Isotropic visual field effect on spatial orientation and egocentric localization

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Abstract—The aim of this paper is to demonstrate the presence of a similar visual field effect on both spatial orientation and egocentric localization. A first experiment explored an orientation task (Visually Perceived Vertical or VPV determination) and compared the effects of a frame inclined either in the midfrontal plane (in this condition subjects assessed roll VPV) or in the median plane (subjects assessed pitch VPV) or in both combined planes (subjects assessed both roll and pitch VPV). A second experiment compared the frame effects specified above to the frame effect observed in an egocentric localization task (Visually Perceived Eye Level judgment) performed with a frame slanted in the median plane. The results showed that angular frame variations from -15 to $+15$ deg result in the same psychometric function for both orientation and localization tasks. In each experiment, correlations showed that individual differences occur in relation to an overall sensitivity to the visual field. Individual sensitivity may be accounted for by a ratio of visual to graviceptive information which remains constant whatever the perception plane (midfrontal or median plane) and whatever the task (spatial orientation or localization).

INTRODUCTION

It has long been known that a structured visual environment can interfere with spatial orientation and egocentric localization in the midfrontal and the median planes. Moreover, strong differential responses have generally been observed in visual interference. Hence, the question is two-fold: (1) is the visual field effect on spatial orientation and egocentric localization isotropic? In other words is it the same in all spatial directions? (2) Is the individual sensitivity to a visual interference kept in any spatial direction and in any spatial task?

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Visual interference and Visually Perceived Vertical

Concerning spatial orientation in the midfrontal plane, it is commonly accepted that the roll Visually Perceived Vertical (roll VPV) — i.e. visual adjustments of a rod to the gravitational direction are performed in the midfrontal plane — is deviated to a surrounding roll tilted frame (Witkin and Asch, 1948; Ebenholtz, 1977; Goodenough *et al.*, 1979; Ebenholtz and Callan, 1980; Streibel *et al.*, 1980; Dilorenzo and Rock, 1982; Babler and Ebenholtz, 1989). However, there is no study on the specific effect of a pitched frame on pitch VPV — i.e. the frame is inclined in the median plane and the visual adjustments of the rod to the gravitational direction are performed in the median plane — although different displays such as a mirror (Wertheimer, 1912), a room (Kleint, 1936; Matin and Li, 1995) or a small box (Kleinhans, 1970) have been used. Despite the weak structuring nature of a frame as compared to the above-mentioned displays, a substantial influence may be expected because perspective cues contained in a slanted frame alter the visually perceived depth (Kumar and Glaser, 1992). In light of this, does the standard frame effect usually observed in roll adjustments also occur in pitch adjustments?

Visual interference and Visually Perceived Eye Level

Concerning spatial egocentric localization, recent studies have shown that a visual array slanted[1] in the median plane causes a shift in judgments of a target set at eye level relative to the gravitational horizontal (Kleinhans, 1970; Stoper and Cohen, 1986, 1989, 1991; Matin and Fox, 1989; Matin and Li, 1992; Cohen *et al.*, 1995; Welch and Post, 1996). According to most of these authors, the shift results from a deviation of gaze direction relative to the normal of the inclined surface set in front of the observer. This Visually Perceived Eye Level (VPEL) is deviated either by an entire room or by a small box, but no studies have been carried out with slanted frames. Here again, frame influence on VPEL estimations may be expected because a simple slanted line, subtending a large visual angle, is sufficient to modify the VPEL judgment (Matin and Li, 1992, 1994). Regarding the links between eye level and visual influence, Stoper and Cohen (1989) suggested that VPEL judgments are mediated by processes similar to those described in orientation tasks. Hence a relationship may be expected between VPV and VPEL based mainly on interactions between visual and gravity cues. Indeed, VPV and VPEL adjustments may be determined by an additional mechanism relying on weighted dual control by visual and gravity fields (Poquin *et al.*, 1995 and Guerraz *et al.*, in press for VPV; Matin and Fox, 1989 for VPEL). Yet, such relationships cannot be expected for all types of spatial tasks such as straight-ahead determination which seems relatively independent of gravity information (Kleinhans, 1970; Li and Matin, 1995).

Angular functions of inclined displays

According to Koffka's normalization theory (Koffka, 1935), the dimensions of space are indicated subjectively and mainly by the orientation of the dominant lines of the visual field. According to this assumption, we may expect visual field effects to occur

equally in all spatial directions, i.e. those effects may be considered as isotropic. Our first hypothesis was that angular frame variations may result in the same psychometric function in an orientation task (for roll VPV and pitch VPV adjustments) as well as in an egocentric localization task (VPEL determinations).

