
Interaction between reference frames during subjective vertical estimates in a tilted immersive virtual environment

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Received 23 May 2008, in revised form 7 January 2009; published online 17 July 2009

Abstract. Numerous studies highlighted the influence of a tilted visual frame on the perception of the visual vertical ('rod-and-frame effect' or RFE). Here, we investigated whether this influence can be modified in a virtual immersive environment (CAVE-like) by the structure of the visual scene and by the adjustment mode allowing visual or visuo-kinaesthetic control (V and VK mode, respectively). The way this influence might dynamically evolve throughout the adjustment was also investigated in two groups of subjects with the head unrestrained or restrained upright. RFE observed in the immersive environment was qualitatively comparable to that obtained in a real display (portable rod-and-frame test; Oltman 1968, *Perceptual and Motor Skills* **26** 503–506). Moreover, RFE in the immersive environment appeared significantly influenced by the structure of the visual scene and by the adjustment mode: the more geometrical and meaningful 3-D features the visual scene contained, the greater the RFE. The RFE was also greater when the subjective vertical was assessed under visual control only, as compared to visuo-kinaesthetic control. Furthermore, the results showed a significant RFE increase throughout the adjustment, indicating that the influence of the visual scene upon subjective vertical might dynamically evolve over time. The latter effect was more pronounced for structured visual scenes and under visuo-kinaesthetic control. On the other hand, no difference was observed between the two groups of subjects having the head restrained or unrestrained. These results are discussed in terms of dynamic combination between coexisting reference frames for spatial orientation.

1 Introduction

Since the observations of Wertheimer (1912), who noticed that a room seen in a tilted mirror progressively appeared upright, the influence of a tilted visual frame on the ability to perceive the vertical has been extensively investigated (see Howard 1982 for a review). The pioneer work of Asch and Witkin (1948a, 1948b) demonstrated that a rod that was to be aligned with the gravitational vertical was actually displaced towards the tilted visual environment in front of which the observers stood. Not only tilted scenes containing familiar objects, but also simple tilted square frames, were found to affect the subjective vertical (SV) despite high interindividual differences (Witkin and Asch 1948). Further research on the differential aspects of verticality judgments (eg cognitive style—Witkin et al 1954) has led to the 'rod-and-frame test' (RFT), which requires SV judgments in front of a visual square frame tilted at different extents (Oltman 1968). Results are generally represented as a sinusoidal function of the tilt of the visual square. Hence, classical 'rod-and-frame effects' (RFEs) may be illustrated by this representation through which maximal deviations of the SV towards the tilted frame occur between 18° and 28° of visual tilt. Some 60 years later, virtual-reality displays became promising tools for investigating the influence of tilted 3-D visual scenes upon SV. Using this novel technology, the present study was designed to further investigate combined influences upon RFE, such as the structure of the visual scene and the mode of SV adjustment.

Head-mounted displays, although enabling to create 3-D visual information, suffer most of the time from a reduced field of vision and from the residual presence of a

head-fixed visual frame which might concurrently influence the perception of verticality (Mars et al 2004). Projection-based immersive virtual environments with larger fields of vision have been recently developed and manipulated to study spatial orientation. The advantage of these large-scale displays is that they provide both experimental control and close-to-real situations (Loomis et al 1999). Most contributions involving such apparatus focused on the influence of stereoscopic moving scenes upon postural responses (Keshner et al 2006; Keshner and Kenyon 2000; Mergner et al 2005). To our knowledge, subjective orientation relative to the gravitational vertical in large-scale virtual-reality displays has been explored only by Jenkin and her colleagues (2003). In their study, the perceived direction of 'up' was investigated in a tilted virtual room by adjusting the orientation of a shaded disc until it appeared most convex, which has been shown to depend on the direction of illumination. The underlying assumption of this experiment was that light always comes from above. However, one might argue that other luminous sources, usually present in a room, could modify the lighting of objects, thus challenging the 'light from above' assumption. Despite these methodological differences with respect to classical SV estimates, it seems that the use of a large-scale virtual-reality display could generate an RFE when the virtual room was tilted. Nevertheless, no direct comparison between judgments of verticality performed in real-world and in immersive virtual environment was provided.

The first aim of the present study was to investigate whether the tilt of a large-scale immersive virtual environment could yield similar effects on the judgment of verticality as the tilt of real visual surroundings. In other words, we addressed the question of comparability of the RFE between real and virtual worlds. This first step would allow us to validate the immersive virtual environment as a powerful tool for studying the perceived orientation of objects in structured visual surroundings.

Numerous papers reported an influence of the characteristics of visual surroundings in front of which subjects had to set their SV. Regarding the size of the frame, some experimenters suggested that a larger frame is likely to induce a greater RFE (Brooks and Sherrick 1994; Spinelli et al 1991). However, retinal size was found more important than perceived size in the occurrence of the RFE (Ebenholtz 1977). Other studies emphasised the role of the gap between the ends of the rod and the inner edge of the frame in modulating the RFE, showing that rod orientation is affected by elements that immediately surround it in the visual field (Rock 1990; Nyborg 1977; Spinelli et al 1995, 1999; Zoccolotti et al 1993). In the same vein, Wenderoth and Beh (1977) emphasised the importance of axes of symmetry relative to different inducing figures in the RFE. Li and Matin (2005a, 2005b) also clearly demonstrated that the separate influences induced by the individual lines composing the frame are much more important than the effect produced by the whole frame itself. Overall, all these studies gave support to a 'geometrical' approach to the RFE, in which automatic visual-information processing determines its occurrence and magnitude (Ebenholtz 1985).

On the other hand, it has been shown that the RFE also depends on cognitive influences. By manipulating the polarity of different objects (eg a mouse, an elephant, a clock whose numbers were displaced but not tilted) used as surrounding frames, Cian et al (2001) showed that the orientation of the rod relative to vertical is also modulated by the tilt of meaningful visual features which contain neither geometrical shapes nor linear segments. This finding suggests that high-level cognitive processes might also be involved in the RFE when polarised objects (ie with a clearly defined up and down) constituting the visual surroundings are tilted. The importance of polarity of the visual frame has also been considered by Howard and Childerson (1994), who found a greater influence of a tilted furnished room upon vertical settings than that of a simple dotted room without floor or ceiling.

The second aim of the present study was to manipulate the 3-D structure of visual surroundings during SV estimates in order to characterise the implication of geometric and polarised features in the occurrence of the RFE.

Moreover, since Howard and colleagues (Howard and Childerson 1994; Howard and Hu 2001) reported occasional (and unprocessed) differences between settings performed with a visible rod and settings performed with an unseen 'felt' rod, we also examined the adjustment mode of SV, that is the manner in which subjects set the rod to the perceived vertical. The adjustment mode, which implies that one or several sensory channels are used in the control of settings, has been surprisingly often neglected in the literature. SV estimates of body tilt have been investigated in several studies through haptic or kinaesthetic settings: subjects were instructed to adjust a hand-held object (eg a rod, a joystick, or a glass of water) to the perceived vertical without visual feedback (Bauermeister 1964; Bortolami et al 2006; Lejeune et al 2004; Wright and Glasauer 2003, 2006). Specific effects of body tilt and context dependence upon SV were reported, but no direct comparison with adjustments performed under visual control was made. Although influences of kinaesthetic/haptic and visual orientational estimates were investigated in studies dealing with the oblique effect (Appelle and Gravetter 1985; Gentaz et al 2001; Lechelt and Verenka 1980; Luyat et al 2001; McIntyre and Lipshits 2008), the contrast between kinaesthetic and visual outputs in SV judgments was addressed only in the work of Mars et al (2001). Investigating the influence of galvanic vestibular stimulation on SV, these authors reported a weaker but significant effect when adjusting a hand-held light rod in darkness than when controlling the orientation of a visible rod. To our knowledge, there is no comparative study focusing on the influence of different adjustment modes of SV in the presence of a tilted visual frame.

