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Visually perceived vertical (VPV): induced changes in orientation by 1-line and 2-line roll-tilted and pitched visual fields

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Abstract

We report a series of nine experiments which show that a single roll-tilted line in darkness induces changes of the orientation perceived as vertical (VPV) that are similar in magnitude and direction to those measured by Witkin and Asch (1948a) [Studies in space orientation. I. Perception of the upright with displaced visual fields. *Journal of Experimental Psychology*, *38*, 762–782] with the classical square 4-sided frame, and we describe the configuration-independent mass-action rules by which the influences of the individual lines influences are combined. Clockwise (cw) and counterclockwise (ccw) orientations of a line produce cw and ccw displacements of the VPV setting, respectively, with effect magnitude increasing approximately linearly with line orientation (e.g., a 66.25°-long line at 25° horizontal eccentricity that varies in roll-tilt through ±13.2° around vertical generates a systematic variation in VPV over ±7°). The slope of the VPV-vs-roll-tilt function increases with line length along a negatively accelerated exponential function (length constant = 17.1°). The influences of two bilaterally symmetric lines combine linearly and algebraically and the combined influence is linearly related to the sum of the VPVs for the 1-line components with a slope equal to 0.91 for short lines and 0.66 for long lines; thus, VPV for short lines manifests nearly complete additive summation, but for long lines, the 2-line VPV is nearer to the average of the VPV values for the two components measured separately. The effectiveness of the conjunction of two line segments within a visual scene does not depend on their separate orientations, only on their sum. Individual lines from pitched-only planes or from combinations of such planes generate identical influences to those generated from lines in frontoparallel planes with the same image orientations at the eye of the observer (their "retinal orientations"). Retinal orientation is the key to the induction of VPV change independently of the line's plane of origin.

Keywords: Visually perceived vertical; Space perception; Spatial orientation; Linear summation; Egocentric localization; Spatial Induction

1. Introduction

In a classic series of articles Witkin and Asch brought the study of the visual perception of egocentric spatial orientation into the arena of modern science. They manipulated the orientation (roll-tilt) of the field of view, first, by replicating Wertheimer's experiment with the subject viewing the visual field presented by a tilted mirror (Asch & Witkin, 1948a; Wertheimer, 1912), then by having the subject view a large well-illuminated roll-tilted room containing furniture attached to the floor and walls that filled the field of view while the subject remained erect in physical space (Asch & Witkin, 1948b), and then by roll-tilting a large luminous square frame in the subject's frontoparallel plane in otherwise total darkness (Witkin & Asch, 1948). The main psychophysical measurement was the subject's setting of a rod within a frontoparallel plane to appear vertical (we refer to this as a VPV setting). Tilting the view in the mirror, rotating the room, or rotating the frame from an orientation in

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which the main lines in the visual field deviated from an erect orientation relative to gravity typically resulted in the physically vertical rod appearing to deviate from vertical in the direction opposite to the tilt of the field of view; for the rod to appear vertical, it had to be set to a roll-tilt within the frontoparallel plane in the same direction as the field of view. Asch and Witkin (1948a) stated, "The present experiment has provided striking evidence of the predominance of the visual framework over postural factors in perception of the upright". They drew similar conclusions in their subsequent articles. The conclusion has held up remarkably well. The substantial involvement of the body-referenced mechanism[1] has also been made clear along with the contribution by the visual field to VPV (see Gibson & Mowrer, 1938), and the work by Witkin and Asch (see particularly, Witkin, 1949) and subsequent work has helped to delineate the body-referenced mechanism's contribution in relation to influences from the visual field (Bauermeister, 1964; Chelette, Li, Esken, & Matin, 1995; Dichgans, Held, Young, & Brandt, 1972; Dichgans & Brandt, 1974; DiZio, Li, Lackner, & Matin, 1997; Higashiyama & Koga, 1998; Held, Dichgans, & Bauer, 1975; Howard & Childerson, 1994; Li, Dallal, & Matin, 2001; Mittelstaedt, 1986, 1988, 1992, 1997; Schöne, 1964; Trousselard, Cian, Nougier, Pla, & Raphel, 2003; see Howard, 1982; Howard & Templeton, 1966 for earlier summaries).

The square roll-tilted frame was originally employed by Witkin and Asch as a reduced and readily manipulable surrogate for the normal visual environment. However, since that work, the basis for the influence of the frame has also become a subject of study in itself. The nearly invariable use of the square frame as an entity whose parameters were varied while retaining its squareness and its closed figural character in a very large number of studies indicates the frame's treatment as a unitary gestalt; an emphasis on the configurational aspects of the square frame has been at the center of substantial research efforts in several laboratories concerned with the basis for the frame's influence: Witkin and Asch first suggested that the perceptual ambiguity of the physically tilted square—it sometimes appeared as a tilted diamond and at others as a tilted square—had a bearing on the VPV settings; a similar view regarding the frame's appearance as a diamond was later expressed by Wenderoth and Beh (1977), and Wenderoth (1977, 1982). As an interpretation of experiments in which the orientation of the frame was systematically varied, Beh, Wenderoth, and Purcell (1971) had proposed a "main axes hypothesis" which stated that VPV settings were biased in the direction of the main axes of the inducing frame where "main axes" included all axes of symmetry of a frame, including the main diagonals of the square frame, not only the two axes parallel to the sides of the frame. They continued to explore this with triangles and hexagons as inducing figures in experiments measuring VPV, originally reporting support for it (Beh & Wenderoth, 1972), and subsequently reporting mixed support for the hypothesis from work with partial frames (2-line-angle and 2-line-parallel stimuli) in Wenderoth and Beh (1977) and Wenderoth (1977). In work centered on other configurational aspects of the frame, Ebenholtz and his colleagues replaced the entire tilted frame with its four corners or with filled circles at its corners (Streibel, Barnes, Julness, & Ebenholtz, 1980), and from small effects with corners only they concluded that Koffka's theory (1935) regarding field organization in perception, as applied to the square frame's influence on VPV, did not hold.

A sizable number of studies manipulated the parameters of the frame as a unitary stimulus, including the separation between rod and frame both within the frontoparallel plane and in depth, the orientation of the frame, the area of the frame and the length of the rod, separately, together, and in conjunction with other measures of frame size, and/or in conjunction with variation of body tilt or head tilt (e.g., Ebenholtz, 1977, 1985; Ebenholtz & Benzchawel, 1977; Gogel & Newton, 1975; Poquin, Ohlmann, & Barraud, 1998; Wenderoth, 1977; Zoccolotti, Antonucci, & Spinelli, 1993). Spinelli, Antonucci, Goodenough, Pizzamiglio, and Zoccolotti (1991) systematically varied the orientation and size of the frame over a 90° range and described their angle functions as a weighted sum of the relative amplitudes of the first two Fourier components and also reported reduced effects with smaller frames. Ebenholtz and his colleagues had further demonstrated that the influence on VPV was due to retinal size, not perceived size (Ebenholtz, 1977; Ebenholtz & Callan, 1980). In addition to the numerous explorations of these and other parameters, the square frame was treated as the concrete embodiment of the concept of frame of reference and become the focus of numerous experimental and theoretical articles in space perception, in cognition, and in the study of connections between cognition and personality where it has become known as the rod-and-frame test (e.g., Bertini, Pizzamiglio, & Wapner, 1986; Goldstein & Chance, 1965; Hudson, Li, & Matin, 1997; Hudson, Li, & Matin, submitted for publication; Linn & Peterson, 1985; Sherman, 1969; Wapner & Demick,

[1] The term 'body-referenced mechanism' was introduced (Matin & Fox, 1989) to refer to the combination of all extraretinal influences on the perception of interest—here the visual perception of vertical—including extraretinal eye position information, extraretinal head orientation information (including information regarding the head relative to the body and the head relative to gravity), other effects of gravity on the body, pressure cues from the surfaces of the body, joint receptors, and the vestibular organ; it includes, in addition, the basic local sign information from the visual target employed to measure the discrimination itself. There is some overlap with the term "postural factors" as employed by Witkin and Asch (1948).

1991; Weiner, 1955 Witkin, 1977; Witkin, Dyk, Faterson, Goodenough, & Karp, 1962; Witkin & Goodenough, 1977, 1981; Witkin, Karp, & Goodenough, 1959; Witkin et al., 1954).

While the perception of squareness of the frame certainly depends on the configurational aspects of the physical stimulus (i.e., specific relations between the relative orientations, relative locations, and lengths of the four constituent lines) leading to its unitary perceptual quality, whether the effect of the frame in influencing the orientation perceived as vertical is connected with such qualities or has another basis is a question that has not been addressed experimentally. The present article begins to address this by studying the influence on VPV of single lines ("1-line stimulus") and pairs of lines ("2-line stimulus") in darkness in order to assess whether such configuration-dependence is necessary for the induction effect. The experiments are concerned with: (1) the influence of the individual roll-tilted line; (2) the rules of combination for influences between two simultaneously viewed lines of the same or different orientations; (3) whether inducing lines from differently pitched planes and their combinations have the same or different influences on VPV as do those from the frontoparallel plane; (4) whether the induction effect depends on the test rod being roll-tilted around an axis in the same plane from which the inducer arises.

2. Method

The nine experiments reported in the present article have been grouped into four sets and will be reported here as Expts. 1–4 (Fig. 1). Expts. 1, 2, and 3 employed roll-tilted inducing lines of various orientations and lengths at one or both of two bilaterally symmetric locations in the frontoparallel plane. Expt. 4 employed inducing lines from pitched-only planes that stimulated the same retinal orientations[2] as did the lines in the frontoparallel plane in Expt. 3. However, stimulation at the retina from the lines from different planes with the same retinal orientation was *not* identical; the parameters of stimulation from the different planes differed along several different dimensions as shown in Table 1 and described in Section 2.3 below.

[2] We use the term "retinal orientation" to designate the orientation of the geometric image of the line in the spherical approximation to the eye (see Fig. 2b and Fig. 3 and Eq. (1)) under the assumption that the eye is erect, and that projection is through a pupil centered in the midfrontal plane of the sphere. The angle specifying retinal orientation on this spherical projection is the angle of intersection of the great circle containing the image of the line with the circumference of the midfrontal plane.

