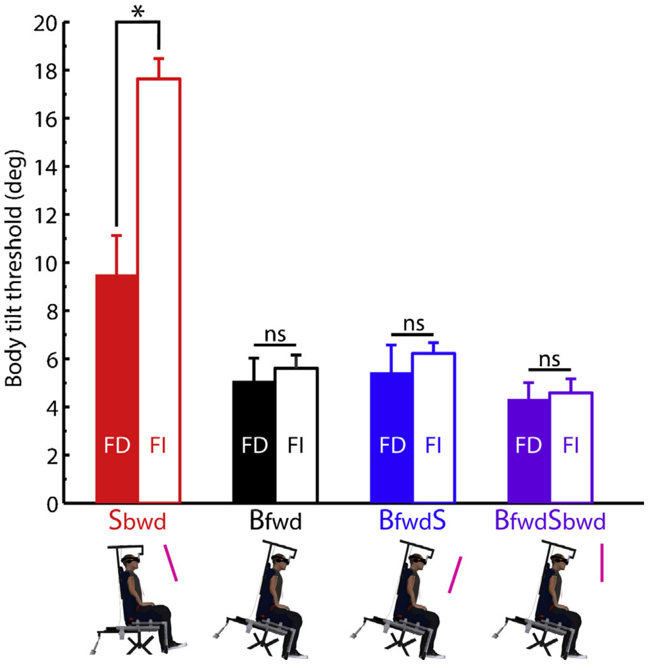

Fig. 2. Self-tilt detection threshold as a function of group (FD: coloured bars, FI: white bars) and condition (S_{bwd}, B_{fwd}, $B_{\mathrm{fwd}}S$, $B_{\mathrm{fwd}}S_{\mathrm{bwd}}$). Vertical bars denote positive standard errors. *: $p < .05$; ns: non significant comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

$(1-\beta) = .36$) but showed a significant main effect of condition ($F_{(3,42)} = 38.3$; $p < .001$; $\eta^2 p = .73$; $(1-\beta) = 1.00$) as well as an interaction group × condition ($F_{(3,42)} = 7.8$; $p < .001$; $\eta^2 p = .36$; $(1-\beta) = .98$). Both groups (FD, FI) exhibited higher body tilt thresholds when only the visual scene was rotated (mean ± SE: $13.6 \pm 1.6°$), as compared to other conditions involving body rotation (B_{fwd}: $5.3 \pm 0.8°$, $B_{fwd}S$: $5.8 \pm 0.8°$, $B_{fwd}S_{bwd}$: $4.5 \pm 0.6°$). Indeed, S_{bwd} statistically differed from all body rotation conditions ($p < .001$ for all comparisons) while body rotation conditions were not different from each other (B_{fwd} vs. $B_{fwd}S$: $p = .61$; B_{fwd} vs. $B_{fwd}S_{bwd}$: $p = .37$ and $B_{fwd}S$ vs. $B_{fwd}S_{bwd}$: $p = .34$). As a core finding, although tilt detection thresholds were markedly different between FD and FI subjects in the condition involving a rotation of the visual scene alone (FD: $9.5 \pm 1.6°$ vs. FI: $17.6 \pm 0.8°$; $p < .05$), there was no difference between both groups for all body rotation conditions, whatever the presence and the orientation of the visual scene (B_{fwd}, $p = .98$; $B_{fwd}S$, $p = .96$; $B_{fwd}S_{bwd}$, $p = .93$). This absence of difference between FD and FI was observed despite our subjects' selection criteria, which were expected to magnify statistical differences (see Section 2.1).

Similar results appeared when comparing the mean percentage of positive responses. Indeed, the ANOVA revealed no effect of group ($F_{(1,14)} = 1.9$; $p = .19$; $\eta^2 p = .12$; $(1-\beta) = .25$) but showed a main effect of condition ($F_{(3,42)} = 36.0$; $p < .001$; $\eta^2 p = .72$; $(1-\beta) = 1.00$) as well as an interaction group x condition ($F_{(3,42)} = 8.76$; $p < .001$; $\eta^2 p = .39$; $(1-\beta) = .99$). Post hoc analyses showed that the percentage of positive responses was lower for S_{bwd} ($32 \pm 7\%$) compared to the other body tilt conditions B_{fwd} ($67 \pm 4\%$, $p < .001$), $B_{fwd}S$ ($64 \pm 4\%$, $p < .001$), $B_{fwd}S_{bwd}$ ($72 \pm 3\%$, $p < .001$) which remained statistically not different from each other (B_{fwd} vs. $B_{fwd}S$, $p = .43$; B_{fwd} vs. $B_{fwd}S_{bwd}$, $p = 0.23$; $B_{fwd}S$ vs. $B_{fwd}S_{bwd}$, $p = 0.12$). Here again, the interaction between group and condition showed that the percentage of positive responses in the S_{bwd} condition was significantly higher for FD ($50 \pm 8\%$) compared to FI ($14 \pm 5\%$; $p < .05$), whereas it was not different between groups when actual body rotation was involved (B_{fwd}: $68 \pm 7\%$ vs. $66 \pm 4\%$, $p = .92$; $B_{fwd}S$: $71 \pm 5\%$ vs. $73 \pm 4\%$, $p = .88$; $B_{fwd}S_{bwd}$: $64 \pm 8\%$ vs. $63 \pm 4\%$, $p = .96$, for FD and FI, respectively).