The third purpose of the present study was therefore to question the role of the adjustment mode on the occurrence of RFE. Classical visual SV settings were compared to 'visuo-kinaesthetic' settings where the rod was seen and hand-held by observers. The originality of the following experiment was to investigate the interaction between the RFE-inducing power of the visual field and the sensory systems controlling the SV output. Specifically, we examined how this interaction evolved over time during single SV adjustments. In addition, we managed to determine whether the rod-and-frame influence upon posture, notably reported by Isableu et al (1997, 1998), may also have a repercussion upon SV estimates. To that aim, two group-independent conditions of head restriction (head restrained upright versus head unrestrained) were also tested.

2 Methods

2.1 Subjects

Thirty right-handed subjects with normal or corrected-to-normal vision participated in the experiment. Fifteen subjects (eight males, seven females; mean age 21.8 ± 3.0 years) were tested with their head unrestrained, and fifteen other subjects (six males, nine females; mean age 28.5 ± 3.6 years) were tested with their head restrained upright. None of them presented a previous history of vestibular and neurological symptoms. All gave informed consent in compliance with the ethical committee which governs and regulates human experimentation in France.

2.2 Apparatus

Two distinct setups were used to elicit the RFE. The first one is a replication of the RFT portable apparatus developed by Oltman (1968). It is composed of a box (57 cm deep \times 31 cm wide \times 31 cm high) made of wooden white surfaces whose inside edges and corners were marked by black painted lines. The interior of the box was illuminated and the entire device could be tilted by the experimenter at different roll orientations.

A black rod (30 cm long; apparent size: 29.5 deg), fixed to the centre of a black square frame (apparent side size: 30.5 deg), could be independently rotated by the subjects and the experimenter via distinct hand-levers. A protractor, displayed on a disc mounted at the rear of the box and visible only to the experimenter, indicated the deviation of both the frame and the rod from vertical (measurement accuracy: 0.2 deg). Each subject was seated so that his/her face was aligned with the front edge of the box (not seeing the outer environment), and the eye level coincided with the axis of rotation. Subjects were required to keep their unrestrained heads upright during the adjustment (head unrestrained group) or to fit their heads upright into a restriction device composed of a chin-rest and a head-rest (head restrained group).

The second setup manipulated in the present experiment is the immersive virtual-reality display (CAVE-like) housed in the Mediterranean Virtual-Reality Centre at Marseilles. It is constituted of a 3 m deep \times 3 m wide \times 4 m high cubic space, with three vertical screens for walls and a horizontal screen for the floor. The three vertical surfaces were back-projected and the ground received direct projection with a 1400 \times 1050 pixels resolution and a 60 Hz frame rate. Stereoscopic projection of virtual environments was achieved by two DLP[®] (digital light processing) projectors attached to each projection surface. Stereoscopic separation between left-eye and right-eye images was ensured by colorimetric separation (Infitec[®] technological solution). Infitec[®] filters were installed in the projectors, and subjects were wearing glasses with the same filters for high-quality passive stereopsis. An anti-aliasing mode of projection was used in order to avoid any directional cue mediated by pixel alignment. The projection system was controlled by a cluster of 5 PCs (1 master + 4 slaves, each attached to a two-DLP[®] projection surface). Virtools[®] solution was used to build and control virtual scenarios. Finally, a head-tracking system (ArtTrack[®]), featuring infrared recognition of passive markers placed on the glasses, was used to record the subject's head position and orientation (accuracy: 0.05 $^\circ$), and to update in real-time the stereoscopic images in relation to the subject's point of view. Subjects were seated in the immersive environment, with their heads restrained or unrestrained, 2 m away from the front wall. Their field of vision was thus entirely stimulated by the visual display (the apparent size of the virtually projected rear frame reached 73 deg). A head-rest with straps and back support fixed behind the chair was used to keep the head orientation upright for the head-restrained group of subjects.

Subjects were randomly presented with three different virtual scenes (figure 1a). Scene 1 typically reproduced the RFT environment (with a much larger scale, however). Observers faced a 3 m \times 3 m traditional square frame, being immersed in a tilttable cubic space bounded by contrasted orthogonal lines. Scene 2 consisted of an empty coloured wall-papered room with structured floor and ceiling. Features of the scene essentially reinforced the geometrical cues with increased parallel and orthogonal visual lines. Scene 3 corresponded to a fully furnished room. Virtual furniture included a red bookshelf, a desk with books and green plants, a halogen lamp, a well-known painting by Cézanne attached to the front wall, and a coffee table with a can of soft drink and an ashtray. These elements, lying at different distances from the subjects, added depth cues to the display and were also assumed to enhance high-level (ie cognitive) polarity cues for up and down (Howard and Childerson 1994).

SV judgments were assessed in two ways (figure 1b). In the first SV adjustment mode, subjects were asked to set a virtual rod to vertical by means of a computer mouse controlling its orientation in roll. The very small amplitude of mouse displacements (<1.5 cm) could not yield accurate information about the angular motion of the rod. The projected rod was centred relative to subjects' eye level, at a distance where it could be held with the extended arm. Virtual rod features (colour, apparent size, distance to the observer, projected height) were computed on the basis of the

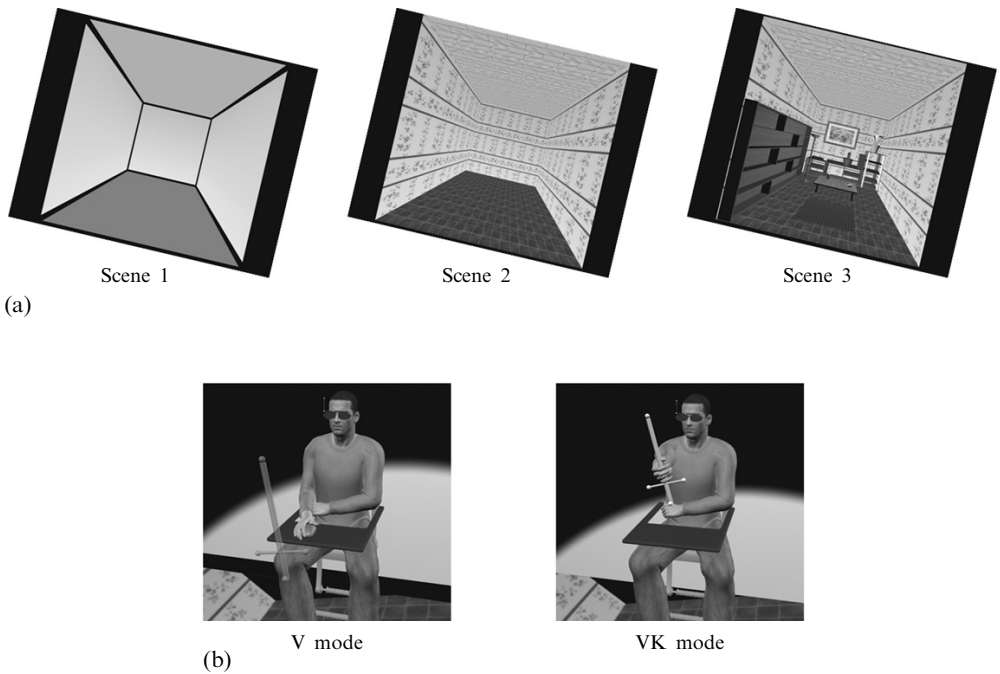


Figure 1. The experimental setup in the virtual immersive environment. (a) Subjects randomly faced three different stereoscopic virtual scenes. Scene 1 typically reproduced a classical 3-D rod-and-frame test (RFT) environment (with a much larger scale). Scene 2 consisted of an empty wall-papered room with structured floor and ceiling, increasing visual directional cues. Scene 3 corresponded to a full furnished room enhancing visual-polarity cues for up and down directions. (b) Subjects adjusted their subjective vertical in two ways: (i) through visual guidance only (V mode); (ii) through visuo-kinaesthetic control (VK mode, see text for further information).

