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Perception of the vertical with a head-mounted visual frame during head tilt

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This study addressed the question of potential disorienting effects associated to head-mounted displays, by investigating the influence of a head-fixed visual frame on the perception of the vertical when the head is tilted in the frontal plane. Subject performance in indicating the vertical was contrasted with the effect of an earth-fixed visual frame as well as with the effect of tilting the head without a frame. With the tilted frames, subjects set the rod in an intermediate direction between the gravitational vertical and the orientation of the frame. Errors were strikingly larger with a head-fixed visual frame during head tilt than with a tilted earth-based frame. The increased effect cannot be attributed to the addition of a postural effect, due to the head being tilted. Moreover, continuous vision of the frame when its orientation changed improved performance only when the head and the frame were dissociated, i.e., with an earth-based frame. Those results suggest that integrating visual information in the head-centric reference frame is crucial for spatial orientation. This property of the perceptual system should be taken into account in the design of head-mounted displays for aeronautics.

1. Introduction

Head-mounted displays (HMD) are now extensively developed and tested to be used in enhanced or virtual reality environments (Loomis *et al.* 1999). In particular, enhanced reality draws a lot of interest from researchers and designers working on the human–machine interfaces in military aircraft. The technique consists in projecting visual information in the pilot's helmet in such a way that some elements of symbology are superimposed on the real world. In that way, the pilot can have access to the symbology whatever his/her head orientation in the cockpit and he/she does not need go head-down to gather information from the panel displays. HMDs were initially introduced to enhance target tracking and targeting, but there is now

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an effort to bring in other elements of symbology, including attitude indicators (Cohen *et al*. 2001, Liggett and Gallimore 2002). Thus, HMDs may contribute to improve the perception of spatial orientation. However, Previc (2000) warned that it may also induce spatial disorientation, a consequent source of accidents in military aeronautics, if the choices made for their design are inadequate. This point is a matter of debate in the aeronautic community, but experimental investigations dealing with this problem are leaving uncertainty about why and how the HMDs may influence spatial perception. The present laboratory study aimed to fill some of the gap by investigating the influence of a head-fixed visual frame on the perception of the vertical.

One way of presenting series of information in the HMD without occluding vision is to dispose them in line in the periphery of the pilot's visual field, on both sides of the head for instance. These displays can be head-slaved in order to be constantly available to the pilot by way of a simple gaze shift, whatever the orientation of his/her head. This solution results in presenting oriented visual information that is tilted relative to the vertical when the pilot tilts the head of the aircraft, during banking manoeuvres for example. In that case, the head-fixed visual information can form a kind of frame surrounding the central symbology. This frame could give rise to misperception of the orientation of any central attitude indicator. Indeed, it is well known that a tilted visual frame impairs judgements of verticality when they are performed in darkness (the frame effect, Witkin and Ash 1948, Rock 1990). Typically, when observers are required to set to the vertical a visual rod presented inside a luminous tilted frame, they tend to indicate an intermediate direction between the gravitational vertical and the direction of the tilted frame. The frame effect can be considered as the result of the competition between visual and graviceptive (vestibular and somesthesic) information. Moreover, the frame effect is increased when vertical settings are performed when the head or the whole body is tilted relative to gravity (DiLorenzo and Rock 1982, Goodenough *et al*. 1985, Zoccolotti *et al*. 1992, Guerraz *et al*. 1998b).

Adding some kind of head-fixed visual frame in HMDs also means that the pilot would be in the presence of an unusual configuration of information: during head motion, the visual frame would move in extra-personal space while remaining stable in the head-centric reference frame. This property may be crucial with regard to actual models of spatial orientation which stress the role of the head-centric reference frame in multisensory integration. Indeed, in order to correctly perceive the orientation of a visual object in space, the central nervous system (CNS) must process retinal information in a geocentric reference frame, defined by the direction of gravity. It has been recurrently suggested that this is achieved by a chain of coordinate transformations involving various sources of information (Howard 1986, Mergner and Rosemeier 1998). The projection of the object's image on the retina must be registered along with the orientation of the eyes relative to the head, which involves eye position signals. Vestibular signals must also be taken into account as they provide information about position and velocity of the head in space. Finally, proprio-somesthesic information provides the link between the head and the body support. In other words, the orientation of a visual object relative to gravity is assessed by transposing retinal coordinates in a geocentric reference frame via intermediate stages, such as head-centric and body-centric reference frames. There is some neurophysiological evidence that populations of multimodal neurons distributed across the posterior parietal cortex carry out such transformations of sensory coordinates (Brotchie *et al*. 1995, Andersen *et al*. 1997, Duhamel *et al*. 1998, Snyder *et al*. 1998). Head-fixed visual information cannot be found in natural conditions, as the coordinates of a visual object always change relative to the head when the head or the object itself moves in space. This implies that the CNS probably did not evolve to process head-fixed visual references and could be confronted as a consequence with informational conflicts to be solved.