4. Discussion

This experiment was designed to investigate whether visual field dependence could influence self-tilt detection relative to upright under different contexts of body/visual slow rotation. The core findings of the present study rely on the different influence of visual field dependence/independence on self-tilt detection regarding the combination of static vs. dynamic visual and postural stimulations. While thresholds for self-tilt detection substantially differed between both groups when the rotation of the visual scene alone was involved, this difference was no longer present when the body was actually rotated, whatever the visual scene condition (i.e., absent, static or in rotation).

Body tilt threshold was consistently lower for FD, as compared to FI subjects during slow rotation of the visual scene alone. More precisely, most of FD subjects felt being tilted from vertical in this condition, while most of FI subjects never felt being tilted, even when the potential effect of the visual scene tilt was maximal (i.e., 18° of tilt; [23]). This result shows that, as for SVV estimates [8,9], visual scene tilt impacts self-tilt perception as a function of visual field dependence. A similar influence of visual field dependence on SVV has also been revealed when facing a dynamic rotation of a visual scene (e.g., [24]). Here we showed that a very slow rotation (i.e., $0.05°\,s^{-1}$) of a structured visual scene differently influenced self-tilt detection relative to upright according to visual field dependence, the latter being classically determined by SVV estimates (i.e., RFT; see Section 2.1). During this particular visuo-postural conflict, FD may largely depend on continuously updated visual cues relative to static postural cues. Specifically, the backward rotation of the visual scene may induce an illusory perception of body rotation in the reverse direction that may lead FD subjects to respond that they feel being tilted forward, in accordance with [25].

By contrast, our data did not reveal any difference between FD and FI in self-tilt detection during actual body rotation, whatever the visual stimulation. In other words, the link we found between visual influence on SVV and self-tilt detection when only the visual background was rotated is abolished as soon as postural orientation changed. Overall, we confirmed that slow pitch body tilts at $0.05°\,s^{-1}$ delayed the detection of body tilt [16], independently from visual field dependence, suggesting that very slow changes in otolith inputs are non-sufficient to convey relevant information for updating actual self-orientation. This assumption is supported by the absence of difference between bilateral labyrinthine-defective subjects and normal subjects in slow self-tilt detection [22]. Somatosensory inputs, and more precisely cutaneous pressure cues might play a major role compared to vestibular cues for body tilt detection [16,26] as well as for postural control [27]. Here, the weight of postural inputs, mediated by touch and pressure cues, might increase as compared to visual cues when the former are regularly refreshed by afferent slow changes. This large influence of postural cues relative to visual cues is in accordance with recent data on spatial perception (e.g., [17,28]).

Here we suggested that sensory reweighting of postural cues, and more likely somatosensory inputs, may be at work for subjects exhibiting a strong dependence on visual cues in otherwise static postural conditions. Visual field dependence may be modulated by the nature of postural cues: static (i.e., unchanged body orientation) vs. dynamic (i.e., actual – even slow – body rotation). Previous studies already claimed for a multisensory reweighting process subjected to interactions between proper singularities and context [14,20,21,29]. For instance, gender influence on SVV estimates was found to depend on postural constraints, since it was recently shown that gender-related differences also disappeared when the body was tilted (i.e., lying on a side; [29]). Gender could also play a role in our study since it constitutes a distinguishing attribute of field dependency (i.e., FD: 8 females vs. FI: 5 males and 3 females), as previously reported [30].

Overall, the results of this study support the hypothesis that the expression of visual field dependence during self-tilt detection relies on postural context. The cancellation of visual field dependence during actual body tilt needs to be extended to other orientation tasks (e.g., subjective body tilt or SVV estimates) to investigate the potential generalization of this attribute [31]. Presumably however, such dominance of dynamic postural cues overruling visual field dependence might be rather task-specific, as it was shown that the weighting of visuospatial inputs during static scene tilt depends on task requirements [32].

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Conflict of interest statement

The authors have declared that no competing interests exist.

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