2.1. General

On each trial of each of the experiments, the monocularly viewing subject (S), seated straddling a stool with head stabilized by a chinrest, viewed a visual field consisting of either a 1-line stimulus at a horizontal eccentricity of 25° to the left or to the right of the median plane of the viewing eye, or a 2-line stimulus that consisted of the two lines simultaneously presented at the two bilaterally symmetric locations (Fig. 2a). On each trial the S set the 4.9°-long x 6′-wide test line to appear vertical; the test line was located within a frontoparallel plane at 1 m from the S and was centered in the median plane of the viewing eye at eye level. Viewing was with the right eye; vision in the left eye was occluded by an eye patch.

In Expts. 1–3 the surfaces containing the inducing stimulus were erect and frontoparallel 1 m in front of the viewing eye; the roll-tilt of the inducing line was varied by rotating the line around its center. In Expts. 1 and 3, the seven roll-tilts of each 1-line stimulus were ±13.2°, ±9.1°, or ±4.3°, or the erect condition (0°); in Expt. 2 the roll-tilts were ±15°, ±10°, ±5°, and 0° (Table 1). The experimenter's settings of inducer orientation were accurate within approximately 6 minarc. A negative (−) sign designates counterclockwise (ccw) roll-tilt and a positive (+) sign designates clockwise (cw) roll-tilt. In Expt. 1 nine inducing line lengths were examined; in Expts. 2 and 3 the lines were 12° long ("short lines") and 66.25° long ("long lines"), respectively.

In Expt. 4 the surfaces containing the inducing lines were pitched around a horizontal axis in the frontoparallel plane. When the surface containing a line was erect and frontoparallel, the line was vertical, 66.25°-long, and centered at 25° horizontal eccentricity at eye level; the pitched-from-vertical line retained its orientation relative to the surface at all pitches. The seven pitches were ±30°, ±20°, ±10°, or 0° (erect); a negative (−) sign designates topbackward pitch and a positive (+) sign designates topforward pitch. Each of the pitched-from-vertical orientations employed in Expt. 4 produced a retinal orientation of the inducing line that was identical to one of those produced by one of the roll-tilted lines in Expt. 3. Table 1 contains the correspondences between the roll-tilted and pitched-from-vertical inducing lines on the right side of the median plane in accord with the geometry of Figs. 2 and 3; the correspondences for the left lines are identical except for the sign reversal between topforward and topbackward pitched-from-vertical lines.

2.1.1. Stimulus display

Each inducing line consisted of a strip of phosphorescent tape that received a brief exposure (≈2 min) to normal room illumination prior to each experimental run; this was refreshed for approximately 30–60 s following each set of 4 VPV measurements. Each of the two strips was 144 cm × 0.2 cm with a luminance of approximately

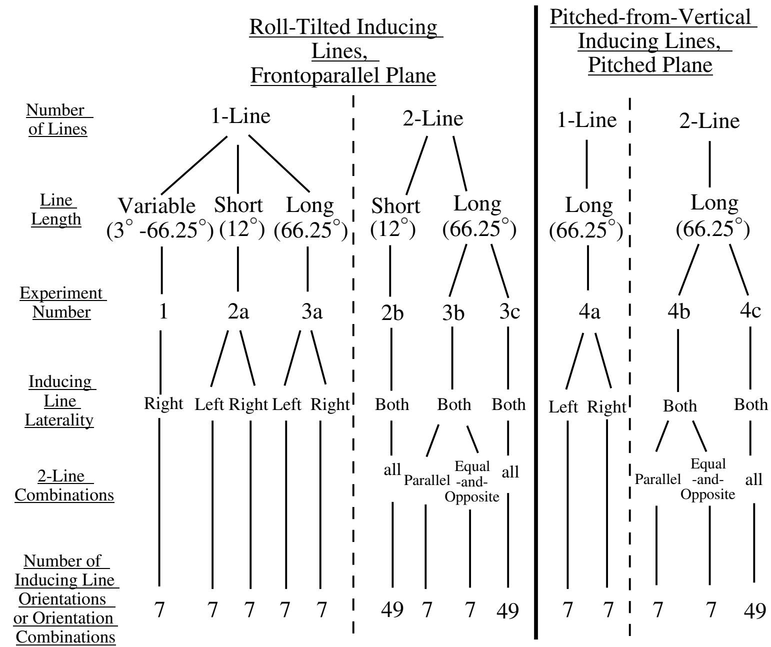

Fig. 1. The tree structure displays the main aspects of the inducing lines that provide the basis for organizing the nine original experiments into the four sets as Expts. 1, 2, 3, and 4.

0.01 mL (EG&G photometer/radiometer 550); each strip was attached to a separate plastic bar mounted on a separate modified, standalone, rotatable, and height-adjustable blackboard (104 cm × 154 cm) by attachment with velcro at the top and bottom. Each bar could be translated or roll-tilted in any direction independently. The two strips were symmetrically placed with respect to the midsagittal plane of the subject's viewing eye at horizontal eccentricities of ±25°. As measured at the normal to the S's eye from the erect blackboard each luminous strip subtended a 66.25° by 6 minarc visual angle at the viewing distance of 1 m. When shorter stimuli were required appropriate segments at both ends of the line(s) were covered with light shields (see Section 2.3 and Table 1 for more detail). There were two reasons for the use of separate rotatable surfaces for each of the two lines: (1) Expts. 4b and 4c required the two lines to be set at different pitches simultaneously. (2) The test line needed to remain erect within the frontoparallel plane and centered regardless of the orientations of the inducing lines. The test line was mounted on a third, separate freestanding erect surface positioned between the two pitchable surfaces containing the inducing lines. The axis for rotation of the test line in the frontoparallel plane was through the test line's center, and the S's eye level was set on this axis by adjustments of the stool/chinrest; the test line was mounted at its center on the front surface of a machined metal protractor with a 16 1/8 in. radius with tic marks separated by 0.25° on its rear surface; data for the concentric test line was recorded to the nearest 0.25°.

2.1.2. Procedure

The same general procedure was followed in all four sets of experiments. A method of adjustment with hunting was employed for setting the test line. A trial began with the S's eyes closed, and following the experimenter's setting of the test line to an orientation that was well out of the region of uncertainty for a VPV setting, the S was instructed to open his/her eyes, fixate the center of the test line, and report whether it needed to be rotated to the left or right in order to appear vertical; immediately after reporting the subject closed his/her eyes, whereupon the experimenter reset the test line by a variable amount and instructed the S to reopen his/her eyes and report again. The sequence was repeated until the S indicated that the test line was at VPV. Four such settings were made before proceeding to another inducer orientation or, with the 2-line stimuli, another combination of inducer line orientations. Two of each set of four trials began with the test line's initial orientation far ccw relative to true vertical, two began at a cw orientation far from vertical; the four were sequenced in abba order. The seven different orientations or orientation combinations examined in a session were sequenced by an independent random order in different sessions in each experiment; different random orders were employed for different Ss. In each session a series of four trials was run in total darkness prior to the seven main conditions, and a second four-trial series in total darkness was run following the seven main conditions.

Table 1
The values for the main parameters and variables for the lines employed in Expts 2, 3, and 4

Roll-tilt	Equivalent pitch	Extent of line segment					Elevation of line's endpoint		Eccentricity of line				Viewing distance (cm)		Elevation of normal to line	Geometric widths of line image (minarc)			Ratio of geometric widths of retinal image	
		Below eye level	Above eye level	Below normal to line	Above normal to line	Total	Top of line above eye level	Bottom of line below eye level	At top	At bottom	At normal to line	At eye level	To normal to surface	To eye level	Relative to eye level	To normal to line	Top	Bottom	Top/ Normal	Bottom/ Normal
(a) Expt. 2: Roll-tilted-from-vertical 1-line (right side) stimulus																				
−15		5.90	6.03	−0.25	12.18	11.93	5.86	5.73	23.44	26.25	23.37	25	100	100	6.10	5.72	5.72	5.46	1.00	0.96
−10		5.94	6.03	1.82	10.15	11.96	5.95	5.86	23.91	25.79	24.27	25	100	100	4.16	5.68	5.67	5.50	1.00	0.97
−5		5.97	6.02	3.91	8.08	11.99	6.00	5.95	24.38	25.33	24.82	25	100	100	2.10	5.66	5.63	5.54	0.99	0.98
0		6.00	6.00	6.00	6.00	12.00	6.00	6.00	24.85	24.85	25.00	25	100	100	0.00	5.65	5.59	5.59	0.99	0.99
5		6.02	5.97	8.08	3.91	11.99	5.95	6.00	25.33	24.38	24.82	25	100	100	−2.10	5.66	5.54	5.63	0.98	0.99
10		6.03	5.94	10.15	1.82	11.96	5.86	5.95	25.79	23.91	24.27	25	100	100	−4.16	5.68	5.50	5.67	0.97	1.00
15		6.03	5.90	12.18	−0.25	11.93	5.73	5.86	26.25	23.44	23.37	25	100	100	−6.10	5.72	5.46	5.72	0.96	1.00
(b) Expt. 3: Roll-tilted-from-vertical 1-line (right side) stimulus																				
−13.2	−30	34.99	22.00	39.87	17.12	56.99	21.48	34.09	15.89	24.78	21.47	21.99	100	100	4.77	5.95	5.88	4.46	0.99	0.75
−9.1	−20	36.14	26.24	39.76	22.62	62.38	25.94	35.70	17.55	23.72	23.40	23.66	100	100	3.59	5.79	5.55	4.44	0.96	0.77
−4.3	−10	35.31	30.01	37.24	28.02	65.32	29.92	35.20	19.15	22.28	24.59	24.67	100	100	1.93	5.68	5.21	4.61	0.92	0.81
0	0	33.13	33.13	33.13	33.13	66.25	33.13	33.13	20.73	20.73	25.00	25.00	100	100	0.00	5.65	4.88	4.88	0.86	0.86
4.3	10	30.01	35.31	28.02	37.24	65.32	35.20	29.92	22.28	19.15	24.59	24.67	100	100	−1.93	5.68	4.61	5.21	0.81	0.92
9.1	20	26.24	36.14	22.62	39.76	62.38	35.70	25.94	23.72	17.55	23.40	23.66	100	100	−3.59	5.79	4.44	5.55	0.77	0.96
13.2	30	22.00	34.99	17.12	39.87	56.99	34.09	21.48	24.78	15.89	21.47	21.99	100	100	−4.77	5.95	4.46	5.88	0.75	0.99
(c) Expt. 4: Pitched-from-vertical 1-line (right side) stimulus																				
−13.2	−30	34.99	22.00	7.37	49.62	56.99	21.48	34.09	15.89	24.78	25	21.99	100	115.47	−26.95	5.65	3.88	5.61	0.69	0.99
−9.1	−20	36.14	26.24	17.88	44.49	62.38	25.94	35.70	17.55	23.72	25	23.66	100	106.42	−18.06	5.65	4.24	5.43	0.75	0.96
−4.3	−10	35.31	30.01	26.23	39.09	65.32	29.92	35.20	19.15	22.28	25	24.67	100	101.54	−9.05	5.65	4.57	5.17	0.81	0.93
0	0	33.13	33.13	33.13	33.13	66.25	33.13	33.13	20.73	20.73	25	25.00	100	100.00	0.00	5.65	4.88	4.88	0.86	0.86
4.3	10	30.01	35.31	39.09	26.23	65.32	35.20	29.92	22.28	19.15	25	24.67	100	101.54	9.05	5.65	5.17	4.57	0.93	0.81
9.1	20	26.24	36.14	44.49	17.88	62.38	35.70	25.94	23.72	17.55	25	23.66	100	106.42	18.06	5.65	5.43	4.24	0.96	0.75
13.2	30	22.00	34.99	49.62	7.37	56.99	34.09	21.48	24.78	15.89	25	21.99	100	115.47	26.95	5.65	5.61	3.88	0.99	0.69