The first goal of the present experiment was to obtain psychometric functions that describe the perception of the visual vertical in function of head tilt magnitude while viewing a head-fixed visual frame. For this a head-mounted video display was used. Wearing this apparatus gives the sensation of viewing a head-centric monitor screen, with clearly seen rectangular contours. Thus, when subjects tilted their head, the vertical symmetry axis of the frame remained constantly aligned with the vertical axis of the head. The effects of tilting the head without visual frame and of tilting an earth-based visual frame without tilting the head were also assessed in similar conditions. These conditions allowed a determination of whether or not the effects of a head-fixed visual frame during head tilts can be explained by the addition of two independent effects: a postural disturbance (error due to the head being tilted, Wade 1968, Mittelstaedt 1986, 1995, Guerraz *et al*. 1998a) and a visual disturbance (the frame effect). Guerraz *et al*. (1998b) investigated the perception of the vertical with a static tilted frame. They argued that the increased frame effect obtained with the head tilted was only the addition of a postural effect. These conclusions are in opposition to those of DiLorenzo and Rock (1982), whose results are more consistent with the idea of an increased weight attributed to visual information when the head is tilted. The reasons why conflicting opinions still exist concerning this point probably reside in the fact that the above mentioned studies used different magnitudes of head and frame tilt. Thus, resolving the conflict between studies and generalizing conclusions is difficult. The interaction between visual and postural disturbance on a large continuum of tilt magnitudes was investigated to clarify this point. In order to assess the potential influence of the motor command or intention associated with voluntary head tilts, vertical settings obtained after active and passive head movements were also compared.

Another goal of the experiment consisted of evaluating the influence of viewing or not the head-fixed and earth-based visual frames while they rotated from one orientation to another on vertical settings. With the head-mounted frame, the perceived direction of gravity could only be assessed by means of head position signals, as the orientation of the frame co-varied with that of the head. In other words, coordinate transformation of visual information in the head-centric reference frame was irrelevant. In contrast, when an earth-based visual frame was rolled, its changes in orientation were dissociated from head orientation. The variations of the frame orientation relative to the head could therefore be processed with head position signals. In consequence, it was hypothesized that viewing the frame during its rotation would decrease its effect on the visual vertical only when the frame was earth-fixed.

2. Method

2.1. *Subjects*

Twelve subjects, nine males and three females, 23 to 41 years old, volunteered for this study. The experiment was carried out with subjects' signed informed consent in compliance with the Huriet Law (Helsinki Convention) on human experimentation.

All subjects were free of vestibular problems and had normal or near-to-normal vision. They all underwent the standard rod-and-frame test with Oltman's portable apparatus (1968), which has been used in numerous studies to quantify subjects' visual field dependence, i.e., reliance on visual information for estimating the vertical direction. The frame was tilted by 18°, a value known to induce maximal effects with this apparatus. The subjects committed a mean error of 3.7° (SD = 1.8) in the direction of the tilted frame, a score that is similar to what can be found in other experiments with a larger body of subjects (Oltman 1968).

2.2. *Material*

The experiment was carried out in total darkness, in a room painted in black with no windows. The subjects were seated on a chair. A visual rod was generated by a computer program and displayed either on a 17 inch (43.18 cm) monitor or on a video headset (Glasstron® PLM-S700 marketed by Sony™), depending on the experimental condition (figure 1).

The head-mounted display gave the sensation of viewing a 30° (width) × 22.5° (height) head-fixed monitor screen. The apparatus weighted 120 g and allowed adjustment of colour, brightness and contrast. The image was displayed on two 1.78 cm LCD screens, which provided no binocular cues (the same video signal is fed into both screens). Due to LCD technology limitations, it is not possible to generate an absolutely dark background with such devices. Thus, the virtual screen appeared as a dark grey rectangle on a completely dark surrounding. This luminance contrast generated a contour which was clearly perceived by the subject as a frame. Using a SVGA connection, the resolution was 800 × 600 pixels. The virtual screen was integral to the head, i.e., its position and orientation relative to the head always remained the same. On the contrary, the visual rod was stable in space. This was completed by monitoring head movements, using a magnetic tracking device, the Polhemus Fastrak® (3Space Devices). Head position and orientation were computed and compensated for in order to keep the rod still in space.

The 17 inch monitor was mounted at eye level on top of a platform that could be manually tilted in the roll plane. A tracker was attached to the monitor in order to record its orientation. At the viewing distance used (about 60 cm), the edges of the pixels were not distinguishable. The retinal size of the frame is the critical parameter that determines the strength of the frame effect. Caution was therefore taken to make sure that the contour of the luminescent screen subtended the same visual angle as the virtual screen generated with the head-mounted display. To do so, before running the experiment, the head-mounted display was set to the see-through mode with the lights on and the subject confirmed that the virtual screen was superimposed on the monitor. When the monitor was used during the experiment, the subject wore sunglasses under lensless plastic goggles, so that the rod and the frame formed by the screen were the only visible elements in an otherwise dark surrounding. A large black panel, having a 15 cm-radius hole at the centre (15°) was fixed on the front of the monitor when oriented visual references provided by the contour of the screen had to be removed ('head tilt' conditions; see procedure). In this case, the rod could be seen through the circular window.