However, if we assume that the frame does have an effect, we have to take into account the differences resulting from the various display types, adjustment planes, and task types. Indeed, in the midfrontal plane, the psychometric function between roll VPV and a roll tilted frame has been described as a sine function with maximum errors at approximately 15 deg of frame tilt (Goodenough *et al.*, 1985; Spinelli *et al.*, 1991). Yet, the effects of a tilted room produce greater deviations than a single frame with maximum influence above 20 deg (Singer *et al.*, 1970). In the median plane, the relationship between a slanted visual display and pitch VPV assessment is not described as a *sine* function but as a *linear* function up to 25 deg in a pitchbox (Kleinhans, 1970), and up to 30 deg using a whole pitchroom (Matin and Li, 1995). Finally, concerning the VPEL-vs-pitch function, several authors have consistently observed a linear relationship with rooms, small boxes or large lines (Matin and Fox, 1989; Stoper and Cohen, 1989, 1991; Matin and Li, 1992; Cohen *et al.*, 1995). Despite all of these variations, the main effect of a frame is likely to be a correlation between errors in roll VPV, in pitch VPV and in VPEL determinations.

Interindividual differences

In all experiments on spatial orientation and localization with a disturbing visual field, large interindividual differences are common. Those differences have mostly been investigated in roll orientation tasks, and have been labeled 'Visual Field Dependence–Independence' (for reviews, see Witkin *et al.*, 1962; Howard, 1986; Goodenough *et al.*, 1987). Also, large individual differences have been found in pitch VPV adjustments (Kleint, 1936; Kleinhans, 1970) and in VPEL estimations (Matin and Fox, 1989; Matin and Li, 1994; Cohen *et al.*, 1995). Matin and Fox mentioned that large VPEL individual differences exhibit strong stability over time. Moreover, Stoper and Cohen (1989) observed that some subjects used different strategies for judging VPEL, and they suggested a possible 'continuum in visual field dependence–independence' (see p. 474) to explain their results. This means that the weighting of visual information may be a constant component for any spatial plane and any task (spatial orientation or localization). Consequently, the second hypothesis was the presence of correlations between the individual differences observed in orientation and egocentric localization tasks. These correlations may thus account for the overall individual sensitivity to the visual field.

For this purpose, a within subject design was used to carry out two experiments. The first experiment was designed to understand the effect of a frame as a whole on the orientation of an object. This is the reason why the effects of an inclined frame on VPV determinations were compared not only in the midfrontal plane and in the median plane, but also in both *combined* planes. The second experiment was conducted to compare the above frame effects to the frame effect observed during an egocentric localization task performed with a slanted frame in the median plane (VPEL judgments).

METHOD

In order to simplify, the common points between both experiments are presented in the paragraph 'Generalities'. The procedures specific to each experiment are described in the following sections. Figure 1 shows the experimental situations and Table 1 defines the various terms used for spatial planes.
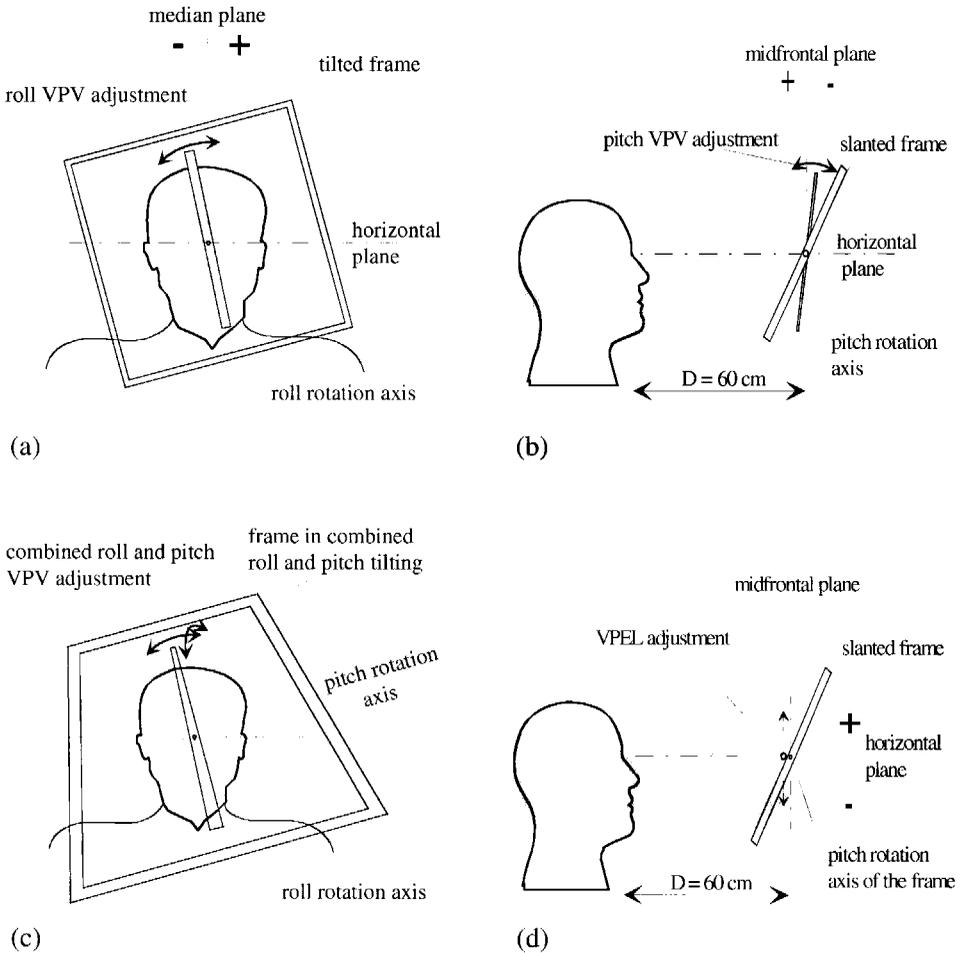
Figure 1. Experimental situations and description of different spatial planes relative to the observer. (a) When the frame is tilted in the midfrontal plane, subjects adjust a rod to the direction of the gravity in the midfrontal plane (roll VPV adjustments in Experiments 1 and 2). (b) When the frame is slanted in the median plane, subjects adjust a rod to the direction of the gravity in the median plane (pitch VPV adjustments in Experiments 1 and 2). (c) When the frame is inclined both in the midfrontal and median planes, subjects adjust a rod to the direction of the gravity both in the midfrontal and median planes (combined roll VPV and combined pitch VPV adjustments in Experiment 1). (d) When the frame is slanted in the median plane, subjects adjust a little bar to the horizontal eye level according to a vertical track in the midfrontal plane (VPEL adjustments in Experiment 2).