(a) Expt. 2 with 12°-long roll-tilted stimuli on a frontoparallel plane; (b) Expt. 3 with 66.25°-long roll-tilted stimuli on a frontoparallel plane; (c) Expt. 4 with 66.25°-long pitched-from-vertical stimuli on a pitched-only plane. Values for extent of line segment, elevation of line endpoint, line eccentricity, and elevation of normal relative to eye level are in degrees visual angles.

Notes: (a) The tabulated values are for the right line; for the left line, line eccentricity is negative (−). (b) The relation between pitch and roll reverses sign for the left line (i.e. for the left line, negative (−) pitch values correspond to positive (+) roll-tilt values and vice-versa). (c) The table distinguishes between the normal to the line and the normal to the frontoparallel or pitched-only surface containing the line. The normal to the surface lies in the median plane of the viewing eye.

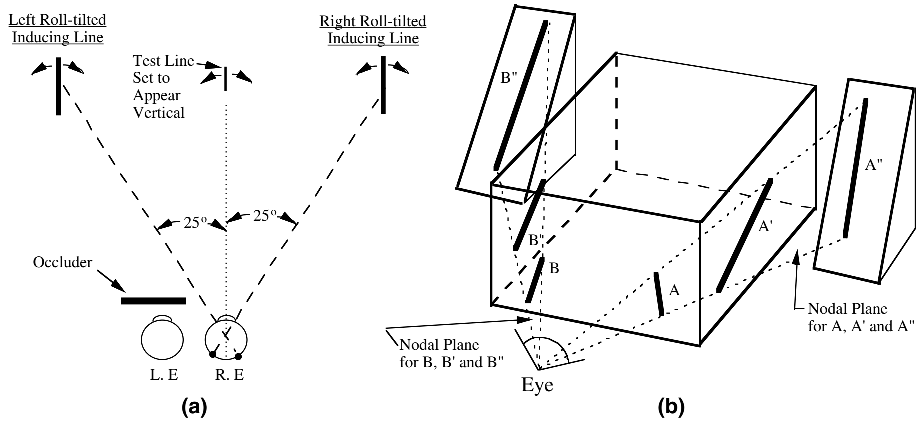

Fig. 2. (a) A sketch of the spatial arrangement employed to measure the orientation of visually perceived vertical (VPV) as influenced by the roll-tilted inducing lines in Expts. 1–3. The arrows adjacent to the inducing lines indicate that they were independently set by the experimenter to one of the clockwise or counterclockwise orientations (Table 1), or was erect. For the conditions in which a 1-line stimulus was employed, the other line was removed. The test line was centered in the median plane of the viewing (right) eye and was adjusted to appear vertical by means of the subject's instruction (VPV setting). In Expt. 4 each of seven orientations of the pitched-from-vertical line(s) (oriented as line A′ or B′ in panel (b)) was employed; the retinal orientation of each pitched-from-vertical line was identical to one of the orientations of the roll-tilted line in Expt. 3 (see Section 2 for further details). (b) Lines from three different planes in space that produce identical retinal orientations: A, A′, and A″ lie in the same nodal plane and stimulate the same retinal orientation; B, B′, and B″ lie in the same nodal plane and stimulate the same retinal orientation. Lines A and B lie in the frontoparallel plane and are located bilaterally symmetrically relative to the median plane of the viewing eye; they are also oriented bilaterally symmetrically (i.e., roll-tilted at equal and opposite orientations—counter-roll-tilted). Lines A′ and B′ are pitched-from-vertical and parallel as are A″ and B″.

2.1.3. Subjects

Although several Ss were run in more than one experiment, only WL (one of the authors) acted as a subject in all of them. Each S provided complete data in all conditions of any experiment in which s/he participated. Expt. 1 (Fig. 1) employed 3 Ss (2 males, 1 female; ages 19–22 years + WL); Expts. 2a and 2b employed 6 Ss (3 males, 3 females; ages 20–22 years + WL); Expts. 3a and 4a employed 5 Ss (2 males, 3 females; ages 19–22 years + WL); Expts. 3b and 4b employed 4 Ss (3 males, 1 female; ages 20–22 + both authors); Expts. 3c and 4c employed 6 Ss (3 males, 3 females; ages 20–22 years + WL). With the exception of the authors all Ss were Columbia undergraduates who were paid an hourly wage for participating; recruitment and the experimental protocol met the requirements of the human subject committee at Columbia University.

2.2. The four sets of experiments

Expt. 1: Variable length (3°—66.25°) roll-tilted inducing line from a frontoparallel plane:

1-line conditions: Expt. 1 measured VPV for each of the seven line orientations at each of nine lengths of the right roll-tilted inducing line: 3°, 6°, 9°, 12°, 18°, 24°, 32°, 48°, and 66.25°, with each length run in a different randomized order in a separate session.

Expt. 2: Short (12°-long) roll-tilted inducing lines from a frontoparallel plane:

Expt. 2a (1-line conditions): The roll-tilted 1-line inducing stimulus was presented on the left side (one session) or right side (separate randomly ordered session) of the median plane.

Expt. 2b (2-line conditions: 49 orientation combinations): Each of the 49 conditions involved one of the seven roll-tilted orientations of the short left line in combination with one of the seven roll-tilted orientations of the short right line. In a session only one left line roll-tilt was employed along with all seven roll-tilts of the right line. The order of left line roll-tilt was randomized separately among sessions for each S. The entire experiment occupied seven sessions for each S.

Expt. 3: Long (66.25°-long) roll-tilted inducing lines from a frontoparallel plane:

Expt. 3a (1-line conditions): The roll-tilted 1-line inducing stimulus was presented on the left side (one session) or right side (separate randomly ordered session) of the median plane.

Expt. 3b (2-line conditions: parallel or equal-and-opposite line pairs): The seven orientations of a parallel, 2-line stimulus was run in one session; the seven combinations of equal-and-opposite orientation line pairs were run in a separate session.

Expt. 3c (2-line conditions: 49 orientation combinations): Each of the 49 conditions involved one of the seven roll-tilted orientations of the long left line in combination with one of the seven roll-tilted orientations of the long right line. Each of the seven conditions in a given session involved the same left line orientation along with a different 1 of the seven right line orientations. Each S was run in seven sessions, with a different left line in each session.