The visual rod was white and oblong, 10° long and 2° wide at the middle. This shape was chosen in order to prevent subjects from using the vertical alignment of pixels as a cue to orientation, as can be done with a stimulus with a linear contour.

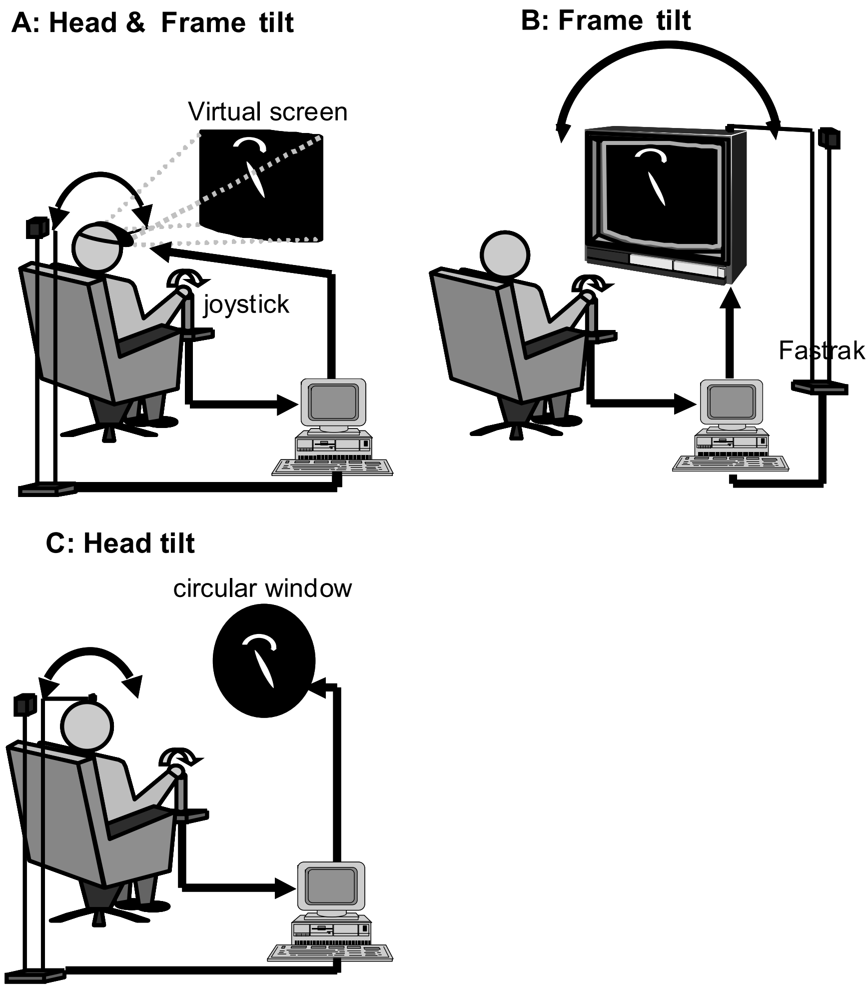

Figure 1. Experimental setup, for the three types of condition: head and frame tilt (A), frame tilt (B) and head tilt (C). In the two latter conditions, the distance between the viewer and the monitor was set in such a way that the screen had the same apparent size as the head-mounted virtual screen used in the former condition.

The rod could be rotated clockwise (CW) or counterclockwise (CCW) by acting on a joystick situated on the right arm of the chair.

2.3. *Procedure*

Subjects were instructed to set the visual rod to the vertical in eight experimental conditions. The vertical was defined as the direction of gravity, parallel to the surrounding walls, to a tree or to a standing person. The subjects were asked to perform the task intuitively, without putting too much thought into it.

The rod was continuously visible to the subjects while they made their settings and could be rotated back and forth. No time limit was imposed for adjusting the rod, but it rarely exceeded 5 s. When they were satisfied with their setting, subjects pressed the trigger of the joystick and the rod disappeared. For each push on the trigger, the error relative to the real vertical was automatically computed by the program and recorded on the hard disk, together with the screen and/or the head orientation. When a new trial was to be performed, subjects had to release the trigger in order to make the rod reappear. The computer program randomized the initial orientation of the rod. One experimental condition consisted of 40 trials.

2.3.1. *Head and frame tilt conditions (head-fixed visual frame)*: Subjects wore the head-mounted display. The first setting was always performed with the head aligned on the trunk. In the following trials, the subject tilted the head in the frontal plane at various positions (figure 1a). Both the virtual screen and the head were then tilted identically relative to the vertical. The head remained still while the subject attempted to set the rod to the vertical. Immediately after the trial completion, the head was tilted to a new orientation. Hence, trials followed one another in such a way that static head tilts did not last longer than the time required to adjust the rod orientation.