Table 1.
Synopsis of the conditions and the tasks, presented in each experiment and illustrated in Fig. 1

Experiment	Condition	Task	Frame orientation		Figure 1
			in the mid-frontal plane	in the median plane	
Experiment 1	Roll VPV	Rod adjustments to gravity in the midfrontal plane.	tilted	upright	a
	Pitch VPV	Rod adjustments to gravity in the median plane.	upright	slanted	b
	Combined roll and pitch VPV	Rod adjustments to gravity both in the midfrontal and median plane.	tilted	slanted	c
Experiment 2	Roll VPV	Rod adjustments to gravity in the midfrontal plane.	tilted	upright	a
	Pitch VPV	Rod adjustments to gravity in the median plane.	upright	slanted	b
	VPEL	Little bar adjustments to the horizontal eye level.	upright	slanted	d

Generalities

Material. The experiments made use of the principle of the 'Rod and Frame Test' paradigm (RFT: Witkin and Asch, 1948) with a rod (Experiments 1 and 2) or a little bar (Experiment 2) as targets to respectively adjust to the gravitational vertical and to the gravitational horizontal through the eyes. When the observer had to determine the VPV, a luminous rod measuring 25 × 1 cm (23.5 deg retinal size in Experiment 1) and 20 × 1 cm (19 deg retinal size in Experiment 2) was used. A motorized device allowed the rod to rotate in the midfrontal plane (roll adjustment) and/or in the median plane (pitch adjustment) relative to the observer. The roll and the pitch pivot axis went through the center of the rod (Fig. 1).

When the observer had to determine the VPEL (Experiment 2), a luminous and horizontal bar measuring 1 × 0.2 cm (0.9 deg retinal size) was used. A motorized device allowed the bar to move up and down in the midfrontal plane relative to the observer along a vertical track. The rod and the little bar were surrounded (experimental condition) or not surrounded (control condition) by a luminous frame measuring 30 × 30 × 1 cm (28 deg retinal size) which could be inclined in the midfrontal plane and/or in the median plane. The roll and the pitch pivot axis went through the center of the frame. Rotation of the frame and of the rod was coaxial when the rod was present (Fig. 1). Each of the luminous lines was a segment of a phosphorescent strip with a luminance of $7.5e^{-002}$ cd/m^2 (Photoresearch PR 704 SpectraColorimeter$^®$).

In both experiments, the subjects were seated upright in front of the device. They placed the center of their forehead (between the eyes just above the nasal pyramid) on the lower extremity of a thin metal rod so that the subject's eyes were set on an horizontal plane 60 cm away from the center of the luminous frame, and to prevent the thin metal rod from disturbing the subject's task. Subject's head was in erect position and binocular viewing was employed. To eliminate unwanted external references, the room was in total darkness.

Instructions. When the observers had to determine the VPV, they were instructed to adjust the luminous rod to the direction of the gravitational vertical. They could rotate the rod with a joystick connected up to a computer which piloted the experimental device. Before beginning the test, three examples of the vertical were shown: a visual vertical (wall ridges), a gravitational vertical (falling stone) and a postural vertical (a person standing up). This precaution was taken to ensure that all subjects understood correctly what was meant by 'vertical'. Before the roll VPV adjustments, the starting position of the rod was tilted either 20 deg to the left (rod turned counterclockwise), or 20 deg to the right (clockwise) relative to the gravitational vertical. In the pitch VPV conditions, the rod was slanted either 20 deg top away (rod turned top away from the subject relative to the gravitational vertical), or 20 deg top towards (rod turned top towards the subject).

When the observers had to determine the VPEL, they attempted to adjust their direction of gaze to make it horizontal, and simultaneously attempted to set the position of the bar so that it appeared to be on their horizon. Before beginning the test, an

example of the horizontal eye level was given: the subjects had to imagine a horizontal spirit level gone through their eyes to the target. This precaution was taken to ensure that all subjects understood correctly what was meant by 'horizontal eye level'. Before the VPEL adjustment, the starting position of the little bar was deviated either by 10 deg to the top, or by 10 deg to the bottom relative to the gravitational horizontal through the subject's eyes.