characteristics of a real hand-held rod (used for the second adjustment mode) measured for each subject before starting the experiment. In this first condition, the rod orientation was controlled only by visual inputs (V mode). The second SV adjustment mode required the subject to hold a light plastic rod (40 cm long; 1 cm in diameter; weighing 60 g with uniform mass distribution) in the right dominant hand, and to adjust it along the vertical axis with an extended arm. Subjects were instructed to keep the centre of the rod at eye level and to look at it during adjustment. Markers positioned on the rod enabled us to continuously record its orientation via the ArtTrack[®] system (measurement accuracy: 0.05°), and ensured that the final location of the centre of the rod was kept around the same position across the trials. In that second adjustment mode, both visual and kinaesthetic inputs allowed the subjects to control the rod orientation (VK mode).

2.3 Procedure

The experiment was divided into two counterbalanced sessions, corresponding to the two adjustment modes manipulated in the immersive environment. Before the first session, both groups of subjects (head-unrestrained group and head-restrained group) were required to perform SV judgments through the portable RFT. Specifically, they were asked to “align the rod along the gravity axis” by rotating the hand lever. Nine frame tilts ($+38^\circ$; $+28^\circ$; $+18^\circ$; $+8^\circ$; 0° ; -8° ; -18° ; -28° ; -38°) and four initial rod orientations ($+45^\circ$; $+25^\circ$; -25° ; -45°) were manipulated to define basic individual RFE profiles. Pseudo-random presentations of initial rod positions and frame tilts were counterbalanced in order to cancel any order effect.

For each experimental session in the immersive environment, subjects were first seated and equipped with stereoscopic glasses after their interocular distance had been measured and taken into account for binocular-vision calibration of the rendering software. They were initially familiarised with the task and environment by experiencing 10 blank trials. A typical trial went as follows: an auditory signal launched an 'exploration phase', lasting 5 s, during which subjects had to inspect their visual surroundings (ie one of the three visual scenes previously described). At that stage, the rod was either not projected in the scene (V mode), or handled out of sight by the subjects whose supporting arms rested in a gutter aside (VK mode). Before the end of this first phase, subjects with their heads unrestrained had to reorient them in a stereotyped neutral position, closest to the trunk alignment. A second auditory signal marked the beginning of the 'adjustment phase', lasting 5 s. In V mode, the virtual rod appeared in the visual field at pseudo-randomised roll orientations and subjects were instructed to use the mouse to set their SV. They were allowed to make corrective adjustments throughout this phase if they judged them necessary. In VK mode, subjects were asked to extend an arm straight ahead (relative to the mid-sagittal body axis) and to orient the hand-held rod to the vertical, again with possible online corrections during the adjustment. Finally, a third auditory signal marked the end of the adjustment phase, coinciding with the removal of the virtual scene (V and VK modes) and allowing the subjects to move the arm back in the gutter, alternating different prone and supine initial rod positions (VK mode). The subjects were deliberately free to set the angle of these initial orientations (ie randomly). In this way, they could not control the motor execution of a multi-joint coordinated arm movement so that it was similar across trials but, rather, they had to focus on the control of the rod orientation relative to vertical. A 1.5 s transition period was set before a new trial was initiated. A 5 min resting period was inserted in the middle of each session so that the subjects could keep a stable level of concentration throughout a session. Overall, each session in the immersive environment (V mode or VK mode), separated by an interval of two days, crossed 9 scene tilts ($+38^\circ$; $+28^\circ$; $+18^\circ$; $+8^\circ$; 0° ; -8° ; -18° ; -28° ; -38°) and three visual scenes (scene 1, scene 2, scene 3) with randomised initial rod orientations, for a total number of 162 trials (a similar set of combined conditions was repeated six times and averaged for subsequent statistical analyses).

2.4 Data processing

Final SV adjustments were collected during the RFT and averaged for obtaining mean individual signed deviations relative to the gravitational vertical (constant errors) for each scene tilt. Analyses of correlations (Bravais-Pearson tests) were performed to investigate the links between individual and mean subjective visual vertical settings recorded in real and virtual environment.

Rod and head location as well as orientation in 3-D were monitored by the tracking system throughout each trial in the immersive environment. For each trial, we selected two singular kinematic events during the adjustment phase, at which rod and head roll orientations were recorded, in order to characterise any evolution throughout the adjustment (figure 2). The first kinematic event corresponded to the moment at which the rod angular velocity reached zero for the first time during the adjustment (first movement endpoint). The second kinematic event corresponded to the end of the trial (SV final position).

Mean signed and unsigned deviations of the rod relative to the gravitational vertical (constant and variable errors, respectively) were processed for characterising SV judgments in the immersive environment.

Differences between 'raw' SV adjustments were tested by a multifactorial analysis of variance (ANOVA) conducted on the mean signed deviations of the rod relative to vertical.