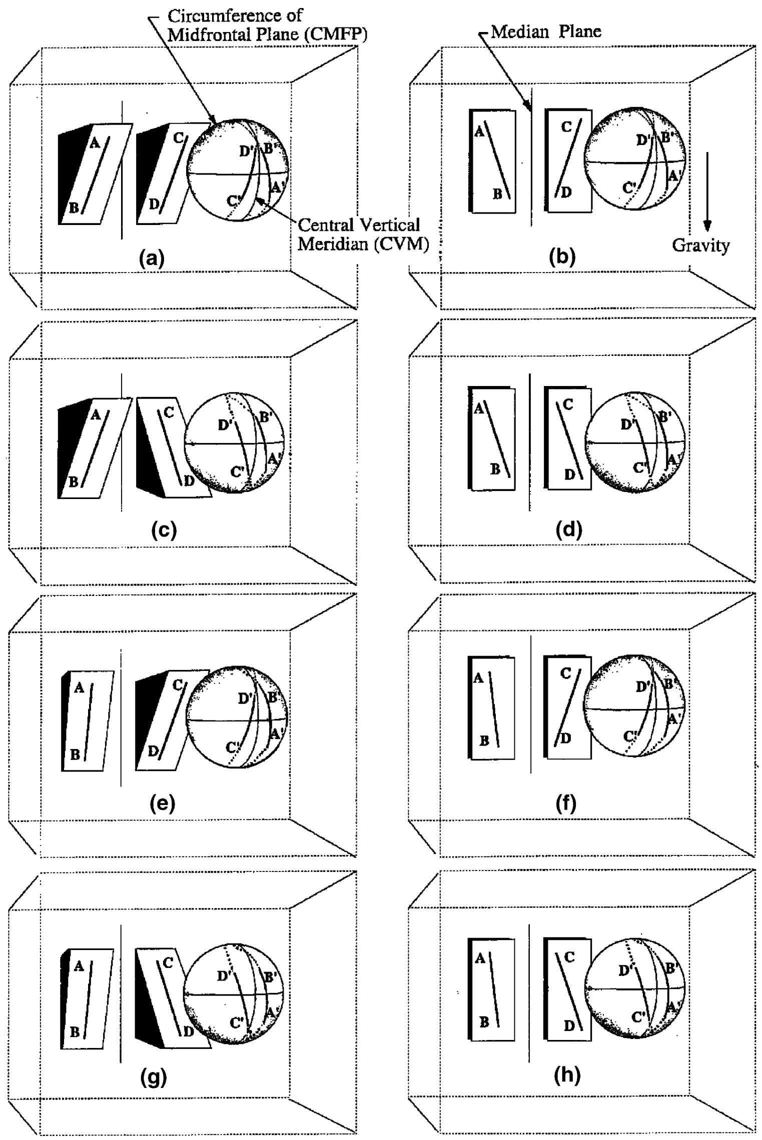

Fig. 3. Sketches of a projection sphere centered at the nodal point of the eye of an erect subject viewing a 2-line visual field in primary position. Each of the four pairs of panels ((a)/(b), (c)/(d), (e)/(f), (g)/(h)) displays the identity of central projections on the projection sphere from two pitched-from-vertical lines on pitched-only plane(s) (left panel) with two roll-tilted (oblique) lines on an erect frontoparallel plane (right panel). The four pairs are examples of the four cases examined in the present experiments. The central vertical meridian (CVM) is the great circle that corresponds to the median plane of the viewing eye of the observer; the circumference of the midfrontal plane (CMFP) is a frontoparallel section through the center of the sphere; the equator is horizontal at the observer's eye level. Projection is through a pupil (not shown) in the midfrontal plane. In each panel the two lines of the stimulus are at equal horizontal eccentricities on opposite sides of the median plane. The two lines in (a) are parallel and lie in a single pitched-only plane whereas the two lines in its erect-plane counterpart in (b) are mirror symmetrical; the two lines in (c) lie in pitched-only planes of equal and opposite pitch whereas the two lines in its erect-plane counterpart in (d) are parallel; the two lines in (e) arise from different pitched-only planes and are pitched by different amounts in the same direction whereas the two lines in its erect-plane counterpart in (f) are roll-tilted by different amounts in opposite directions; the two lines in (g) arise from pitched-only planes that are pitched by different amounts in opposite directions whereas the two lines in its erect-plane counterpart are roll-tilted by different amounts in the same direction.

Expt. 4: Long (66.25°-long) pitched-from-vertical inducing lines:

Expts. 4a (1-line conditions): Except for the fact that the inducing lines were pitched-from-vertical instead of being roll-tilted, Expt. 4a was identical to Expt. 3a: The pitched-from-vertical line was presented on the left side (one session) or right side (separate randomly ordered session) of the median plane.

Expt. 4b (2-line conditions; parallel [same pitch] or equal-and-opposite [opposite pitch] line pairs): The seven orientations of a same-pitch 2-line stimulus were run in one session; the seven combinations of equal-and-opposite line pairs were run in a separate session.

Expt. 4c (2-line conditions: 49 orientation combinations): Expt. 4c was identical to Expt. 3c except that the inducing lines were pitched-from-vertical instead of being roll-tilted. Each of the 49 conditions involved one of the seven pitched-from-vertical orientations of the long left line in combination with one of the seven pitched-from-vertical orientations of the long right line. Seven conditions were run in a given session with only one right line pitch in combination with all seven left line pitches; the entire experiment thus took seven sessions with a different left line in each session.

2.3. Relations between roll-tilted lines on frontoparallel planes and pitched-from-vertical lines on pitched-only planes and some second-order adjustments

Seven roll-tilts in the frontoparallel plane employed in Expt. 3 were originally chosen so that the orientation and location of the image of each line matched the calculated projected orientation of the pitched-from-vertical line for one of the pitches to be utilized in Expt. 4 (see Figs. 2 and 3 and Table 1). Eq. (1) is the transform between the visual pitch, θ, of a plane that contains a pitched-from-vertical line at a horizontal eccentricity, μ, and the roll-tilt, ρ, of a line within a frontoparallel plane that possesses the equivalent roll-tilt (same retinal orientation; see footnote 2) to that of the pitched-from-vertical line for the case in which the plane is pitched-only and the normal to the plane lies at a fixed distance from the eye (see Appendix in Li & Matin, 1996 for derivation and details):

$$\rho = \arctan(\tan\mu \times \sin\theta). \quad (1)$$

Simply transforming the physical orientation of a pitched-from-vertical line on a pitched-only plane to a roll-tilted line on a frontoparallel plane so that the retinal orientation of the line and viewing distance to the surface would remain constant introduces six differences between the retinal stimulus of the line in the two different physical planes: (1) Whereas the normal line of visual direction to the pitched-from-vertical line from the viewing eye declines with increasing topbackward pitch or with decreasing topforward pitch, it rises with equivalent-pitch changes in obliqueness of the roll-tilted lines on the erect frontoparallel plane that correspond to these real-pitch changes. Since the normal line of visual direction to a line stimulus intersects the line at a distance from the eye that is shortest for any point on the line, the gradient of geometric width of the retinal image of the line is broadest at this intersection with the normal; and since the normal undergoes oppositely directed changes in elevation with real pitch as compared to the corresponding equivalent pitch, so too do the centers of these width gradients and thus the entire gradients (Table 1). (2) As a consequence of these oppositely directed variations in the width gradients, the gradients of luminous flux in the roll-tilted and the equivalent roll-tilted lines also change in opposite directions with change in roll-tilt than they do with equivalent roll-tilt. (3) The individual pitched-from-vertical line possesses different depth gradients for different pitches; these are larger than the comparable depth gradients for the roll-tilted lines in the erect plane which stimulate identical retinal orientations to those stimulated by the pitched-from-vertical lines (Table 1), producing different stimuli to accommodation. (4) There are small differences in line length. (5) There are small differences in height-in-the-field of the lines. (6) There are small differences in line eccentricity. We did not attempt to modify the differences in (1)–(3); thus, the proximal stimulation from the roll-tilted lines and lines of equivalent roll-tilt was not completely equated. However, by adjustment of the oblique-line stimulus, we did eliminate the three other differences ((4)–(6)), that could have influenced the comparison; this involved small height changes of the physical line stimuli and appropriate covering of their ends to equalize projected length in comparable conditions of Expts. 3 and 4. Following the adjustment of height-in-the-field and length of an oblique line, in Expt. 3 the line was horizontally translated by the small amount required to set the eccentricity at true eye level to the same value as for the comparable condition for the pitched-from-vertical line (see Table 1).

3. Results

The mean value of the settings from the four successive trials for each S in a condition will be treated below as the VPV for the condition for that S. In describing the results for each condition, the slope of the VPV-vs-roll-tilt function or VPV-vs-equivalent-roll-tilt function will be treated as the main measure of interest. Each slope makes use of VPV values from seven line orientations for each S and provides the single most reliable bias-free measure of sensitivity of the VPV response to the visual inducer, and thus also the most sensitive basis for comparison.

Fig. 4 displays the growth of sensitivity with length of the single inducing line from Expt. 1; the growth is well-fit by the negatively accelerated exponential function with a length constant of 17.1° and an asymptote at 0.55; fits for each of the 3 Ss is similar to the average curve shown, but possess different asymptotes, 0.39, 0.63, and 0.68, leading to the large statndard error of the means (SEMs) for the averages with the longer lines.

The average results from Expts. 2, 3, and 4 comparing the 1-line and parallel-only 2-line stimuli for the short roll-tilted line, the long roll-tilted line, and the long pitched-from-vertical line (equivalent roll-tilt) are displayed in Fig. 5a, c, and e respectively (see Fig. 3d and c). The difference in slopes between each of the short 1-line results, 0.18 and 0.17, for the left and right lines,

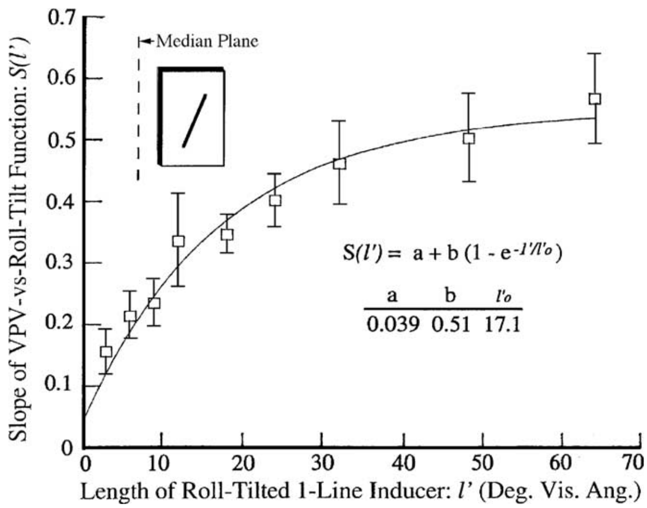

Fig. 4. The curve is the best fitting exponential (least squares) to the average slopes of the VPV-vs-roll-tilt functions from Expt. 1. At each of the nine line lengths the seven roll-tilts employed were ±13.1°, ±9.2°, ±4.3°, or 0°. The vertical bars above and below a data point represents ±1 standard error of the mean.

respectively, and the short parallel-only 2-line slope, 0.32, is significant ($p < .01$, 5 df), but the difference between the sum of the two 1-line slopes, 0.35, and the 2-line slope is not significant; thus, these short-line results approximate complete linearly additive summation. The slope values for the long real and equivalent roll-tilted 1-line inducers in Fig. 5c and e, respectively, are similar, with 0.42 and 0.50 for real roll-tilt and 0.43 and 0.48 for equivalent roll-tilt ($t = 0.536$, $p > 0.61$ for the left line conditions; $t = 0.368$, $p > 0.72$ for the right line conditions). Neither long-1-line slope differed significantly from the corresponding 2-line slope which equaled 0.49 and 0.50 in the two long-line cases; thus, the 2-line slope in each long-line case closely approximates the average of the corresponding 1-line slopes.

The seven 2-line inducers for which the 2 paired members have equal and opposite roll-tilt orientations and the corresponding pitched-from-vertical pairs (e.g., Fig. 3b and a) are of additional interest. The average results for these 2-line functions are displayed in Fig. 5b for the short-lines (Expt. 2b), in Fig. 5d for the long roll-tilted lines (Expt. 3b), and in Fig. 5f for the pitched-from-vertical case (Expt. 4b); the VPV-vs-roll-tilt (or equivalent roll-tilt) slope in all three cases are flat with best-fitting slopes of 0.01, −0.01, and 0.00, respectively, indicating that the influences of the inducing lines is algebraically additive.