Dependent variables. There were 4 trials per subjects and per inclination of the frame whatever the condition. For each trial, the algebraic angular deviation from the physical vertical in VPV conditions and from the physical horizontal in VPEL condition was noted down. According to conventions in the VPV conditions, rod deviations to the left or top away were counted as negative, and deviations to the right or top towards as positive. In the VPEL condition, bar deviations to the bottom were counted as negative, and deviations to the top as positive (Fig. 1).

Two types of dependent variables were computed from the collected data:

(1) The first variable was the constant error (Experiments 1 and 2). It is the average of errors noted in each situation. It indicates their average direction. It is important to notice that in the combined pitch and roll adjustments (Experiment 1), the final position of the rod was measured by its spatial coordinates relative to the midfrontal and to the median plane. In the latter case, there were hence two values for each adjustment error: one for the algebraic deviation from the midfrontal plane, and one for the algebraic deviation from the median plane.

(2) The second variable was the slope of the linear regression analysis (Experiment 2). It was computed between the position of the frame and the corresponding constant errors. It shows sensitivity to visual interference (Matin and Fox, 1989; Stoper and Cohen, 1989; Matin and Li, 1992). A slope of 1.00 would reveal that the optical pattern variations entirely determine the variations in VPV or VPEL adjustments. If so, the rod would be set parallel to the frame plane, and the subjective eye level axis would join a line normal to the plane given by the slanted frame. Conversely, a slope of zero would indicate that the optical pattern has no influence. In such a case, the rod would be set to the physical vertical and the subjective eye level axis would join the physical horizontal for any frame orientation.

Experiment 1

Subjects. Fourteen women and fourteen men aged from 19 to 41 took part in the experiment. All of them had normal or corrected to normal visual acuity and stereoacuity. The experiment was carried out with their informed consent.

Procedure. In Experiment 1, there were three counterbalanced conditions of VPV adjustments (Table 1). One was carried out in the single midfrontal plane (roll VPV condition), another in the single median plane (pitch VPV condition) and the last in both midfrontal and median planes (combined roll and pitch VPV conditions). In roll VPV condition, the frame was fixed upright in the median plane, but it could be tilted

sideways to the left or to the right. In the same way, the rod was fixed upright in the median plane, and could be rotated only in the midfrontal plane. In the pitch VPV condition, the frame was fixed upright in the midfrontal plane, but it could be slanted backwards and forwards, i.e. top away from the subject or top towards the subject. In this condition, the rod was fixed upright in the midfrontal plane, and could be rotated only in the median plane. Finally, in the combined roll and pitch VPV conditions, the two conditions above were combined. The frame was tilted sideways, backwards and forwards. Also, the rod could be rotated both in the midfrontal and in the median plane.

In each of those three conditions, either the frame was absent (control condition), or the frame was successively set in seven directions: upright (0 deg) and respectively, 7, 15 or 25 deg on both sides of the vertical direction according to the spatial plane involved. Each frame orientation was presented at random.

In summary in Experiment 1, three factors were analyzed in a within subject design: the 'frame orientation' factor with seven modalities (corresponding to each inclination of the frame), the 'adjustments plane' factor with two modalities (midfrontal and median plane) and the 'number of freedom degrees of the frame' factor with two modalities (One or Two corresponding to single or combined planes, respectively).

Experiment 2

Subjects. Six women and eight men aged from 20 to 41 took part in the experiment. All of them had normal or corrected to normal visual acuity and stereoacuity. The experiment was carried out with their informed consent.

Procedure. In Experiment 2, the subjects were tested in three counterbalanced conditions (Table 1). There were two conditions with VPV adjustments, one in the midfrontal plane (roll VPV condition), the other in the median plane (pitch VPV condition) and one condition with VPEL adjustments (VPEL condition). In both VPV conditions, the frame was inclined and the rod was rotated as described in Experiment 1.[2] In the VPEL condition, the frame was fixed upright in the midfrontal plane, and it was slanted backwards and forwards as in the pitch VPV condition. The little bar was right in front of the observer and could be moved up and down in the midfrontal plane relative to the observer along a vertical track.

In each of the three conditions, the frame was successively set in five positions: upright (0 deg) and respectively, 7 or 15 deg on both sides of the vertical direction according to the spatial plane involved. Each frame orientation was presented at random. The VPEL was also assessed without frame in Experiment 2. The control condition for VPV estimations is reported in Experiment 1.

RESULTS

An analysis of variance with repeated measures and a paired samples *t* test were used for all mean comparisons, and a Spearman coefficient for correlations. A 0.05 significance level was used throughout.

Experiment 1

Mean adjustments of VPV as a function of the orientation of the frame are reported in Table 2 and depicted in Fig. 2.