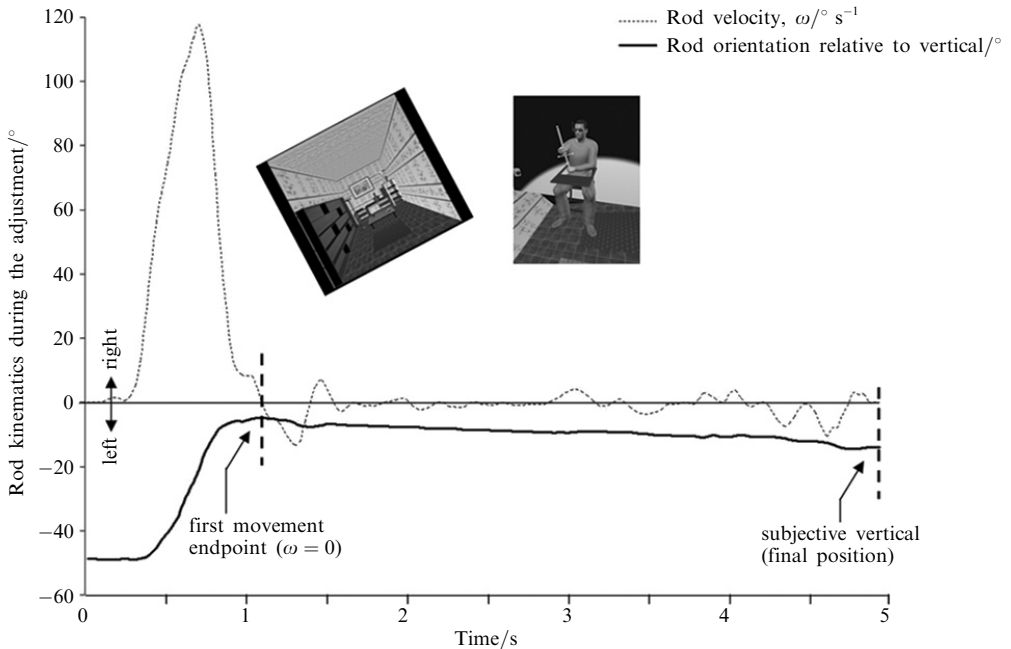


Figure 2. Typical recording of rod angular position in roll-over time during a subjective-vertical setting. The depicted trial corresponds to a setting performed by a subject under visuo-kinaesthetic control (VK mode) when facing scene 3 presented at -28° of tilt. Two events are distinguished in the trial: the ‘first movement endpoint’ corresponds to the rod orientation when angular velocity reaches zero for the first time. The subjective vertical (SV) corresponds to the rod orientation at the end of the trial. Noteworthy in this representative example the rod orientation is close to the physical vertical at the first movement endpoint, but is progressively drawn towards the scene orientation at the end of the trial (SV final position). Some other settings revealed a more sudden shift of SV after the first movement endpoint which was almost stabilised until the end of the trial. Although illustrated here for the VK mode only, the sample descriptors (first movement endpoint, final SV) were analysed in both V and VK modes.

The factors were: head restriction group (head restrained versus unrestrained), scene tilt (-38° ; -28° ; -18° ; -8° ; 0° ; $+8^\circ$; $+18^\circ$; $+28^\circ$; $+38^\circ$), visual scene (scene 1, scene 2, scene 3), adjustment mode (V versus VK), and kinematic event (first movement endpoint versus SV final position). Repeated measures were applied for the last four factors.

Differences in RFE were tested by a four-way ANOVA conducted on the mean unsigned deviations of the rod relative to vertical, averaged across the different scene tilts. Factors were head restriction group (head restrained versus unrestrained), visual scene (scene 1, scene 2, scene 3), adjustment mode (V versus VK), and kinematic event (first movement endpoint versus SV final position). Repeated measures were applied on the last three factors.

The influence of experimental conditions on head orientation was also evaluated for the head unrestrained group with a four-way repeated-measures ANOVA applied to the mean signed deviations of the head relative to vertical. Factors were scene tilt (-38° ; -28° ; -18° ; -8° ; 0° ; $+8^\circ$; $+18^\circ$; $+28^\circ$; $+38^\circ$), visual scene (scene 1, scene 2, scene 3), adjustment mode (V versus VK), and kinematic event (first movement endpoint versus SV final position).

The effect magnitude (η_p^2) and the power ($1 - \beta$) of each test were provided. A posteriori analyses (Newman–Keuls tests) were conducted when necessary to further study significant interactions between factors.

3 Results

3.1 SV in real and virtual environments

As illustrated in figure 3, the SV appeared as a sinusoidal function of the scene tilt from -38° to $+38^\circ$ in both the RFT and the immersive environment. This shape is typical of classical RFE reported in the literature. The correlation between the mean data recorded in the RFT and the immersive environment was high and significant.

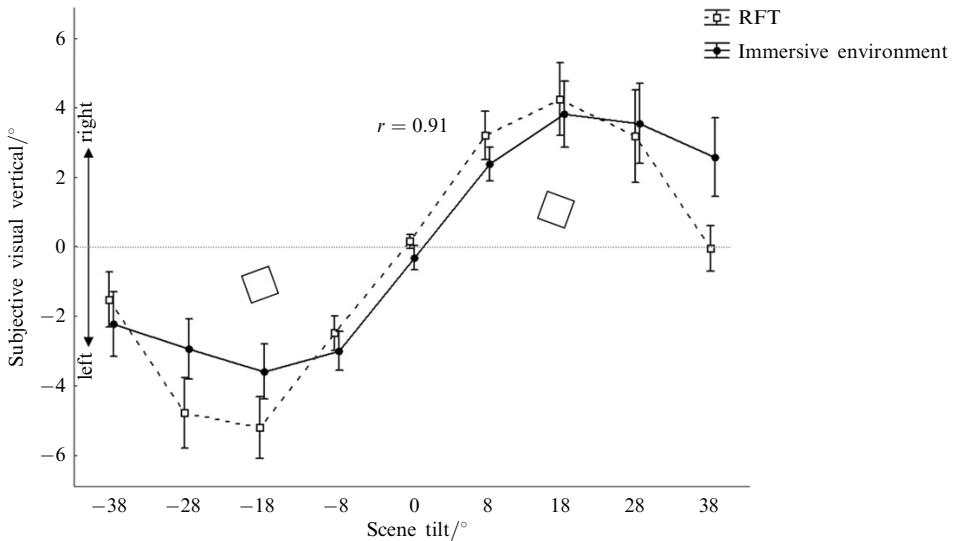


Figure 3. Mean SV settings as a function of tilt of the visual scene in real (portable rod-and-frame test, RFT) and the virtual immersive environment. Sinusoidal curve is typical of a classical rod-and-frame effect (RFE). Error bars represent 95% confidence intervals.

Correlation analyses conducted on each subject's set of data confirmed the previous observation. Except for subject 3, individual correlations were all high and significant (figure 4). Despite the difference between visual environments (eg apparent size, luminosity), the SV deviations elicited in both displays were qualitatively comparable within subjects and constituted specific 'signatures' of individual RFEs.

3.2 Rod-and-frame effects in the immersive environment

In line with the previous results, the ANOVA conducted on the mean signed deviations of the rod relative to vertical revealed a main effect of scene tilt ($F_{8,224} = 59.40$, $p < 0.001$, $\eta_p^2 = 0.68$, $[1 - \beta] = 1$). This confirmed the presence of RFE in SV estimates in the immersive environment, whatever the experimental condition.

3.2.1 Influence of the visual scene on RFE. A significant interaction was found between scene tilt and visual scene when comparing the mean signed deviation of the rod relative to vertical ($F_{16,448} = 28.93$, $p < 0.001$, $\eta_p^2 = 0.51$, $[1 - \beta] = 1$). It shows that the RFE increased as a function of the structure of the visual scene (figure 5a). Indeed, as revealed by the ANOVA performed on the mean unsigned deviations of the rod relative to vertical ($F_{2,56} = 57.82$, $p < 0.001$, $\eta_p^2 = 0.67$, $[1 - \beta] = 1$) and illustrated in figure 5b, the RFE magnitude was larger for scene 3 than for scene 2 ($p < 0.001$), and was larger for scene 2 than for scene 1 ($p < 0.001$).

3.2.2 Influence of the adjustment mode on RFE. A significant interaction was also found between scene tilt and adjustment mode when comparing the mean signed deviations of the rod relative to vertical ($F_{8,224} = 12.75$, $p < 0.001$, $\eta_p^2 = 0.31$, $[1 - \beta] = 1$).

It shows that the RFE was greater for SV adjustments performed in V mode than in VK mode (figure 6a). This was further supported by a main significant effect of adjustment mode on the mean unsigned deviations of the rod relative to vertical ($F_{1,28} = 20.48$, $p < 0.001$, $\eta_p^2 = 0.42$, $[1 - \beta] = 0.99$; figure 6b).