Four 'head and frame tilt' conditions were realized. In two of them, subjects produced voluntary head tilts of self-selected magnitude. Prior to these conditions, they were trained to perform head tilt without yaw rotation and without moving the shoulders or the trunk. Hence, head tilts larger than 40° were not demanded. Subjects were instructed to explore the range of possible CW and CCW head tilts in a pseudo-random sequence. In the remaining conditions, the head was tilted passively by the experimenter from one position to another. Subjects were instructed to relax, without resisting or assisting the movement. The experimenter tried to reproduce as accurately as possible the characteristics (acceleration, speed) of natural head tilts. For both active and passive movements, one condition was performed with the subjects' eyes closed while the head was tilted to a new position, and another condition was performed with the subjects viewing the frame.

2.3.2. '*Frame tilt' conditions (earth-based visual frame)*: Two 'frame tilt conditions' were performed. In both conditions, head movements were restrained using a neck brace. The experimenter changed the frame orientation in the roll plane by acting on the tiltable platform (figure 1B). Each new orientation was chosen at random between 40° CCW and 40° CW. In one condition, subjects were instructed to close their eyes between trials, in order to prevent continuous vision of the visual display during its rotation. In the other condition, vision of the screen while its orientation changed was allowed.

2.3.3. '*Head tilt' conditions (no visual frame)*: Similar to the 'head and frame tilt' conditions, subjects were required to tilt their head at 40 different positions and to estimate the vertical direction for each position (figure 1C). The rod was displayed on the monitor used in the 'frame tilt' conditions, placed at the same distance. This time, the borders of the screen were hidden using the black panel with the circular window. This condition was replicated with passive head movements.

Each subject was exposed to all experimental conditions in a within-subjects design. The order of presentation of the eight conditions was randomized. Between conditions, the room lights were switched on and the subjects could see their surroundings.

2.4. *Data analyses*
By convention, positive and negative values were respectively assigned to CW and CCW head tilts and errors in vertical settings. Figure 2 shows the responses of one subject in one of the 'head and frame tilt' conditions. This example is typical of most of the psychometric functions observed in this experiment, whatever the experimental condition. Indeed, the error made in estimating the vertical was, most of the time, a linear function of the head and/or the frame orientation from 0° up to 25° of tilt or more, where the error reached a maximum and sometimes decreased. Some other subjects presented pure linear responses. So, in order to fit at best all individual sets of data with the same method, third order polynomial regression analyses were performed. In this way, each response curve could be modelled by the following equation:

$$y = ax^3 + bx^2 + cx + d,$$

where y is the predicted rod setting and x is the orientation of the head and/or the frame. The statistical significance levels of each parameter were tested for individual analyses by dividing the estimates by their respective standard errors, computed from the finite difference approximation of the Hessian matrix of second order derivatives (Non-linear estimation module of Statistica®). The third order component of the equation, *a*, reflects the tendency of the subject to reach a maximum error before maximum head tilt, whereas the second order parameter, *b*, tests the symmetry of the curve. The first order parameter, *c*, is the slope of the linear part of the curve. Finally, the constant *d* is the error committed when the head was upright.