On the whole, the frame had a significant effect on the VPV adjustments ($F(6, 162) = 49.53$). This overall effect was confirmed by the analysis of each condition. Indeed, VPV adjustments were significantly set in the direction of the inclined frame (roll VPV condition: $F(6, 162) = 28.15$; pitch VPV condition: $F(6, 162) = 35.77$; combined roll VPV condition: $F(6, 162) = 36.36$; combined pitch VPV condition: $F(6, 162) = 38.24$). Error settings increased with frame tilts increasing from 0 to ± 15 deg. Further increases in frame tilts produced slightly decreasing errors or a stabilization in orientation judgments, except for the combined pitch condition where errors increased up to the 25 deg slanted frame (Fig. 2).
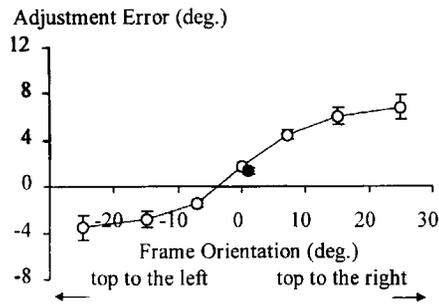
For a fixed tilt of the frame, the magnitude of errors depended on the adjustment plane: errors were greater in the pitch conditions than in the roll conditions ($F(6, 162) = 6.59$). In the same way, control conditions without frame yielded simi-
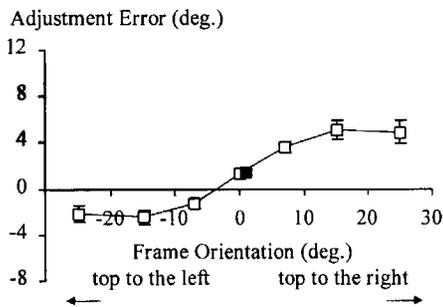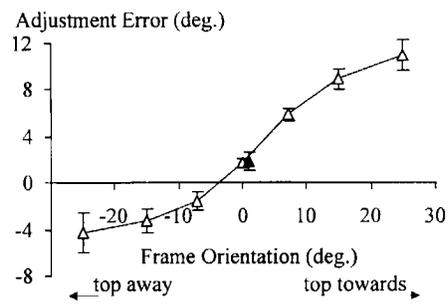

ROLL VISUALLY PERCEIVED VERTICAL
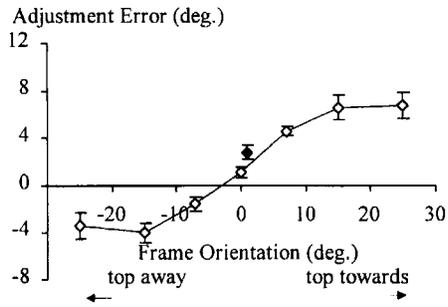
PITCH VISUALLY PERCEIVED VERTICAL

COMBINED ROLL VISUALLY PERCEIVED
VERTICAL

COMBINED PITCH VISUALLY PERCEIVED
VERTICAL

Figure 2. Visually Perceived Vertical (VPV) adjustment errors as a function of different frame orientations. White dots represent VPV adjustments with an inclined frame and black dots without frame. Rod deviations 'counterclockwise' or 'top away from the observer' relative to the gravitational vertical are counted as negative. Error bars are the standard errors of the mean (SEM).

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Table 2.

Mean (M) in degrees and standard deviation (SD) of adjustment errors of the Visually Perceived Vertical (VPV) in the midfrontal (roll VPV adjustments) and the median (pitch VPV adjustments) planes without frame and as a function of frame inclinations (in degrees). Rod deviations 'counterclockwise' or 'top away from the observer' relative to the gravitational vertical are counted as negative, $N = 28$

Condition	Without frame		Frame inclination															
	M	SD	−25 deg		−15 deg		−7 deg		0 deg		7 deg		15 deg		25 deg	
			M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Roll VPV	1.44	1.44	−2.15	4.13	−2.49	3.57	−1.33	2.09	1.32	1.32	3.61	2.46	5.08	4.03	4.98	5.06
Pitch VPV	2.81	3.81	−3.43	5.75	−4.01	4.39	−1.58	3.22	1.13	2.17	4.6	2.27	6.6	5.67	6.8	5.76
Combined roll VPV	1.33	1.51	−3.51	5.66	−2.83	3.55	−1.44	2.01	1.7	1.69	4.47	2.23	6.04	3.97	6.85	5.66
Combined pitch VPV	1.8	4.08	−4.25	9.01	−3.24	5.39	−1.53	4.05	1.66	2.22	5.87	2.71	8.94	4.5	11.0	7.13

Table 3.

Spearman correlation coefficients of adjustment errors between, on the one hand, single and combined conditions in roll and pitch dimensions taken separately (rows 1 and 2), and, on the other hand, roll and pitch dimensions in single and combined conditions taken separately (rows 3 and 4) according to the frame inclination (in degrees). For example, the correlation coefficient between roll VPV and pitch VPV adjustments is 0.48 when the frame has a -25 deg inclination respectively in each spatial plane, $N = 28$

Correlated conditions	Without frame	Roll and/or pitch frame inclination						
		-25 deg	-15 deg	-7 deg	0 deg	7 deg	15 deg	25 deg
Roll VPV-vs- combined roll VPV	0.89*	0.85*	0.80*	0.73*	0.52*	0.82*	0.90*	0.87*
Pitch VPV-vs- combined pitch VPV	0.72*	0.73*	0.71*	0.38*	0.25	0.49*	0.52*	0.70*
Roll VPV-vs- pitch VPV	0.15	0.48*	0.47*	0.21	0.13	0.31	0.45*	0.20
Combined roll VPV-vs-combined pitch VPV	0.08	0.56*	0.41*	0.14	-0.27	0.41*	0.44*	0.60*

*$p < 0.05$.

lar results: mean errors in pitch conditions were significantly higher ($F(1, 27) = 4.97$) than mean errors in roll conditions (Table 2 and Fig. 2). Besides, for a fixed tilt of the frame, VPV adjustments were more deviated in the combined conditions than in both single conditions ($F(6, 162) = 7.71$). However, there was no difference between single and combined conditions without a frame ($F(1, 27) = 1.8$, $p = 0.19$).