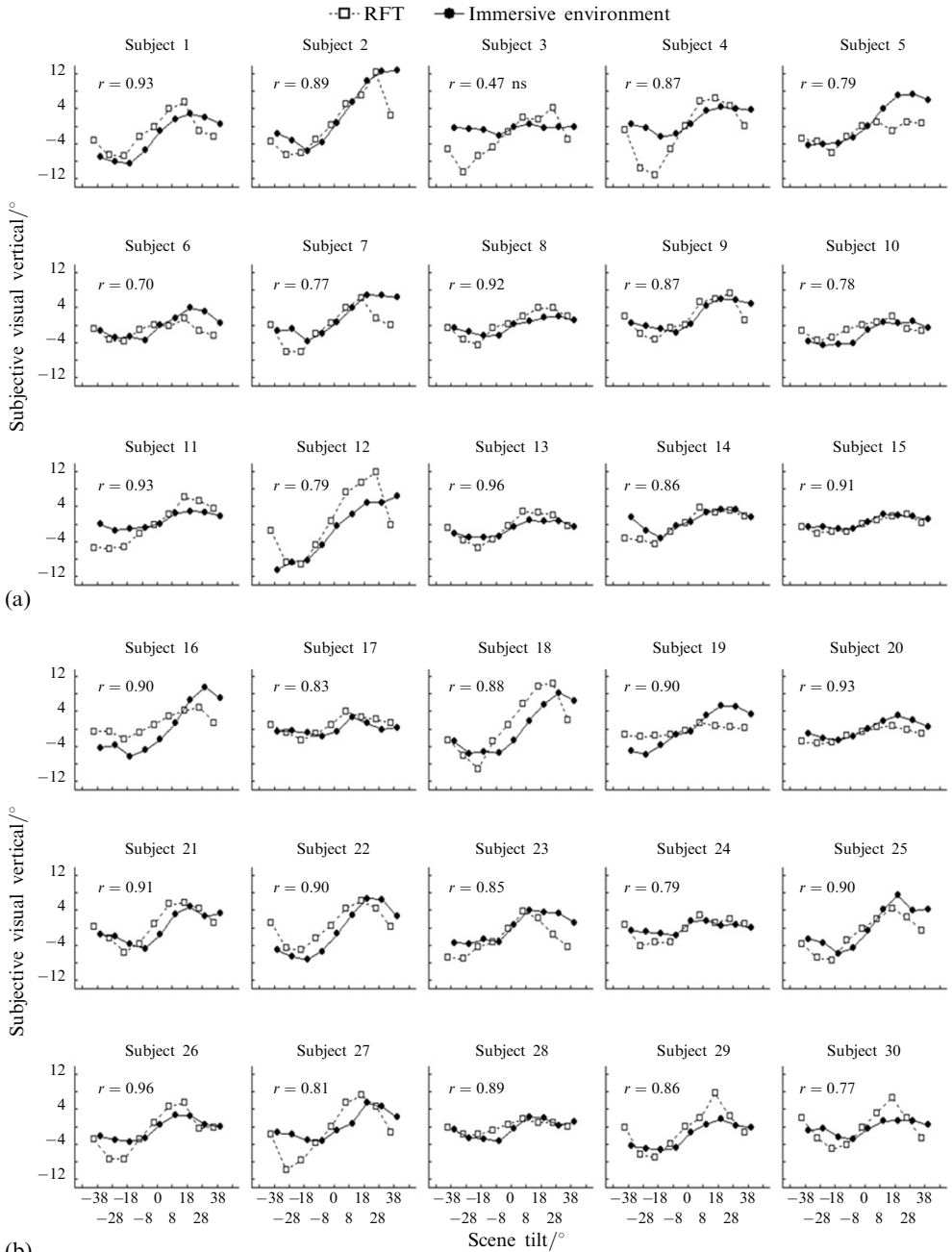


Figure 4. Individual correlations between SV settings recorded in the rod-and-frame test (RFT) and the immersive environment. Except for one subject, individual measures are highly and significantly correlated. (a) Head unrestrained (fifteen subjects); (b) head restrained (fifteen subjects).

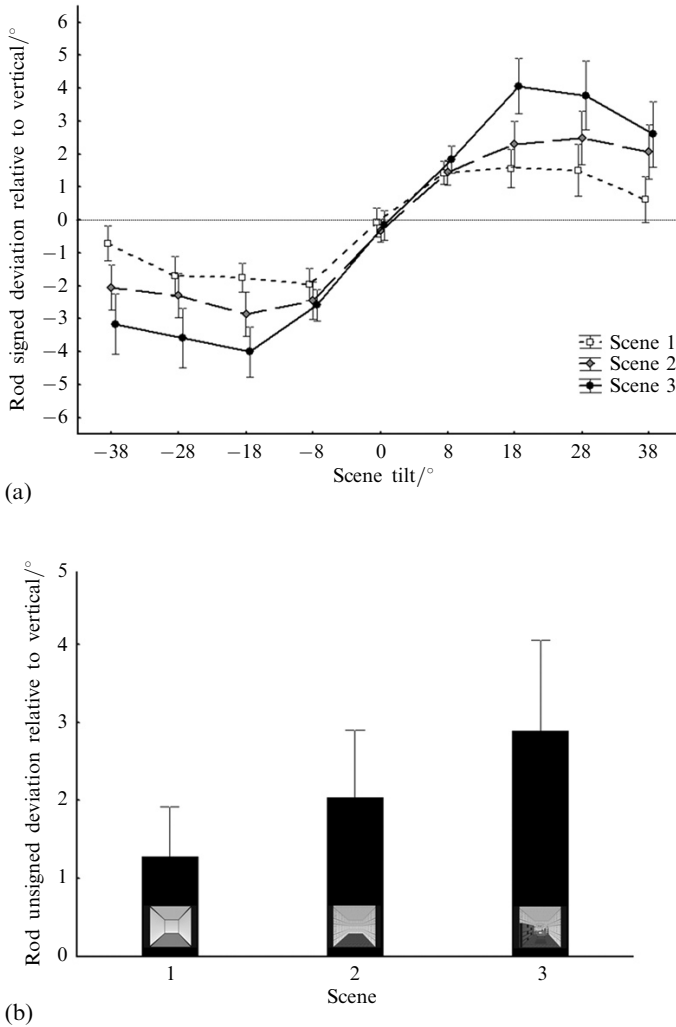
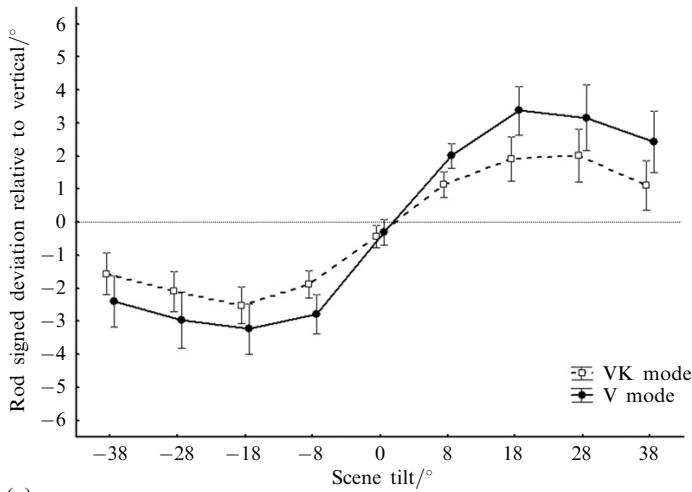


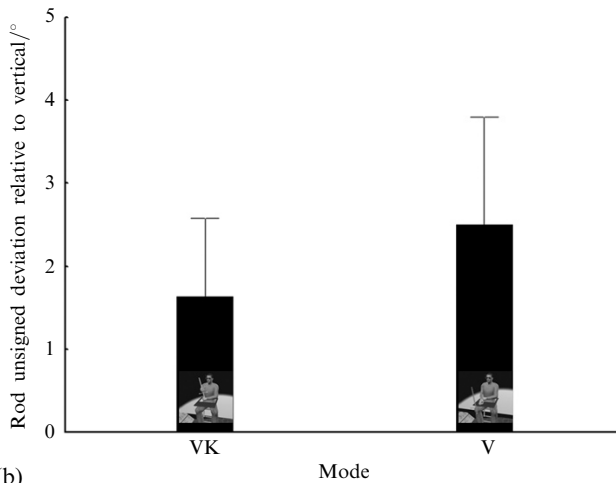
Figure 5. (a) Mean signed deviation of the rod relative to vertical during SV settings as a function of tilt and structure of the visual scene. (b) Mean unsigned deviation of the rod relative to vertical across the different scene tilts as a function of structure of the visual scene. Error bars represent 95% confidence intervals. The more structured the scene, the greater the rod-and-frame effect (RFE).