The forty nine-condition results of Expts. 2b, 3c, and 4c are displayed in Fig. 6a, c, and e, respectively, showing that for short and long roll-tilted lines and for pitched-from-vertical lines, when the orientation of one of the two simultaneously presented lines is constant, VPV changes linearly with the orientation of the other line.[3] In each case, for a more clockwise orientation of the first (parameterized) roll-tilted or equivalent roll-tilted line, the entire linear function is shifted to more clockwise VPV values, but the slope of the function does not change. Both of these aspects—the essential constancy of the slope and the linear shift of the function (change in the y intercept) with roll-tilt or equivalent roll-tilt of the parameterized line—are clear in Fig. 7a and b, respectively. The slopes of the short-line results in Fig. 6a range from 0.15 to 0.18. The slopes of the long roll-tilted and pitched-from-vertical lines are extremely similar to each other with slope values that range from of 0.30 to 0.34 for the pitched-from-vertical case and from 0.30 to 0.33 for the roll-tilted case; the *y*-intercept varied from −2.4° to 5.3° for the pitched-from-vertical case and −2.9° to 4.8° for the roll-tilted case, respectively. The magnitude of the slopes in Fig. 7a indicate the variation in magnitude of the influence of the orientation of a second line (e.g., the right line) on VPV when another equally long line of a single orientation is present simultaneously (e.g., the left line). The existence of smaller slopes for the short roll-tilted lines in Fig. 6a than those of the long real and equivalent roll-tilted lines are an indication of the lessened influence of the variation of the orientation of the second short line, and goes along with the smaller difference in *y*-intercept among the short-line functions than among the long-line functions (Fig. 7b), a result that also indicates the lessened influence of the variation of the parameterized short line as compared to the influence of the parameterized long line. Although Expts. 3c and 4c provided considerable opportunity for differences between the long roll-tilted and pitched-from-vertical (equivalent roll-tilt) line stimuli to be revealed with regard to their ability for inducing changes in VPV, none have appeared. The two sets of results as displayed above in Figs. 6 and 7 appear essentially indistinguishable in every way. A closer look at the consistency of individual Ss across the two experiments is afforded by Fig. 8a. The marked (and statistically significant; $p < .0001$, 292 df) correlation across the two

[3] In Expts. 2b and 3c, the orientation of the left line was fixed throughout a session and varied between sessions whereas the orientation of the right line was varied within each session (the 'variable'); in Expt. 4c, the right line was fixed throughout a session and the orientation of the left line was varied within a session (see Method). In Fig. 6, however, the orientation of the right line is plotted on the abscissa and the orientation of the left line is shown as the parameter of the set of functions in each of the three experiments. The analogous graphs with the roles of parameter and variable interchanged (not shown) are essentially indistinguishable in each case, indicating that the results did not depend on whether the different orientation combinations into which a given line entered was run in a single session or spread across sessions.

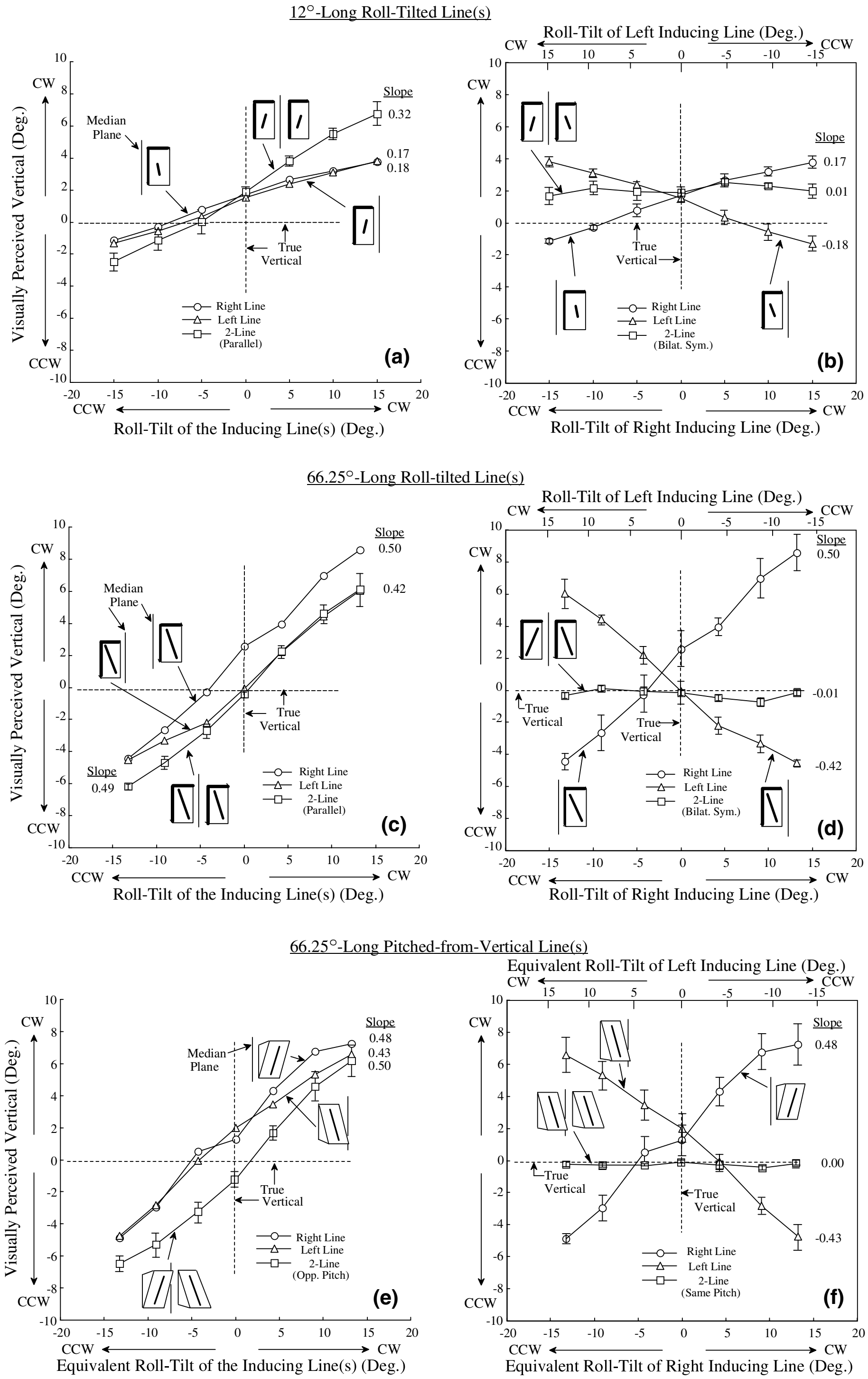

Fig. 5. Panels (a) and (b), (c) and (d), and (e) and (f) plot values from Expts. 2a and 2b (short roll-tilted lines), Expts. 3a and 3b (long roll-tilted lines), and Expts. 4a and 4b (pitched-from-vertical lines), respectively. The left-hand panels, (a), (c), and (e), plot VPV values at each of the seven orientations of each of the two 1-line inducing stimuli, and a parallel 2-line inducing stimulus consisting of the left and right lines simultaneously presented. The right-hand panels, (b), (d), and (f) plot VPV values from the same experiments, repeating the results for the 1-line stimuli in the left-hand panels, and also displaying the results for the equal-and-opposite 2-line stimuli from Expts. 2b, 3b, and 4b, respectively; the results for the left line only are reversed in the right-hand column of figures (utilizing the upper abscissa) in order to place the 2-line condition and the two 1-line conditions containing the 1-line components at the same value of the abscissa. Each plotted point is an average for one of the conditions across all subjects in the experiment. cw: clockwise; ccw: counterclockwise. The vertical bars above and below a data point represents ±1 standard error of the mean.