Concerning the relationship between the different conditions, the main correlations are reported in Table 3. For each orientation of the frame, roll VPV adjustments always correlated with their combined counterpart. The same relationship was observed in the pitch VPV conditions (except for a frame upright). Moreover, roll conditions significantly correlated with pitch conditions when the frame was tilted beyond ± 15 deg for roll VPV-vs-pitch VPV adjustments and for the combined roll VPV-vs-combined pitch VPV adjustments (except for the correlation between roll VPV and pitch VPV when the frame had a 25 deg tilt). No correlation was found between roll and pitch without a frame.

Experiment 2

Mean settings of VPV and VPEL as a function of the orientation of the frame are reported in Table 4 and depicted in Fig. 3.

In the roll and pitch VPV conditions, adjustment errors were set in the direction of the inclined frame. Errors increased with frame tilts increasing from 0 to ± 15 deg (roll VPV condition: $F(4, 52) = 42.77$; pitch VPV condition: $F(4, 52) = 16.1$). Also, VPEL estimation errors were significantly influenced by the slant of the frame ($F(4, 52) = 24.26$). This shows that judgment of eye level shifted down when the frame was slanted top away from the observer, and that it moved up when the frame was slanted top towards the observer.

Table 4.

Mean (M) in degrees and standard deviation (SD) of adjustment errors for roll and pitch Visually Perceived Vertical (VPV) and for Visually Perceived Eye Level (VPEL) as a function of frame inclinations (in degrees). The slope and the Y-intercept are the average of the individual values of the best fitting (least squares) straight line from −15 to +15 deg of frame tilt. In the VPV conditions, rod deviations 'counterclockwise' or 'top away from the observer' relative to the gravitational vertical are counted as negative. In the VPEL condition, target deviations to the bottom relative to the gravitational horizontal are counted as negative (for roll and pitch VPV values without frame, see Table 2) $N = 14$

| Condition | Without frame | | Frame inclination | | | | | | | | | | Slope | | Y-intercept | |
| | | | −15 deg | | −7 deg | | 0 deg | | 7 deg | | 15 deg | | | | | |
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Roll VPV	n.m.	n.m.	−3.29	1.85	−2.25	1.73	−0.25	0.56	2.24	1.11	2.76	2.18	0.22	0.12	−0.15	0.82
Pitch VPV	n.m.	n.m.	−2.53	5.3	−1.68	2.94	1.36	1.77	3.67	2.38	5.68	3.69	0.29	0.25	1.29	1.84
VPEL	−3.04	2.63	−4.38	3.68	−3.65	3.32	−2.07	2.91	−1.27	3.06	−0.65	3.54	0.13	0.08	−2.40	3.13

n.m. not measured.
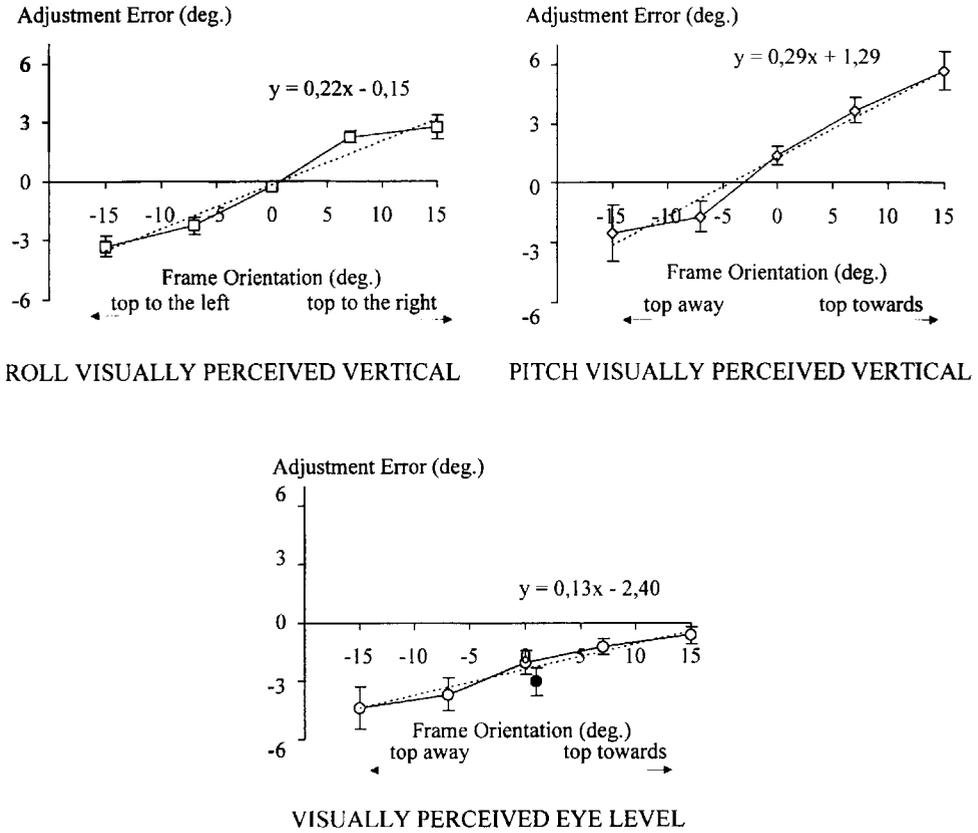
Figure 3. Visually Perceived Vertical (VPV) and Visually Perceived Eye Level (VPEL) adjustment errors as a function of different frame orientations. White dots represent VPV or VPEL adjustments with an inclined frame. Black dot represents VPEL adjustments without frame (for VPV without frame, see Fig. 2). The dotted line represents the linear regression. In the VPV conditions, rod deviations 'counterclockwise' or 'top away from the observer' relative to the gravitational vertical are counted as negative. In the VPEL condition, target deviations to the bottom relative to the gravitational horizontal are counted as negative. Error bars are the standard errors of the mean (SEM).