3.2.3 Evolution of the RFE as a function of kinematic event. Finally, a significant interaction was also found between scene tilt and kinematic event when comparing the mean signed deviations of the rod relative to vertical ($F_{8,224} = 19.26$, $p < 0.001$, $\eta_p^2 = 0.41$, $[1 - \beta] = 1$). It shows that the RFE was greater at the end of the trial (SV final position) than at the moment corresponding to the first movement endpoint of the rod. This was further supported by a main significant effect of kinematic event on the mean unsigned deviations of the rod relative to vertical ($F_{1,28} = 34.06$, $p < 0.001$, $\eta_p^2 = 0.55$, $[1 - \beta] = 1$), with larger deviations observed at the end of the trial.

Further analyses of interactions showed that the effect of kinematic event upon RFE was modulated by the visual scene and the adjustment mode.



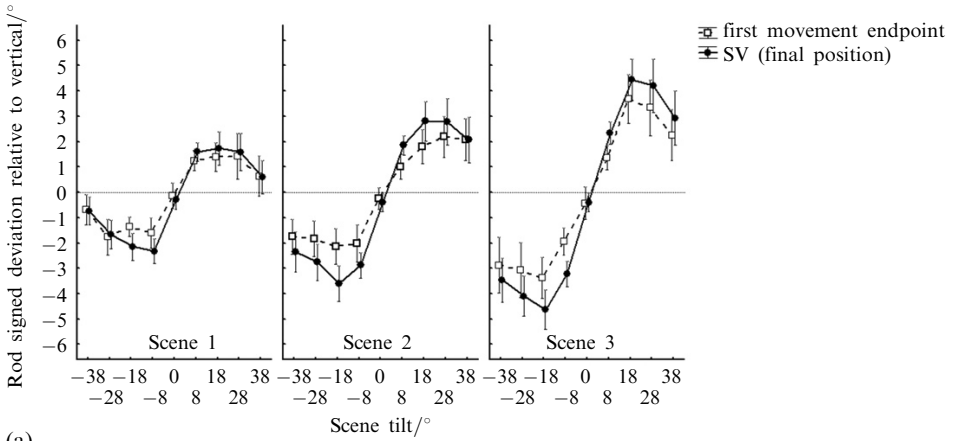
(a)



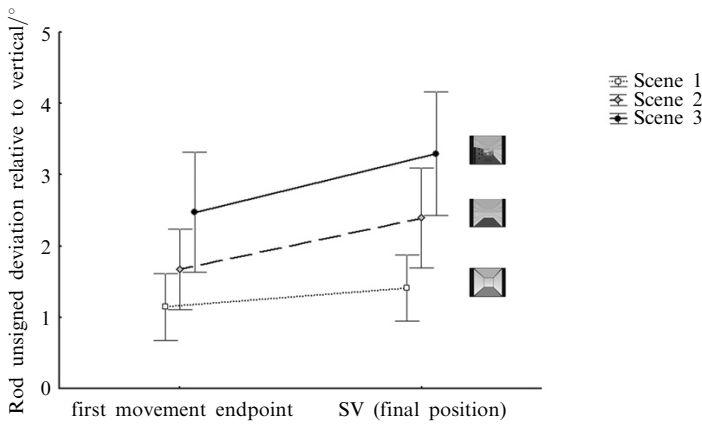
(b)

Figure 6. (a) Mean signed deviation of the rod relative to vertical during SV settings as a function of tilt of the visual scene and mode of adjustment. (b) Mean unsigned deviation of the rod relative to vertical across the different scene tilts as a function of mode of adjustment. Error bars represent 95% confidence intervals. The rod-and-frame effect (RFE) appears greater when SV is assessed under visual control only (V mode), compared to visuo-kinaesthetic control (VK mode).

The effect of kinematic event upon RFE (figure 7a) appeared indeed smaller for scene 1 than for scene 2 and scene 3, as revealed by the kinematic event \times visual scene \times scene tilt interaction found on the mean signed deviations of the rod relative to vertical ($F_{16,448} = 2.87$, $p < 0.001$, $\eta_p^2 = 0.09$, $[1 - \beta] = 0.99$). This was confirmed by the significant interaction between kinematic event and visual scene observed on the mean unsigned deviations of the rod relative to vertical ($F_{2,56} = 13.84$, $p < 0.001$, $\eta_p^2 = 0.33$, $[1 - \beta] = 0.1$). As illustrated in figure 7b, if larger deviations were observed at the end of the trial (SV final position) relative to the first movement endpoint when facing scene 1 ($p < 0.01$), this effect tended to increase when facing scene 2 and scene 3 ($p < 0.001$).



(a)



(b)

Figure 7. (a) Mean signed deviation of the rod relative to vertical during SV settings as a function of tilt and structure of the visual scene and kinematic event. (b) Mean unsigned deviation of the rod relative to vertical across the different scene tilts as a function of structure of the visual scene and kinematic event. Error bars represent 95% confidence intervals. The rod-and-frame effect (RFE) appears greater at the end of the adjustment (SV final position) than at first movement endpoint, this RFE increase being more pronounced for structured visual scenes.

The effect of kinematic event upon RFE (figure 8a) appeared also larger in VK mode than in V mode, as revealed by the kinematic event \times adjustment mode \times scene tilt interaction found on the mean signed deviations of the rod relative to vertical ($F_{8,224} = 4.79$, $p < 0.001$, $\eta_p^2 = 0.15$, $[1 - \beta] = 1$). This was confirmed by the significant interaction between kinematic event and adjustment mode shown on the mean unsigned deviations of the rod relative to vertical ($F_{1,28} = 14.64$, $p < 0.001$, $\eta_p^2 = 0.34$, $[1 - \beta] = 0.96$). As illustrated in figure 8b, if larger deviations were found at the end of the trial (SV final position) relative to the first movement endpoint in V mode ($p < 0.01$), this effect appeared to increase in VK mode ($p < 0.001$).

3.3 Head orientation influences in the immersive environment

Statistical analysis of the influence of experimental conditions on head orientation for the head-unrestrained group revealed a main effect of scene tilt ($F_{8,112} = 14.59$, $p < 0.001$, $\eta_p^2 = 0.51$, $[1 - \beta] = 1$). As illustrated in figure 9, the tilt of the visual scene exerted a comparable, although weaker, sinusoidal influence on head orientation as on rod orientation during SV adjustments.