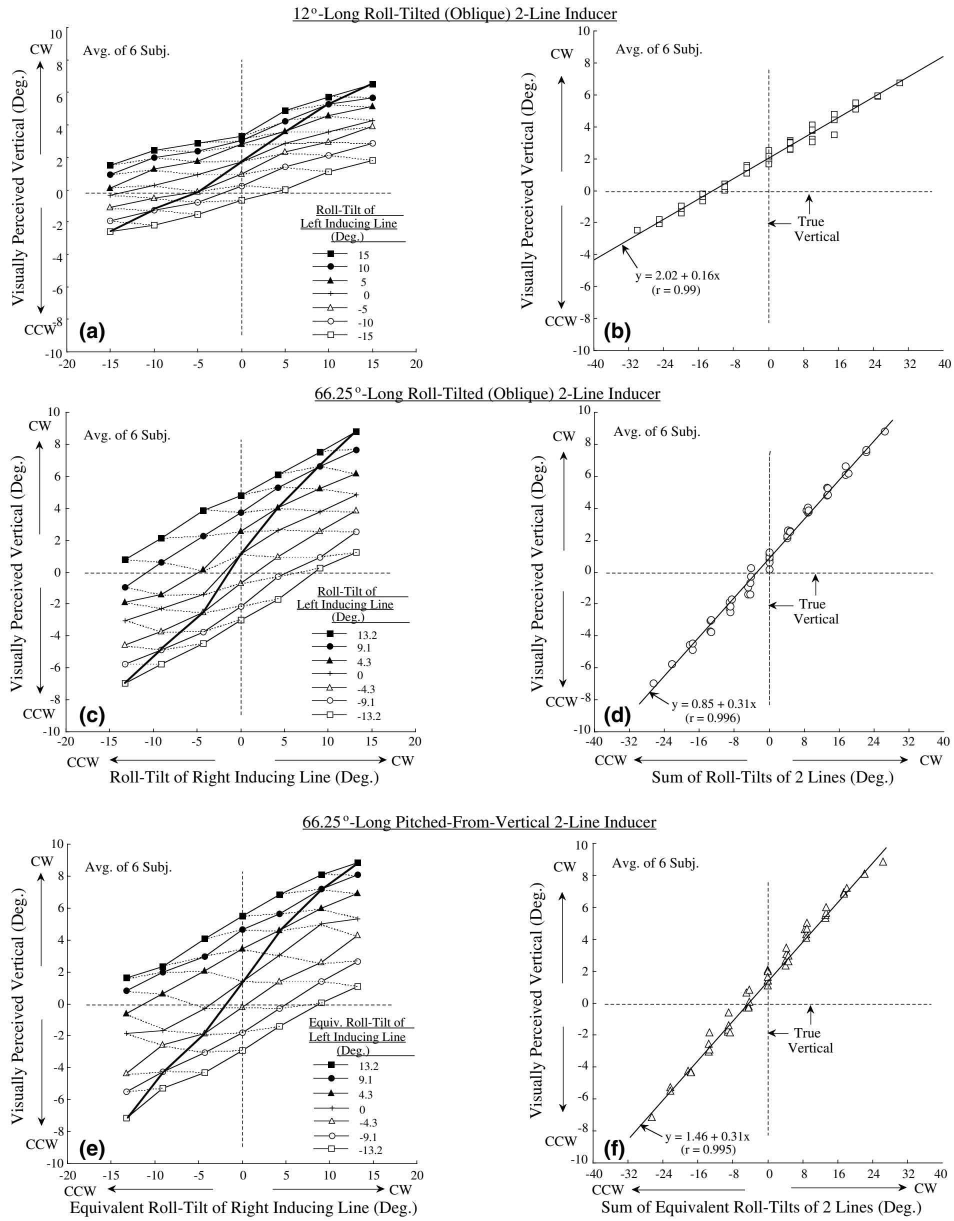

Fig. 6. The solid, upward-sloping lines connecting the data points in the left-hand panels, (a), (c), and (e), display the average values of visually perceived vertical (VPV) for the six subjects in each of the three 49-condition 2-line experiments: Expt. 2b with the roll-tilted short lines (12°-long), Expt. 3c with the roll-tilted long lines (66.25°-long), and Expt. 4c with the pitched-from-vertical (equivalent roll-tilt) long lines (66.25°-long). Each VPV value is plotted with the roll-tilt (or equivalent roll-tilt) of the right line on the abscissa and the roll-tilt (in (e) the equivalent roll-tilt) of the left line as the parameter as displayed by the symbol in the legend on the figure. The solid dark line in each panel connects the set of seven points for the conditions in which the roll-tilts (or equivalent roll-tilts) of the two simultaneously viewed lines are parallel (see Fig. 3c and d). In (a) the light dotted lines connect points for which the sum of the two roll-tilts are identical for all connected points; in (c) and (e) they connect points for which deviations from identity of the sums of roll-tilts or equivalent roll-tilts are small (see footnote 4). In the right-hand panels (b) and (d) the average VPV for each of the 49 2-line condition experiments is plotted against the sum of the roll-tilts of the two lines of the stimulus in Expts. 2b and 3c, respectively, and in panel (f) the average VPV is plotted against the sum of the equivalent roll-tilts of Expt. 4c. Standard error of the means (SEMs) are not displayed in the figure since doing so would make for much too crowded a set of figures; we summarize their values: The average SEMs are 0.43, 0.61, and 0.69 for all conditions in Expts. 2b, 3c, and 4c, respectively; the ranges of the SEMs are 0.27–0.54, 0.25–1.03, and 0.17–0.93 for all conditions in Expts. 2b, 3c, and 4c, respectively.

experiments, +0.95, is, of course, a consequence of the third variable, roll-tilt/equivalent roll-tilt. However, the average correlation between the VPVs in the two experiments for a given one of the 49 combinations of roll-tilt/equivalent roll-tilt, +0.67 (essentially a partial correlation), is itself substantial—and is completely free of any influence of the roll-tilt/equivalent roll-tilt variable; this indicates a great deal of consistency in the

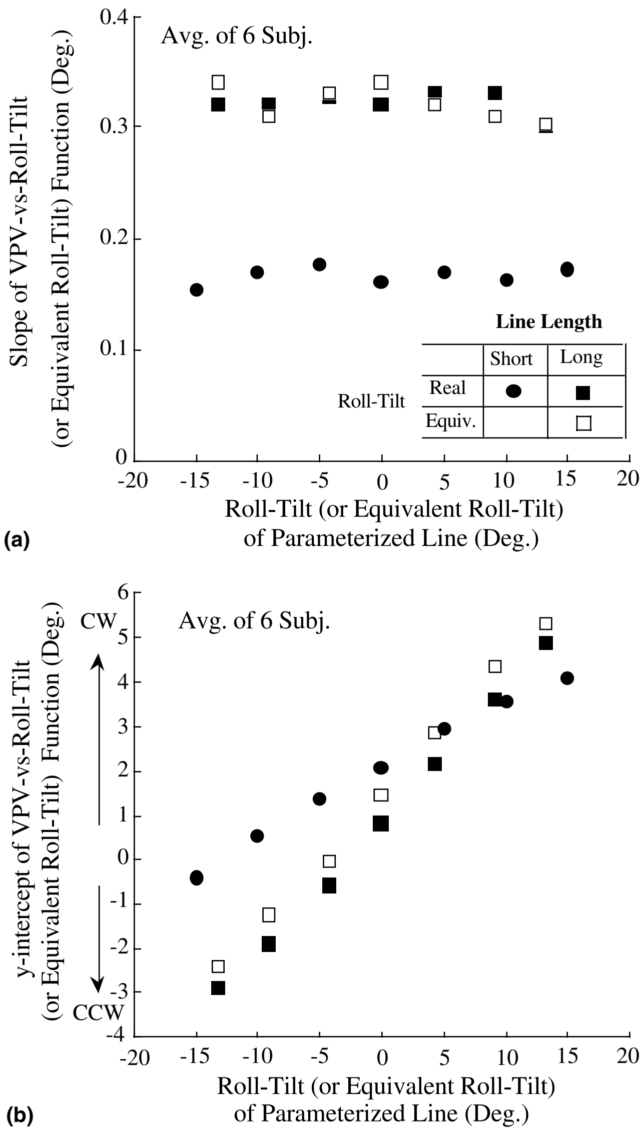

Fig. 7. The best fitting slopes (panel a) and y-intercepts (panel b) for the results in Fig. 6a, c, and e for Expts. 2b, 3c, and 4c, respectively, for the short roll-tilted lines, the long roll-tilted lines, and the long pitched-from-vertical lines (lines of equivalent roll-tilt).

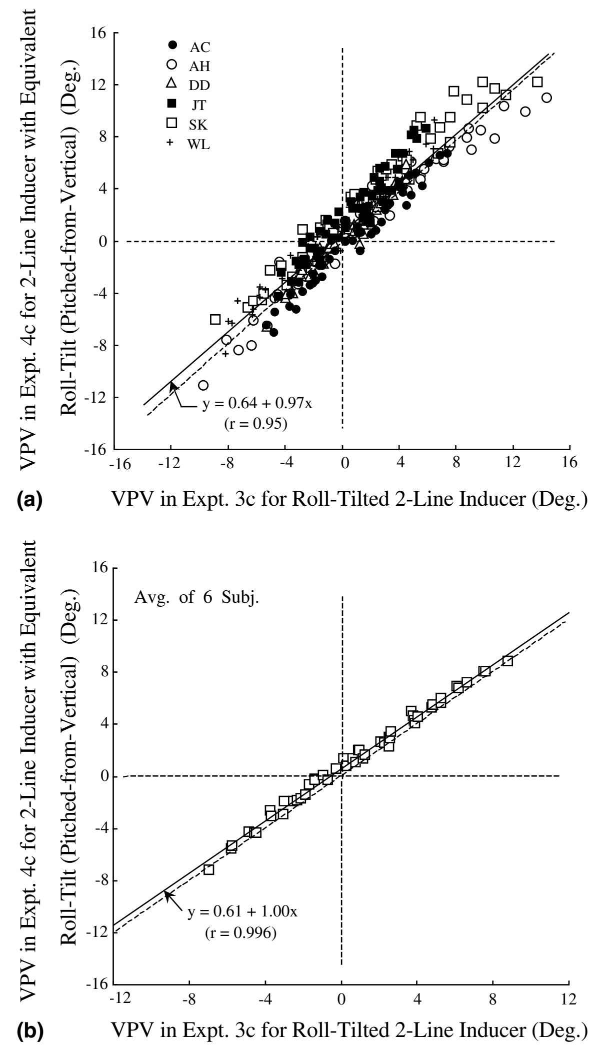

Fig. 8. (a) Each of the VPVs in Expt. 3c with the 2-line roll-tilted visual field (294 VPVs = 49 conditions × 6 subjects) is plotted on the abscissa against the VPV from the condition with equivalent roll-tilt for the same subject in Expt. 4c on the ordinate. (b) Each of the 49 VPVs averaged across the six subjects in Expt. 3c is plotted against the average VPV in the equivalent roll-tilt condition of Expt. 4c. The equation displayed in each panel is the best-fitting straight line. The best fits are shown as the solid lines; the dashed diagonal line is the slope-of-1.00 line.

VPV settings of a given S across the roll-tilted and equivalent roll-tilted conditions.

The results of the individual Ss from the short-line experiments, Expt. 2a and the parallel-only 2-line subset from Expt. 2b, are displayed in the left-hand panels in Fig. 9; the individual results for the equal-and-opposite case from Expt. 2b are displayed in the right-hand panels. Although the magnitudes of effect on VPV are smaller for the short line conditions, and hence relatively more noisy than the effects of long lines, it is clear that the summation effect in the average results of Fig. 5a is reasonably approximated in the left-hand panels of Fig. 9 for the individual Ss, and that the nulling effects in the average results for the equal-and-opposite case in Fig. 5b are approximated in the right-hand panels of Fig. 9 for the individual Ss. The main average effects in each of the experiments described herein are similarly visible in the results of almost all of the individual Ss.