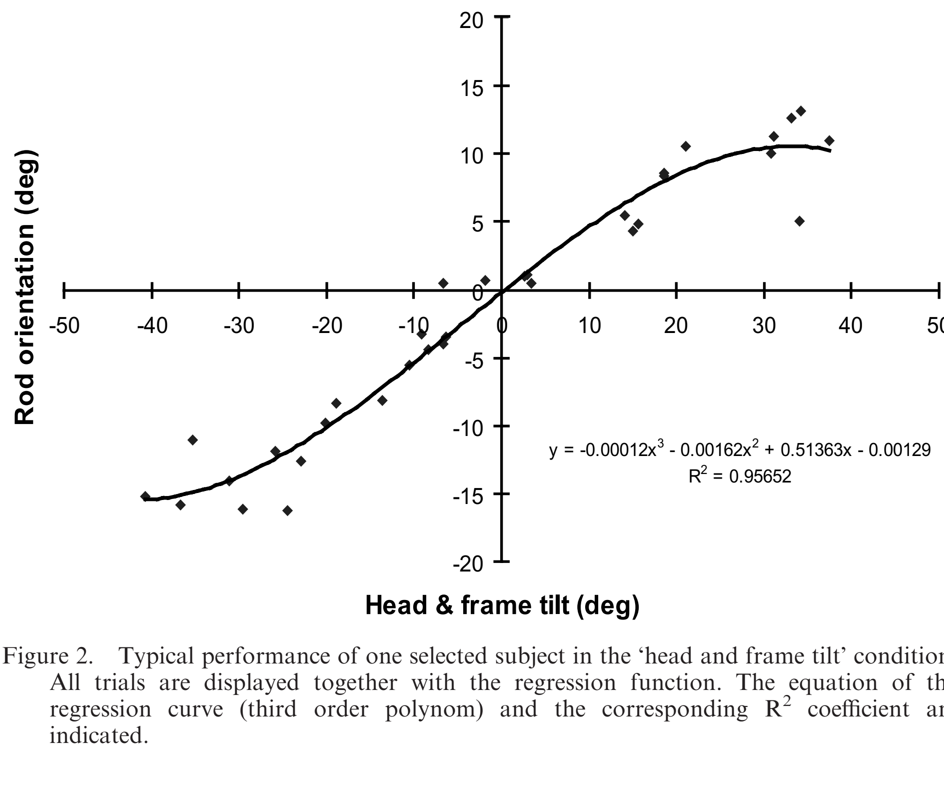

Figure 2. Typical performance of one selected subject in the 'head and frame tilt' condition. All trials are displayed together with the regression function. The equation of the regression curve (third order polynom) and the corresponding R^2 coefficient are indicated.

Screening of individual performances (not detailed here) revealed that whenever a subject was significantly affected by the experimental treatment, the corresponding function could be mostly summarized by its linear component. Thus, the slopes of the curves were the relevant data to estimate the strength of the effects and group statistical analyses were performed on them (constant error). Besides, the variable error was assessed by calculating the mean absolute residual error relative to the fitted curve.

3. Results

The vertical settings were similar with active and passive head movements, either in the 'head and frame tilt' conditions ($t_{11} = 0.90$ with eyes closed and $t_{11} = 0.64$ with eyes open) or in the 'head tilt' conditions ($t_{11} = 0.10$). Thus, data were collapsed along this variable and subsequent analyses were performed on the means. Figure 3 presents the mean response curves for all conditions. Each curve was obtained by computing and taking the mean of the values predicted by the individual models, on the whole range of investigated orientations (step = 2°).

In the 'head and frame tilt' conditions, subjects set the rod in the direction of the tilted head, in the 'eyes closed' condition (mean slope = 0.28) as in the 'eyes open' condition (mean slope = 0.29). An effect in the same direction but of smaller magnitude was observed in the 'frame tilt' condition with the eyes closed (mean slope = 0.17). This effect nearly disappeared when vision of the frame was allowed (mean slope = 0.08). In the 'head tilt' condition, the vertical settings were slightly deviated in the opposite direction to the head on average (mean slope = – 0.03).

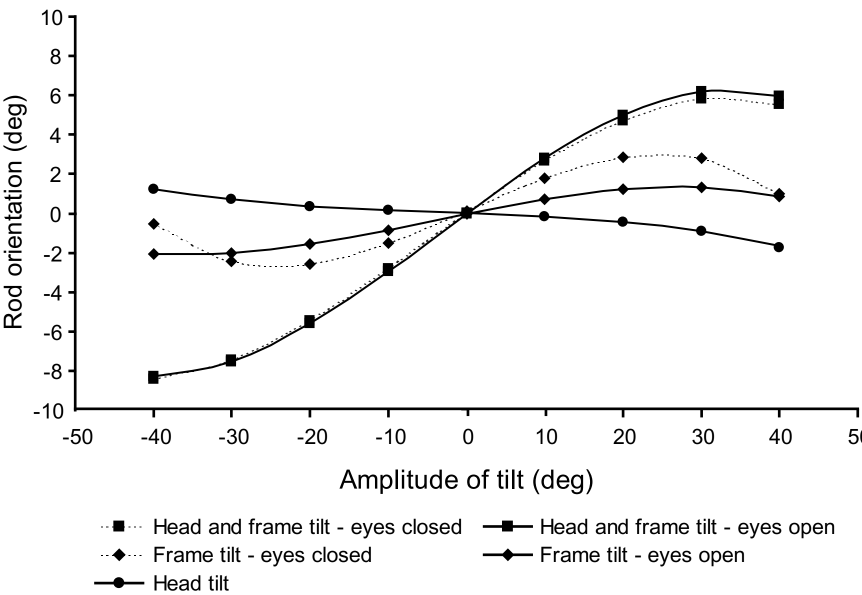

Figure 3. Mean estimates of the subjective vertical (in degrees, 0° corresponds to the gravitational vertical, positive angles correspond to CW rotations) as a function of tilt angle (in degrees) in all conditions. The curves correspond to the mean predicted responses for all subjects, based on the polynomial regression analyses illustrated on figure 2.

A 2 (head-fixed vs. earth-based visual frame) × 2 (closed eyes vs. open eyes) repeated measures ANOVA performed on the slopes of the curves revealed a main effect of the type of visual frame [$F(1,11) = 5.96$, $p < 0.05$], no main effect of vision of the frame [$F(1,11) = 4.15$, $p > 0.05$] and a significant interaction [$F(1,11) = 12.76$, $p < 0.005$]. *Post-hoc* analyses (adjusted Bonferroni comparisons) revealed that the interaction was the consequence of a significant effect of continuously viewing the frame for the 'frame tilt' conditions (the slope was greater in the 'eyes closed' condition in 10 subjects; $p < 0.01$), but not for the 'head and frame tilt' conditions [$p > 0.50$, figure 4].