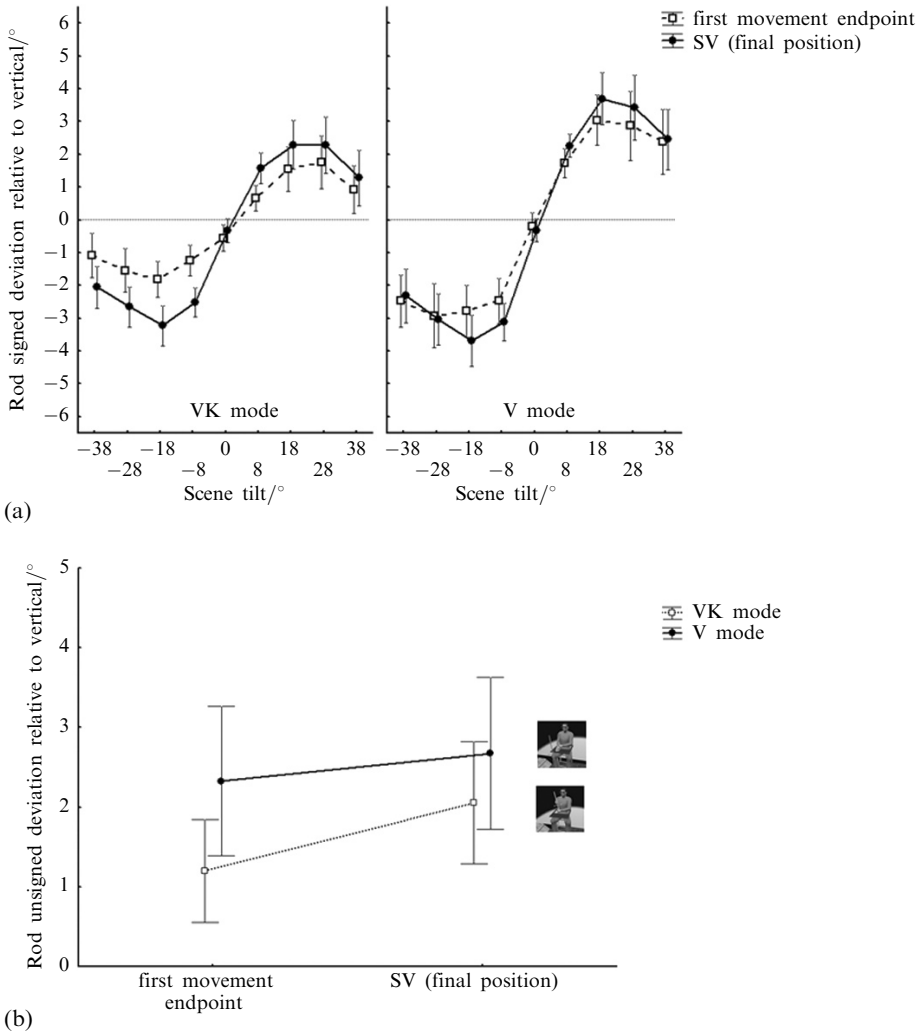


Figure 8. (a) Mean signed deviation of the rod relative to vertical during SV settings as a function of tilt and mode of adjustment and kinematic event. (b) Mean unsigned deviation of the rod relative to vertical across the different scene tilts as a function of mode of adjustment and kinematic event. Error bars represent 95% confidence intervals. The rod-and-frame effect (RFE) appears greater at the end of the adjustment (SV final position) than at first movement endpoint, this RFE increase being more pronounced under visuo-kinaesthetic control.

Despite the slight influence of scene tilt on head orientation, no difference was found between the two head-restriction groups when comparing the mean unsigned deviations of the rod relative to vertical ($F_{1,28} = 0.02$, $p = 0.90$, $\eta_p^2 = 0.001$, $[1 - \beta] = 0.05$). Furthermore, no significant interaction was found between the head-restriction group and scene tilt ($F_{8,224} = 0.14$, $p = 0.99$, $\eta_p^2 = 0.005$, $[1 - \beta] = 0.09$) as well as for the other factors when comparing the mean signed deviations of the rod relative to vertical. In other words, subjects having their head unrestrained, although exhibiting a slight influence of scene tilt upon their head orientation, did not differ from subjects having their head restrained when assessing SV.

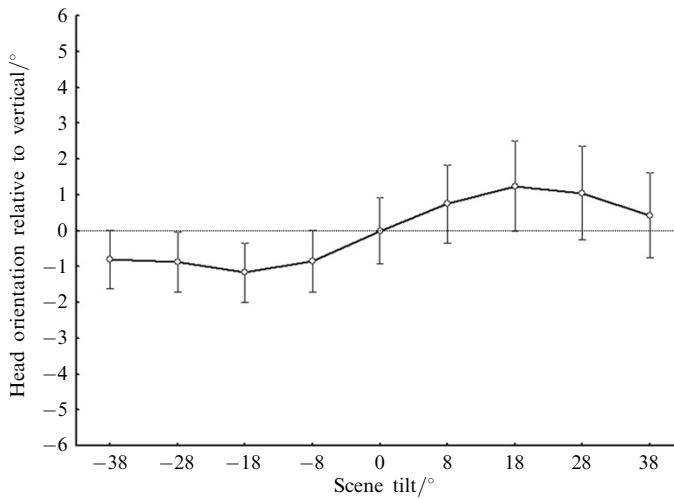


Figure 9. Mean head orientation relative to vertical during SV settings as a function of tilt of the visual scene in the head unrestrained group. This illustrates the existence of a significant although small ‘postural frame effect’.

4 Discussion

The main purpose of the present study was to further investigate how the structure of the visual scene and the mode of adjustment may exert combined and dynamic influences upon SV judgments in a virtual-reality setup. The first part of this work was to determine whether a large-scale immersive virtual environment was able to induce comparable influences on SV as a classical rod-and-frame display (eg a portable RFT apparatus; Oltman 1968). This first step would allow us to focus on the dynamic influences regarding the visual characteristics of the scene and the sensorimotor control of adjustment.

4.1 *Virtual reality as a valid tool for investigating the rod-and-frame effect*

Our results clearly demonstrated the strong inductive properties of the immersive environment for eliciting RFE. Furthermore, the sinusoidal shape of the subjective visual vertical as a function of scene tilt is typical of that reported in the literature, in the range of the test orientations (Oltman 1968). These observations were also supported by the significant individual correlations between visual vertical estimates performed in real versus virtual environments, despite the structural differences between the two displays (eg frame apparent size or luminosity).

Our results confirmed the claim of Jenkin and collaborators (2003), who suggested that virtual-reality displays may be of relevance for manipulating the role of visual cues when observers had to determine the physical direction of gravity (and, more precisely, the perceived direction of ‘up’). Mergner et al (2005) also reported comparable effects between real and virtual large-scale displays upon postural responses to visual motion, and stressed the advantage of virtual technology in its capacity to generate and modify a realistic visual stimulus with little effort in highly controlled conditions.

Physiological, behavioural, and perceptual responses recorded in virtual-reality displays may account for the level of subjective presence of an observer immersed in these virtual environments (Burkhardt 2003; Sanchez-Vives and Slater 2005). Presence may be defined as a state of consciousness of being inside a virtual environment (Slater 2002), and may be related to the responsiveness of the virtual environment to human actions (Heeter 1992). The underlying assumption is that the more a subject feels present

in a virtual environment, the closer his/her responses will be to those he/she would show in a similar real environment (Slater 2002). We therefore assume that the occurrence of RFE in virtually tilted visual scenes may indicate a level of presence of the immersed observer.