Since measurements were made on each S in each of seven sessions in the three 49-condition experiments, nine 2-way ANOVAs were done, 1 each on the slopes of the VPV-vs-roll-tilt (or equivalent roll-tilt) functions, the y-intercepts, and the dark values of each of the three experiments. A great deal of consistency is manifested in the responses of a given S across conditions in each experiment (Table 2a); this is shown by the significance in the Ss' variable for the slopes ($p < .001$ in each case),

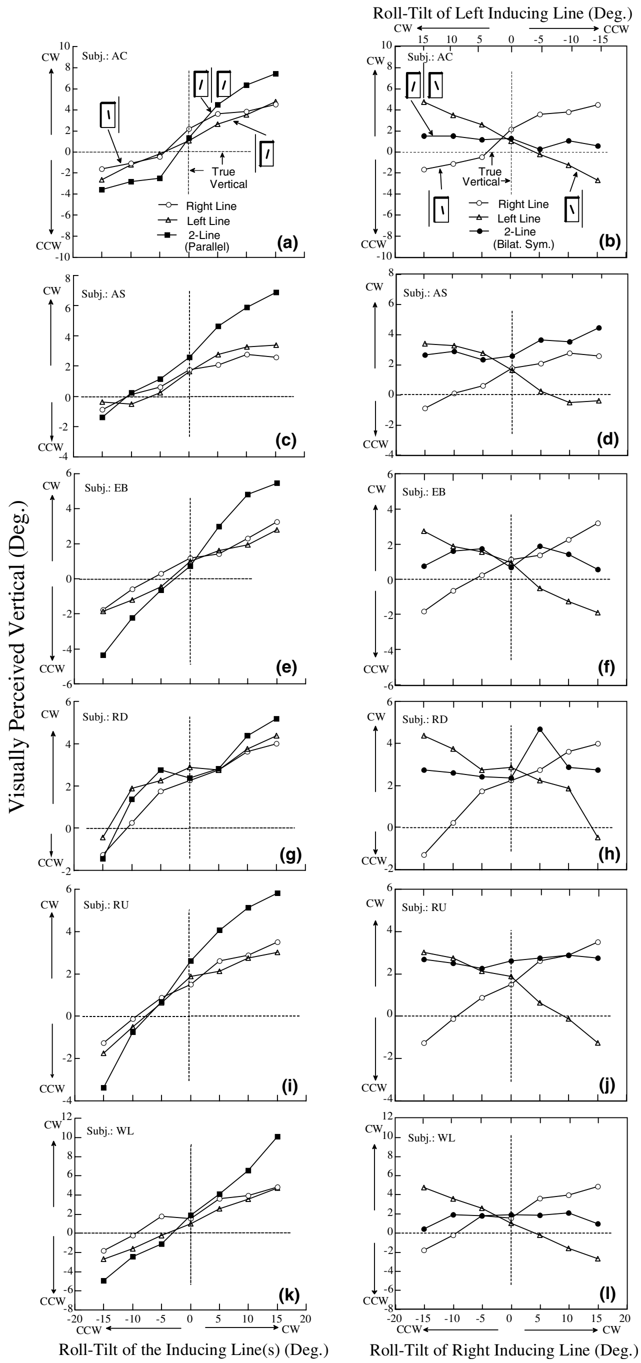

Fig. 9. These are the short-line (12°-long line) results for each of the 6 individual subjects displayed in the form shown in the display of the average results in Fig. 5a and b. Each panel in the left-hand column displays the results for one of the six subjects for the 1-line conditions in Expt. 2a and the 2-line subset for which the 2 roll-tilted lines were parallel in Expt. 2b; the adjacent panel in the right-hand column displays the results for the same subject for the conditions from Expt. 2b in which the 2-line inducers were bilaterally symmetric (equal-and-opposite roll-tilt orientations) along with a replot of the 1-line conditions from Expt. 2a; the results in the right-hand panels for the left line only are reversed (upper abscissa) in order to place the 2-line condition and the two 1-line conditions containing the 1-line components at the same value of the abscissa.

the y-intercepts ($p < .001$ for Expts. 2b and 4c; $p < .03$ for Expt. 3c), and the dark values ($p < .001$ in each case). Kendall's coefficient of concordance (W) (Kendall, 1955) confirmed these outcomes regarding subject consistency. Similar less complete statistics done on several of the other experiments demonstrated similar consistency. The failure at significance for the parameter differences for the slopes and dark values (Table 2a) show that order of stimulus presentation within and across sessions was unimportant for these measures; the significant F values for the y-intercepts show the significant influence of the orientation of the line of constant orientation within a session (Fig. 6a,c,e, and Fig. 7b).

Summary statistics for the standard deviations (SDs), y-intercepts, and dark values, are shown in Table 2b. The average SD across Ss in all conditions was 0.98°; the average y-intercept across conditions in all experiments was 1.15°; the average dark VPV across Ss in all conditions was 0.79°. Since the settings of VPV are highly dependent on signals regarding the direction and magnitude of the gravitoinertial vector, one might expect a close connection between the dark VPV and the y-intercept of the VPV-vs-roll-tilt function, and in fact, such a relation does exist in several of the cases for which a reasonable determination could be made. Thus, in two of the long 1-line experiments, Expt. 3a (left and right lines combined) and Expt. 4a (left and right lines combined), the best-fitting straight line to the y-intercept-vs-dark value functions (each subject is a single point) had slopes of 0.92 and 1.66 with correlations of +0.72 and +0.82, significant at the 0.002 and 0.0003 levels, respectively. However, although the relations were positive, in neither of the corresponding 2-line cases, 3b or 4b, was the dark value/y-intercept correlation significant; nor was the relation significant in Expt. 2 for the short 2-line case.

4. Discussion

Witkin and Asch reduced the visual frame of reference for the perception of verticality in the fully structured, well-illuminated visual field to the square frame from the frontoparallel plane in darkness. The present experiments have carried the experimental reduction two steps further. They have shown that not only is the full square frame not necessary in order to generate substantial, systematic influences on VPV, but also that a single, peripherally presented stationary line, whose variation in orientation is sufficient to generate a variation in VPV of about the same magnitude as that generated by the full square frame, need not even come from the frontoparallel plane; a line from a pitched-only plane suffices. The results in Figs. 4–6 also indicate that not only is the frame-as-an-entity not an aspect of an

Table 2
Results of ANOVAs on the slopes of the VPV-vs-roll-tilt (or equivalent roll-tilt) functions, the *y*-intercepts, and the dark values of the Expts. 2b, 3c, and 4c (upper portion); the standard deviation of VPV, the *y*-intercepts, and the dark VPV of the Experiments 1–4 (all values are in degrees) (lower portion)

Expt.	Measure	ANOVA						Kendall's coefficient of concordance		
		Subj. Diff.			Param. Diff.					
		F	df	Sig. level	*F*	df	Sig. level	W	df	Sig. level
2b	Slope	8.72	5	0.001	0.27	6	0.95	0.48	6	0.01
	y-Intercept	9.96	5	0.001	35.75	6	0.001	0.61	6	0.01
	Dark value	16.30	5	0.001	0.96	6	0.47	0.76	6	0.01
3c	Slope	44.86	5	0.001	0.77	6	0.60	0.96	6	0.01
	y-Intercept	2.96	5	0.03	33.78	6	0.001	0.37	6	0.05
	Dark value	40.36	5	0.001	0.42	6	0.86	0.76	6	0.01
4c	Slope	20.03	5	0.001	0.83	6	0.56	0.61	6	0.01
	y-inter.	10.93	5	0.001	49.40	6	0.001	0.62	6	0.01
	Dark value	51.44	5	0.001	0.84	6	0.55	0.91	6	0.01

Expt.	Standard deviations		*y*-Intercepts		Dark VPVs	
	Avg.	Range	Avg.	Range	Avg.	Range
1	1.09	0.90–1.26	1.31	−0.05–2.34	0.77	0.24–1.66
2	0.94	0.91–0.95	1.85	0.50–3.08	1.09	0.31–2.38
3	0.82	0.64–1.07	0.61	−1.05–4.21	0.45	−1.56–3.13
4	1.05	1.00–1.31	1.00	−0.81–3.93	0.91	−0.87–2.72
Avg.	0.98		1.15		0.79	

Note: Each average is taken across all subjects in all conditions of the experiment.
Each end of a range is the most extreme value for any subject under any condition.

arrangement required for combining influences from individual lines on VPV, but neither is a right angle between lines or a common orientation for the lines a necessary component of the inducer.

The key to the influence of the individual line on VPV is the retinal orientation (see footnote 2). The magnitude of the influence by the single inducing line grows with its orientation over the ±15° range of inducer roll-tilts or equivalent roll-tilts employed in the present experiments, and for a given line orientation the influence grows also with the length of the line, reaching a maximum under our conditions of about ±7° for a 66.25°-long inducer with a roll-tilt or equivalent roll-tilt of ±13.2°. The influence of two short parallel lines from bilaterally symmetric locations are combined to generate a considerably larger influence than either generates alone; with any pair of orientations the combined influence approximates the linearly additive sum of the separate influences of the two constituent lines, with the value decreasing to zero for lines with equal-and-opposite orientations. On the other hand, the additional influence of a second simultaneously presented long parallel line beyond that generated by a first long line is small, being limited by the approach to the asymptote of the first line; thus the resulting magnitude of influence on VPV approximates the average of the two separately measured influences for any combination of orientations, also reaching zero for two lines with equal-and-opposite orientations.

4.1. Linear independence among influences of individual lines

The results in Fig. 6a, c, and e contain the average results from the three 49-condition experiments with the short 2-line roll-tilted stimuli, the long 2-line roll-tilted stimuli, and the long 2-line pitched-from-vertical (equivalent roll-tilt) stimuli, respectively. Each of the seven solid, approximately parallel lines connects a set of seven points for which the left line orientation is fixed and the right line orientation varies. The dark solid line of large slope connects the seven points for which the two inducing lines are parallel in each panel. Each light dotted line connects a set of points for which the sum of the roll-tilts or equivalent roll-tilts of the two lines is either fixed (Fig. 6a) or very nearly fixed (Fig. 6c and e; see[4]). The close approximation to parallel horizontal lines of the dotted lines in each left-hand panel indicates the close approach to constancy of VPV for a given sum

[4] Deviations from identity of the roll-tilt (or equivalent roll-tilt) sums of connected points in Fig. 6c and e are small, the largest being equal to 0.6° (between 8.6° and 9.2°); these variations result from the fact that the spacing between the orientations of individual lines was not uniform; consequently, the sums of the roll-tilts in the two long-line experiments (Expts. 3c and 4c) were not always identical (e.g., 4.6° + 4.6° is not identical to 13.2° − 4.6°). All connected points in Fig. 6a, however, are for data for which the sums of the roll-tilts for all connected points are identical.

of roll-tilts or equivalent roll-tilts, a relation displayed directly in the right-hand column. The slopes of the functions in Fig. 6c and e for the long lines are the same (0.31), providing another indication of the essential identity of influence for lines of the same retinal orientation from different physical planes. The slopes for both long-line functions in Fig. 6c and e are considerably larger than the slope for the short lines in Fig. 6a (0.16), a result that is traceable to the smaller change of influence of the short individual line with variation in roll-tilt than change for the long line, and is another manifestation of the sensitivity difference with length as measured by the slope functions for the individual lines (Fig. 5a, c, and e).