Errors in the 'head and frame tilt' conditions were significantly larger than the sum of errors obtained in the 'frame tilt' conditions and in 'head tilt' conditions. This observation was found in all but one subject with the eyes closed ($t_{11} = 2.96$, $p < 0.05$), and with the eyes open ($t_{11} = 6.65$, $p < 0.001$).

In all the conditions, the residuals (absolute disparity between the observed value for each individual trial and the value predicted by the regression analysis for the same tilt angle) were calculated and the mean found. Mean absolute residuals were significantly different across conditions ($F(2,22) = 9.99$, $p < 0.001$). *Post-hoc* analyses revealed that within-subject variability was lower in the 'frame tilt' conditions than in both the 'head and frame tilt' conditions ($p < 0.005$) and the 'head tilt' conditions ($p < 0.05$). The difference between these latter conditions did not reach a significant level ($p = 0.15$). All other experimental manipulations (eyes open/eyes closed, active/passive movements) did not have significant effects on the variability in the vertical settings. Figure 5 describes the absolute residuals in function of the amplitude of tilt.

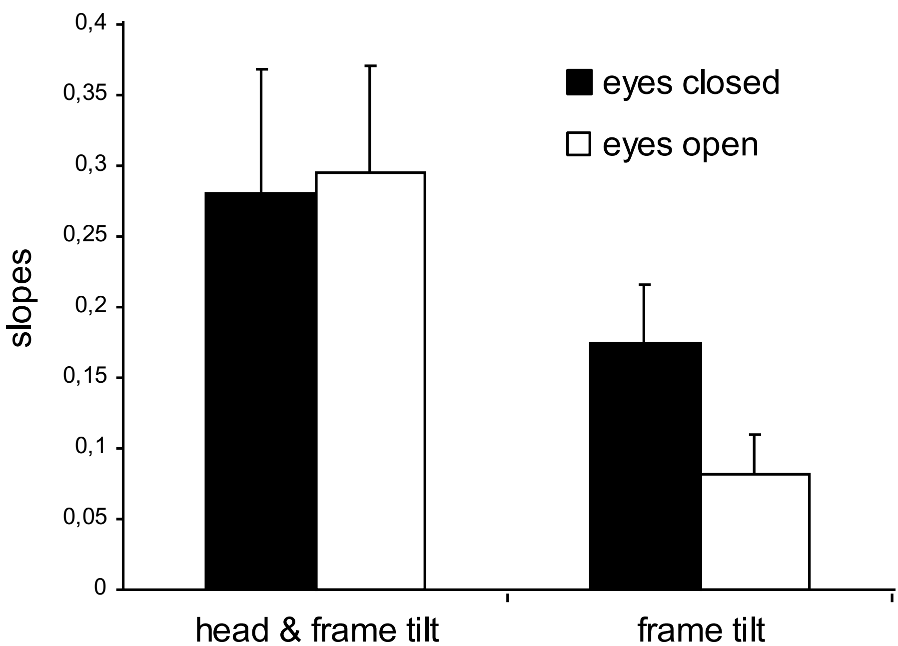

Figure 4. Effect on the subjective vertical of allowing or not vision during movement, in the 'head and frame tilt' and the 'frame tilt' conditions. The first order parameter (i.e., the slope of the line tangent to the curve at zero) was used to assess the strength of the effect of tilt on subjective vertical. Error bars represent the standard error of the mean.