4.2 *Multimodal and dynamic influences in the induction of the rod-and-frame effect*

Having qualitatively validated the immersive setup as a powerful tool for inducing RFE, we aimed to investigate the structural influence of the projected visual scene and the effect of adjustment mode upon SV estimates. In addition, we analysed the evolution of these potential influences by comparing the rod orientations relative to vertical at two moments (ie specific kinematic events) of the adjustment phase.

First, our results clearly showed that RFE was modulated by the features of the visual scene (figure 5). The more 3-D geometrical cues the scene contained (ie the amount of parallel and orthogonal features in scene 2 versus scene 1) and the more additional cognitive cues determining visual up and down direction the scene comprised (ie the amount of meaningful polarised objects in scene 3 versus scene 2), the larger the RFE. Hence, as reflected by the significant difference in RFE between scene 1 and scene 2 on one hand, and between scene 2 and scene 3 on the other hand, the present study gives support to both the low-level 'geometrical' hypothesis, in which RFE is mainly explained by automatic visual processes (Ebenholtz 1985; Li and Matin 2005a, 2005b; Wenderoth and Beh 1977), and the 'cognitive' hypothesis in which high-level representations of up and down direction are involved (Cian et al 2001; Howard and Childerson 1994; Howard and Hu 2001).

As regards the adjustment mode, a significant reduction of the RFE was found when subjects controlled their settings via both visual and kinaesthetic cues, as compared to classic adjustments involving visual control only (figure 6). The mass of the rod maintained in VK mode (weak and uniformly distributed) cannot account for this effect. This clearly suggests that kinaesthetic cues (cues including proprioceptive inputs and information about the motor command) may contribute to counteract the visual attraction induced by the visual frame. This new finding with regard to sensory influences upon the RFE magnitude is in line with previous studies assuming that the kinaesthetic system is highly specialised for perceiving earth-fixed axes (Darling and Hondzinski 1999). Specifically, it was shown that errors in aligning the forearm parallel to the earth-fixed vertical were lower than to body-fixed axes or external visual axes (Darling and Bartelt 2003). More generally, this result demonstrates that the perceived vertical is critically dependent on the sensory inputs available during measurement (Carriot et al 2008).

Another concern was related to the online evolution of the RFE during a single adjustment, in order to better understand how the previously described multimodal influences may occur and dynamically interact over time. Strikingly, RFE occurred as early as the first movement endpoint of the adjustment. In addition, a significant increase of the RFE was found over time, from the first movement endpoint to the SV final position. This RFE increase during the adjustment phase was also found to be modulated by the type of visual scene and by the adjustment mode. Instead, SV judgments deviated towards scene tilt between both kinematic events to a greater extent when the visual scene contained geometric and meaningful 3-D features, and when the adjustment enabled visuo-kinaesthetic control. This might illustrate the progressive increase of visual influence depending on its relevance for orientation judgments and on the presence of other additional sensory inputs. The presence of online modifications regarding the RFE magnitude is in accordance with some findings related to vection phenomena. Vection intensity, defined as the strength of a visually induced perceived self-motion, was shown to evolve over time, with different perceptual

stages (Howard and Howard 1994). Online transitions between these stages (such as vection entrance latency or vection saturation) have been found sensorily related (Lepecq et al 1999), depending on the weight accorded by the central nervous system (CNS) to visual or vestibular inputs during the integration process.

A last issue concerned the involvement of head orientation in the reported RFE. As shown for subjects having their heads unrestrained, the scene tilt exerted a significant, although smaller, effect upon head posture. This result is in accordance with a 'postural frame effect' which has been shown to exist at the head level as well as for the whole-body in both field-dependent or field-independent subjects (Isableu et al 1997, 1998). Nevertheless, no significant difference was found between the two groups of subjects (head restrained versus head unrestrained) when comparing their SV estimates. This may suggest that the head deviation from vertical observed in the head-unrestrained group was too small to yield an additional postural influence (eg E-like effect—Bischof 1974; Müller 1916; or A-like effect—Aubert 1861; Mittelstaedt 1986) upon the perceived orientation of objects relative to gravity.

Overall, our results suggest that the RFE exerted by the tilted scene is not only influenced by the visual structure of the scene but also by the mode of adjustment, and may also rapidly evolve over time. In parallel to the previous sensory interpretations, these results may be explained in terms of interaction between different reference frames for orientation judgments.

4.3 *The subjective vertical as the result of a combination between reference frames*

As proposed by Howard (1982, 1986), different reference frames may contribute to the cognitive determination of the SV. A reference frame may be defined as a system of coordinates including sets of axes or references used to code and update the location and the orientation of objects in space (Batista 2002). For instance, the rod tilt may be referred to the direction of gravity (geocentric reference frame), to the main head-and-trunk axis (egocentric reference frame), or to the spatial features of the surrounding scene (allocentric reference frame). However, as shown in the present study, SV estimates are not fully aligned with any one of the above references. Therefore, the existence of subjective 'composite' reference frames (Luyat et al 2001; Bringoux et al 2008) may be advanced to explain our results.

It is well-known that SV is not only influenced by the visual frame, but also by body tilt (Schöne 1964) and by modifications of the gravitational field (Clark and Graybiel 1968). This clearly suggests that all the reference frames mentioned above are potentially involved in the perceptual elaboration of the SV. The question remains how they may interact and combine at the CNS level to yield a unique—currently used—subjective reference frame. In line with our hypothesis, we can reasonably assume that a specific weight is attributed to each reference frame in the combination process, and that this weight may be dynamically modified, depending on task constraints. To illustrate this in our experiment, one may consider that the allocentric reference frame could be differentially weighted as a function of some initial task constraints (eg tilt and structure of the visual scene, adjustment mode), and might also be re-weighted over time during the adjustment, depending on the same task constraints. Consequently, the CNS might have integrated this information with a specific weight when combining the multiple reference frames.

The analogy with the sensory re-weighting processes which have been found to occur during multisensory integration (Carver et al 2006) is, of course, intentional. However, we claim that different sensory inputs may be processed in the same reference frame, although some are naturally specialised to convey information relative to a specific coding. For instance, if visual inputs are essentially related to the allocentric reference frame, and vestibular signals are referred to the geocentric reference frame,

somatosensory cues could convey information related to either egocentric (eg limb position relative to others—Sherrington 1900), geocentric (eg gravitational torque referred to the limb orientation in space—Darling and Hondzinski 1999), or even allocentric (eg haptic spatial representation for blind subjects) coding. Recent studies confirmed the existence of neurophysiological substrates related to allocentric, egocentric, or geocentric coding (Committeri et al 2004; Galati et al 2000; Lopez et al 2005). However, further research is needed to better understand the role of sensory inputs in the construction as well as in the combination between reference frames.

5 Conclusion

To our knowledge, the present study is the first to show dynamic influences related to the visual structure of a virtual environment and to the mode of adjustment upon the perception of verticality. These effects may result from the dynamic combination between reference frames, which may occur and evolve throughout the SV adjustment. The use of a virtual immersive environment has been found to be effective in easily manipulating the structure of the visual scene, and promising for further investigations concerning the richness of the visual scene as a function of the sensory modalities involved in the perception of verticality.

Acknowledgments. We are grateful to Jacques Crémieux and Gabriel M Gauthier for RFT design, and to Véronique Chastres for statistical support.

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ISSN 0301-0066 (print)

ISSN 1468-4233 (electronic)

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VOLUME 38 2009

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