The linear regression analysis shows that adjustment errors in each condition were linearly deviated as a function of the frame orientation (Roll VPV: $F(1, 68) = 141.85$, $R^2 = 0.67$; Pitch VPV: $F(1, 68) = 56.8$, $R^2 = 0.45$; VPEL: $F(1, 68) = 12.75$, $R^2 = 0.15$). VPV adjustments changed with a 0.22 deg slope per degree of frame roll ($t(13) = 11.91$) and with a 0.29 deg slope per degree of frame pitch ($t(13) = 7.53$). VPEL estimations changed with a 0.13 deg slope per degree of frame pitch ($t(13) = 3.57$). All of these slopes were correlated (pitch and roll VPV conditions: $r(14) = 0.74$; VPEL and roll VPV conditions: $r(14) = 0.67$; VPEL and pitch VPV conditions: $r(14) = 0.71$). However, the VPEL slope significantly differed from the roll VPV slope (paired samples $t(13) = 3.01$), and from the pitch VPV slope (paired samples $t(13) = 3.06$), whereas the roll VPV slope did not differ significantly from the pitch VPV slope (paired samples $t(13) = 1.38$, $p = 0.19$).

DISCUSSION

Angular function of the frame effect: an isotropic effect

Both experiments show that the frame effect is not merely restricted to the midfrontal plane (i.e. a roll frame effect on roll VPV adjustments), but that it occurs in the median plane on pitch VPV adjustments as well as for VPEL determinations. Pitch VPV adjustments are deviated towards a slanted frame as in the roll conditions. VPEL judgments are deviated to the bottom when the frame is slanted top towards the subject and above when the frame is conversely slanted.

Concerning the function of the frame effect in Experiment 1, roll VPV deviations increase regularly with frame tilts from 0 up to 15 deg. Then, they decrease beyond the 15 deg tilt. This sine shape of the roll frame effect is in accordance with the findings of others authors (Goodenough *et al.*, 1985; Spinelli *et al.*, 1991; Brenet and Luyat, 1995). It was also observed with a frame inclined in pitch or in roll-pitch combined condition. This sine shape of the pitch frame effect is not in accordance with the findings of Kleinhans (1970) and Matin and Li (1995) who found a linear effect with respectively a pitch box and a pitch room up to a 25 deg tilt. However, Experiment 2 confirmed the linear frame effect on the roll and pitch VPV deviations up to a 15 deg tilt of the frame. In the same way, the slanted frame effect on VPEL estimations is also linear up to a 15 deg tilt of the frame. The latter result confirms the findings of all the authors who have studied VPEL judgments with other visual displays (Kleinhans, 1970; Stoper and Cohen, 1989; Matin and Li, 1992, 1995; Cohen *et al.*, 1995). Consequently, the frame effect on VPV and VPEL determinations is expressed by a comparable linear function between ± 15 deg tilt of the frame in the midfrontal and median planes.

These overall results have three specific features. First, Experiment 1 shows that the pitch VPV condition led to more interference than its roll counterpart. This could be explained by the relative complexity of the processes brought into play in the pitch VPV adjustments. In addition to the frame effect which may play a similar part in both roll and pitch conditions, the pitch VPV assessments also require the processing of a third dimension. This additional process may have an effect on the optical bias by increasing the imprecision of the pitch VPV judgment. Indeed, the perceived relative depth of isolated central features in a visual scene has been shown to be influenced not only by the disparity of the surrounding displays (Nelson, 1977; Mitchison and Westheimer, 1984; Kumar, 1988) but also by perspective cues contained in a surrounding frame (Kumar and Glaser, 1992). It may be assumed that the pitch VPV adjustments were influenced by both of those factors.