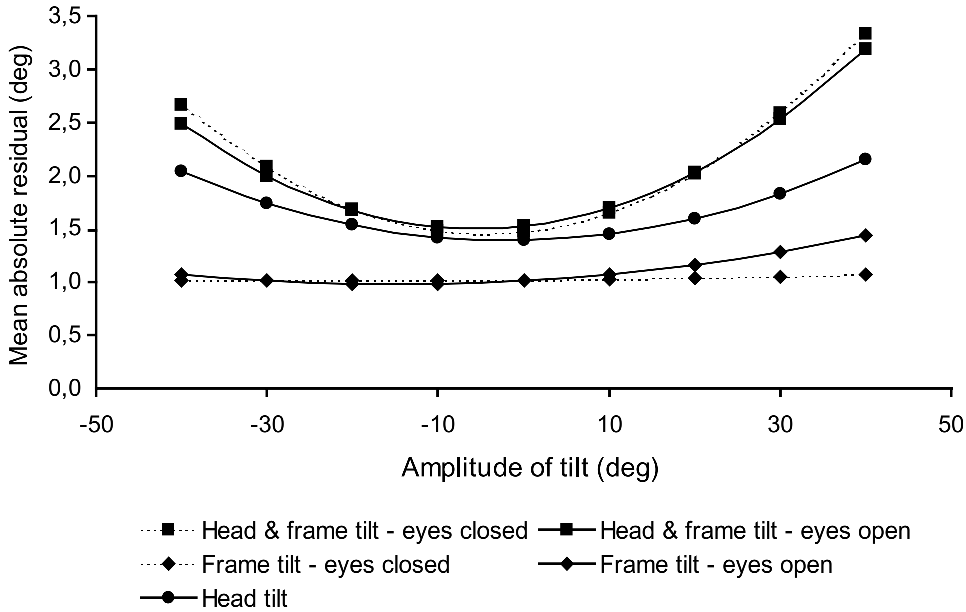

Figure 5. Distribution of mean absolute residuals (response variability) as a function of tilt angle in all conditions. The absolute disparity between the observed values for each individual trial and the predicted value for the same tilt angle was computed and the mean across subject determined.

When the head was upright ('frame tilt' conditions), mean absolute residuals remained nearly constant for the different orientation of the frame. On the contrary, variability increased with the degree of head tilt. This profile was striking, especially when head and frame tilts were combined ('head and frame tilt' conditions).

4. Discussion

The present study investigated the effect of a head-mounted visual frame on the visual vertical when the head is tilted. The effects of the head-fixed frame were compared to the single effects of tilting an earth-based visual frame and of tilting the head in the absence of oriented visual information. Tilts of the head and frame were systematically varied in order to describe precisely the shape of the resulting psychometric functions. Two main results can be stressed. Firstly, errors in estimating the vertical were markedly larger with a head-fixed visual frame during head tilt than with a tilted earth-based frame and an upright head. The difference cannot be explained by a postural effect, as tilting the head in the absence of visual frame did not significantly influence the mean setting of the subjects. Secondly, continuous vision of the frame when its orientation changed only improved performance when the head and the frame were dissociated, i.e., with an earth-based frame.

4.1. *Altered perception of the visual vertical with a head-fixed frame: addition of visual and postural effects?*

Previous studies resulted in inconsistent conclusions about whether postural and visual effects on the subjective vertical were additive or not (DiLorenzo and Rock

1982, Guerraz *et al*. 1998b). Guerraz *et al*. (1998b), in particular, suggested that the increased frame effect obtained during head tilt was only the addition of the single effect of head orientation on the subjective vertical. Results of the present study do not support such additivity hypothesis. The discrepancy between the present results and those obtained by Guerraz *et al*. (1998b) could be due to methodological differences. Indeed, Guerraz *et al*. (1998b) assessed the effect of the head and frame in only one constrained tilted orientation (28°), whereas it was systematically varied in the present experiment. Moreover, it can be noted that Guerraz *et al*.'s subjects demonstrated a significant error in the direction of head tilt without a tilted visual frame. Thus, postural and visual effects, evaluated independently, were in the same direction. This was a favourable situation to conclude for an additive effect when disturbances were combined.

In a general point of view, multisensory integration requires calibration of signals from different sources in a common form, i.e., they must be processed with respect to a common spatial framework. This fusion of sensory information cannot be accounted for by a simple summation, most of the time because of differences in spatial and temporal characteristics of the various sensors (Howard 1997). Current models try to characterize the integration of multiple sensory inputs in terms of non-linear combination (Mergner *et al*. 1997, 1998). At best, multisensory integration can be approximated with weighted means of sensory inputs (for a comprehensive and updated review, see Jeka *et al*. 2000). Depending on conditions, one sensory modality can prevail over the others. More specifically, otolithic signals seem to be reliable only when they are integrated through dynamic processes (Teasdale *et al*. 1999). When the head is tilted, reliability of otolith inputs decreases and, as a consequence, weighting of vestibular information is lowered relative to vision (Parker *et al*. 1983).

4.2. *Spatial disorientation: a two-fold phenomenon*

Impaired reliability of head position signals when the head is tilted is further suggested by response variability. It was rather small when the head was upright in presence of an earth-based visual frame, whatever the orientation of the latter. In contrast, when visual references were absent or anchored to the head, variability was larger and tended to increase with the amplitude of head tilts. Interestingly, this quantitative observation matches comments made by the subjects, who experienced more difficulties in performing the task when the head was tilted, especially in combination with the head-fixed visual frame. In these latter conditions, subjects often reported a state of strong uncertainty. There are two ways of defining spatial disorientation. On the one hand, the constant error relative to the veridical vertical gives evidence of the perceptual output of the CNS in function of available information. When the brain must come to terms with impoverished or conflicting sensory inputs, perception may be systematically biased in favour of one modality or another. On the other hand, the variable error, which reflects the level of reproducibility of the subject's response, can be considered. As far as the measurement of subjective estimates is concerned, variability of the data can often reflect the subjects' confidence level in their response. In this case, disorientation is not necessarily synonymous of impaired performance. These results illustrate this distinction. Indeed, variability (and its subjective counterpart) always increased with the amplitude of head tilt as seen in figure 5. Conversely, perceptual biases reached a plateau and sometimes decreased when variability keep on increasing (figure 3).