Secondly, when the frame was inclined in the combined conditions — i.e. both in the midfrontal and median planes — VPV errors were larger than in the single conditions. Luyat *et al.* (1997) also showed that a combined roll and pitch inclination of a frame results in larger roll VPV adjustment errors than a single roll tilt of the frame. The orthogonal fixed plane probably provides sufficient references for decreasing the uncertainty in finding the upright, as in the single interference condition. There may be another interpretation to account for the increasing errors in combined pitch VPV

assessments. It is an acknowledged fact that the threshold of perception of the visual depth between two thin lines increases as the orientation of the lines in the midfrontal plane departs from the vertical (Ebenholtz and Walchli, 1965; Blake *et al.*, 1976). One may assume that the increase in pitch VPV errors in the combined conditions is a manifestation of stereoacuity impairment since the rod also deviates from the roll upright. Nevertheless, Ebenholtz and Glaser (1982) conducted an experiment to verify the effect of pitch inclination on the frame effect measured in the midfrontal plane. In this combined situation, they reported no effect of the rod and the frame pitch inclination. However, it is important to note that in their experiment the rod could only move in the midfrontal plane. At all events, it can be asserted that the combined condition is more complex than the single condition for judging VPV.

Thirdly, the comparison of the slope means in Experiment 2 shows that a tilted frame does not seem to have the same weight in each spatial task. The frame effect is more important for assessing a rod orientation than for judging a target egocentric localization. In other words, errors are larger for VPV adjustments than for VPEL adjustments. It should be noted that though the visual frame effect may occur in all spatial directions, it does not occur with equal weighting. Based on this, one may come to the conclusion that the general weighting of visual information changes with the spatial task. However, there again based on Kleinhans' findings (1970), we observe no difference between the slope of pitch VPV (0.44 deg per degree of box slant) and the slope of VPEL (0.48 per degree of box slant). Besides, Matin and Li (1994) showed that the slopes of VPEL-vs-pitch function increase with the degree of structuring of the display. One might assume that the frame used in Experiment 2 was sufficient to cause a frame effect on the VPV and VPEL adjustments, but that it was not sufficient to equalize these effects because of its weak degree of structuring.

Interindividual differences: an overall sensitivity to the visual field

Another way to demonstrate the isotropic effect of a visual field lies in the correspondence of individual differences whatever the spatial plane involved. Indeed, the correlations between roll and pitch VPV adjustments for a given tilt of the frame in Experiment 1, and between roll VPV, pitch VPV and VPEL slopes in Experiment 2 lead to assume a generalization of the frame effect. In Experiment 1, the observed correlations support the notion of similarity in frame effect for roll and pitch conditions, and suggest that intraindividual sensitivity to a visual field is maintained as a whole in any adjustment condition (single or combined plane) and for any plane of interference (midfrontal or median plane). The correlations between roll and pitch dimensions with a tilted frame are all the more interesting as, on the one hand, control adjustments without frame do not correlate, and, on the other hand, high correlations are observed within the same dimension in the absence of the frame (roll VPV-vs-combined roll VPV conditions, pitch VPV-vs-combined pitch VPV conditions).

In Experiment 2, the correlations between all the slopes underline the stability of individual sensitivity to a visual interference, and confirm the involvement of a general process whatever the spatial plane and whatever the spatial task. Indeed, those slopes suggest an interaction between the visual and graviceptive[3] information involved in VPV and VPEL determinations. The observed slopes run between

the diagonal (here, the slope should be equal to 1 deg per degree of frame incli-
nation and should mean a complete visual capture) and the horizontal lines (here,
the slope should be equal to 0 deg per degree of frame inclination and should
mean no visual effect) along a straight line with an approximate value of 0.2 for
roll VPV, 0.3 for pitch VPV and 0.1 for VPEL. This shows that even though vi-
sual information does contribute to adjustments, it is the graviceptive cues that are
mostly taken into account in front of a frame with a 28 deg retinal size. Hence,
the whole correlation means that each subject would preserve his own ratio be-
tween visual and graviceptive information whatever the plane and whatever the spatial
task.

In summary, the study of both the function of an inclined visual frame effect
and the correlations between roll and pitch dimensions made it possible to gener-
alize the frame effect on VPV and VPEL estimations in the midfrontal and me-
dian planes. On the one hand, angular frame positions result in the same psy-
chometric function in orientation and egocentric localization tasks with some vari-
ations in slopes probably linked to the degree of structuring of the display. On the
other hand, the correlations between roll and pitch dimensions mean that individ-
ual differences are related to the overall individual sensitivity to the visual field.
In others words, the ratio between visual and graviceptive information seems to
be a constant component whatever the perception plane and whatever the spatial
task.

NOTES

1. We specifically use the term of 'tilt' to mean an inclination in the midfrontal
plane and the term of 'slant' to mean an inclination in the median plane.

2. In the roll VPV condition, the frame was fixed upright in the median plane,
and it was tilted sideways to the left or to the right. The rod was also fixed upright
in the median plane and could only be rotated in the midfrontal plane. In the pitch
VPV condition, the frame was fixed upright in the midfrontal plane, and it was slanted
backwards and forwards. In this condition, the rod was fixed upright in the midfrontal
plane, and could only be rotated in the median plane.

3. Matin and Li (1995) used the term of 'body-referenced-mechanism' which refers
to extraretinal signals regarding eye position relative to the head and head orientation
relative to the body and to gravity.

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