4.3. *Processing visual motion cues in the head-centric reference frame*

When a head-mounted visual frame was used, continuous vision of the frame during head movements did not improve the subject's performance. In this case, the CNS had to deal with oriented visual information stable in the head-centric reference frame and moving in the gravitational reference frame at the same time. In fact, the orientation of the frame could only be appreciated through head position signals, i.e., vestibular information and neck proprioception. No effect of the motor command can be assumed as nearly identical results were obtained with passive and active movements of the head. The present results contrast with the clear improvement in indicating the vertical in the condition where the subjects were allowed to look at the earth-based visual frame while it was rotated from one orientation to another. This experimental situation is closer to natural conditions, where the visual scene moves in the head-centric reference frame when the head is moving or when elements of the environment are moving. The fact that continuous vision of the frame was only effective in reducing the errors when the head and the frame were dissociated suggests that the processing of visual motion cues in the head-centric reference frame is an important step in orientation constancy mechanisms.

It could be argued that head-fixed visual references are also found in normal life in the form of spectacles frames or helmets, for instance. This is true, but such frames are not salient visual stimuli that can influence the perception of verticality. Moreover, spectacles or helmets are in close contact with the body. Thus, they can be adapted to through experience by being incorporated in the body schema, i.e., the implicit knowledge of the individual's own body delimitation (Gallagher and Cole 1995, Graziano *et al.* 2000). On the contrary, the virtual visual frame used here is projected in extra-personal space and is a powerful stimulus which can not be overridden without contradicting visual landmarks when vertical setting are performed in the dark.

The present experiment supplements a previous study where the whole body was tilted sideways by 15 or 30 deg (Mars and Vercher 2003, Mars *et al.* 2004). The effects of a head-fixed visual frame on the subjective vertical and on the voluntary control of head orientation were assessed and compared to the effects of a trunk-fixed frame (the frame moved with the rotating platform where subjects were seated). When subjects were tilted at one given orientation, they were instructed to keep the head straight on the trunk and then to perform vertical settings. Maintaining a constant head orientation relative to the trunk required to voluntary decrease the gain of the vestibulocollic reflex, which produces compensatory muscular activity in order to stabilize the head with respect to gravity. Results showed that subjects could correctly perform the head orientation task with the trunk-fixed visual frame, but committed errors with the head-fixed frame. Moreover, errors in estimating the vertical were larger with the head-fixed frame than with the trunk-fixed frame. The difference between both conditions in the latter task was strongly correlated to the errors observed in the head orientation task when the head-fixed frame was used. In other words, not only the head-mounted frame could not be used as an external reference for the control of head orientation, but it also contributed to increase the visual frame influence on the subjective vertical.

4.4. *Potential implications for the design of head-mounted displays*

This experiment demonstrated that a head-fixed visual frame can substantially influence the perception of the vertical when the head is tilted relative to gravity.

This observation, together with the fact that HMDs can influence head behaviour during aircraft manoeuvres (Taylor and Kuchar 2000), leads to the conclusion that including head-fixed visual information in a pilot's HMD could have disorienting effects under some circumstances. This may be of interest to display designers who are considering the inclusion of aircraft attitude symbology in HMDs. Of course, the present experimental conditions differs from what a pilot would experience in an aircraft. While manoeuvring the aircraft, pilots are exposed to gravitational conditions that might change the influence of a visual frame on spatial orientation. For instance, Sarès *et al*. (2002) demonstrated that a visual frame could significantly influence the interaction between vestibulocollic and cervicocollic reflexes in an altered gravitational field. Elements of symbology included in the HMD would also be quite different. However, the mechanisms described here may certainly come into play if any kind a visual frame was surrounding an attitude indicator such as a horizon line. Oriented visual information does not need to consist of a full frame such as the one used in the present study, as incomplete frames or subjective contour have been shown to have a significant effect on the subjective vertical (Streibel *et al*. 1980, Antonucci *et al*. 1995, Spinelli *et al*. 1999). Thus, head-fixed oriented information may impair attitude awareness, especially during night flights where episodes of spatial disorientation are frequently reported.

5. Conclusion

The head has been proposed to be an important reference frame for orientation judgements (Friedman and Hall 1996, Guerraz *et al*. 1998b, Spidalieri and Sgolastra 1999). This study confirmed this hypothesis by investigating the influences of a head-fixed visual frame on the perception of verticality. Firstly, when oriented visual references were integral to the head during head tilts, they gave rise to large errors in vertical setting which could not be explained by the addition of visual and postural effects. Secondly, viewing a visual frame while its orientation changed in space decreased the errors induced by the frame only if the frame was dissociated from the head. With a head-fixed frame, continuous vision of the frame did not improve the perception of verticality. Thus, processing visual information in the head-centric reference frame is crucial for orientation constancy. This property of the perceptual system may be taken in consideration for the design of HMDs.

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