Fig. 10a–c plot the average VPV for each of the three 49 2-line combinations from Expts. 2b, 3c, and 4c against the sum of the average VPV values for the two constituent 1-line inducers. Dashed and dotted lines in each panel represent the complete linear summation and averaging predictions, with slopes of 1.00 and 0.50, respectively; both are drawn through the best-fitting y-intercept so that the comparison of slopes—providing a measure of sensitivity—can be viewed as a bias-free measure. The best-fitting slope to the short-line data equals 0.91, thus following a direction close to the line representing linearly additive summation. With best-fitting slopes of 0.66 and 0.67, the data for the long real roll-tilted lines and the pitched-from-vertical lines (equivalent roll-tilt) fall much closer to the theoretical line representing the averaging process.

Thus, all three of the functions in Fig. 10 can be represented by the same linear equation with only differences in y-intercept and slope:

$$y = -0.59 + 0.91x : \text{near complete summation for the short roll-tilted lines} \quad (2a)$$

$$y = -0.81 + 0.66x : \text{near averaging for the long roll-tilted lines} \quad (2b)$$

$$y = -0.64 + 0.67x : \text{near averaging for the long pitched-from-vertical lines.} \quad (2c)$$

So, although the growth of VPV with line length is a negatively accelerated function (Fig. 4), for each of at least two points on the line-length function—at 12° and 66.25°—the process in control of the 2-line VPV value is closely linear with regard to the combination of influences from the two same or different orientations and in the magnitude of the response to orientation (Fig. 6). We have no reason to believe that a similar linear process would not operate at any other length and suggest that it is likely that for lines even shorter than 12° the slope would be even closer to 1.00, and for lines even longer than 66.25° the slope would be closer to 0.50.

4.2. *Comparisons between influences from roll-tilted lines and pitched-from-vertical lines*

Four considerations led to the experiments in which VPV was measured with pitched-from-vertical (equivalent roll-tilt) lines from pitched-only planes as inducers:

1. As noted above, the common view of the rod-and-frame situation is that the square frame acts as a surrogate for the normal horizontal and vertical elements in our environment. However, the pitched-from-vertical lines from pitched-only planes cannot be treated similarly. To take only one case: If two bilaterally located, parallel lines are roll-tilted counterclockwise, the equivalent pitched-only 2-line stimulus consists of one line that is pitched-only in a topbackward direction and a second that is pitched-only in the topforward direction (Fig. 3c and d). These two equal and oppositely pitched from vertical lines are skew to each other, do not fall into the same plane as the roll-tilted lines with the same retinal orientation, and cannot arise from a planar square frame. Thus, the fact that the results do not differ from those with the roll-tilted lines indicates that there is more to the VPV induction than the surrogate interpretation of the frame.

2. Whereas one might expect that the monocularly viewed lines employed in the present experiments would do little to generate an impression of pitch, several recent reports have shown that this is not so (Li & Matin, 1998; Post, Teague, Welch, & Hudson, 2003). The subjects in these reports made manual pitch matches to parallel, pitched-from-vertical 2-line stimuli, and their experiments demonstrated the presence of reliable perceptions of pitch that were monotonic with physical pitch. There is also some indication that subjects are able to discriminate monocularly between roll-tilted and pitched-from-vertical 1-line stimuli at the same retinal location, orientation, and length (same nodal plane) presented separately in darkness (Matin, Li, & Hudson, 1999).

3. By employing the same retinal orientations for the lines in Expts. 3 and 4 along with the parameters of line length, location, and line number, while leaving the differences in the gradients of line width, luminous flux, and distance of equivalent segments from the eye and accommodative stimuli (see Table 1), we are able to determine whether the key to the influence exerted by the line stimuli was the retinal orientation of the line or if other aspects of the line stimuli might play a role.

4. Obtaining induction effects of indistinguishable magnitude from differently pitched planes and from a single plane, along with a test line whose rotation is limited to the frontoparallel plane tells us that the physical plane of origin of the inducing line is not essential; theoretical considerations can henceforth focus on the stimulus at the eye independently of the pitch of the plane of origin of the line in the external stimulus. These results carry further the earlier result that the induction appears

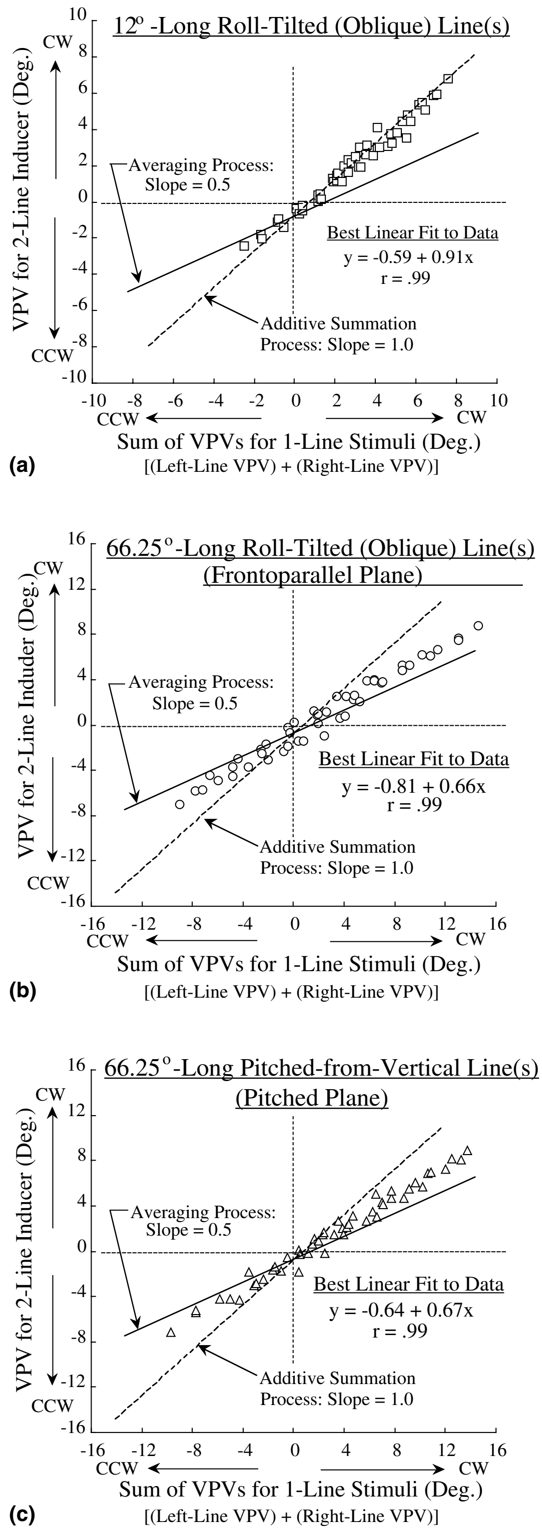

Fig. 10. Each of the three panels plots the VPV for the 2-line inducer against the sum of the VPVs for the two constituent 1-line stimuli measured separately for one of the three 49-condition 2-line experiments: Expt. 2a (left + right lines) vs. Expt. 2b in panel a; Expt. 3a (left + right lines) vs. Expt. 3c in panel b; Expt. 4a (left + right lines) vs. Expt. 4c in panel c. The slopes of the two theoretical straight lines shown in each panel are those that would result if the total visual influence contributing to the 2-line VPV was the sum of the contributions of the two constituent lines ("additive summation process") and the average of the VPVs of the two continuous lines ("averaging process") respectively; both the slope value and the y-intercept for the equation in each panel are from the least squares best fitting straight line.

to work as well across a frame and a rod that lie in frontoparallel planes of different depth as it does within a single frontoparallel plane (Ebenholtz & Glaser, 1982; Gogel & Newton, 1975).

4.3. The basis for the rod-and-frame effect lies in the influence of lines in a mass action rule

The present results show that the frame-organized-into-a-square is not necessary for the influences from a roll-tilted visual field to be manifested. The magnitude of the effects we measure with the single line or with two lines are as large as those originally measured with the full frame by Witkin and Asch. The linear equations (2a)–(2c) accurately describe the rule for combination for two lines of the same or different orientations. Although the present results were only obtained at a single pair of eccentricities and over a limited range of orientation, we have measured the same rule (with different constants) to be operative at each of two different pairs of eccentricities over a much more complete set of retinal orientations in another full set of experiments (Li & Matin, 2002, in press). We thus suggest that the rule is likely to hold more generally. Although our carpentered environments do contain long lines that parallel the horizontal and vertical, most of the objects in our environments—both carpentered and natural—contain short extents of lines, many of which—if not most—are near vertical or horizontal. It is reasonable to think that neural mechanisms have developed that would make use of any conjunction of these pieces within a visual scene with no requirement that they form the relatively rare configuration of a square or any other specific configuration and we thus refer to the generality of the configuration-independence of the linear combination as a rule of mass action.[5]

4.4. The functional basis for the influence of line orientation on VPV

While at least a substantial portion of the influence of the square frame on VPV has a basis in the relation of the square's arms to the orientations of the vertical and horizontal in gravity-based physical space, as noted earlier, this has not been the exclusive basis for investigating the influence of the frame; nor has an explanation for the rod-and-frame effect been presented. It is reasonable to think that the effect is a piece of an overall compensatory mechanism for roll-tilt of the head and/or head-and-body that normally serves to maintain perceptual constancy of orientation, and that this piece does the major work in maintaining constancy in an erect, illuminated environment. This suggests that when a retinal orientation change is generated by a change in the physical roll-tilt of the visual stimulus instead of by a change in roll-tilt of the head and/or head-and-body, the errors in VPV result from the unusual relation between the orientations of the main lines of organization of the visual field and the direction of the gravitoinertial vector, and/or the relation between the main lines of the visual field and the median plane of the body (cf., Mittelstaedt, 1986, 1988, 1992, 1997; Rock, 1954). The existence of a VPV-vs-head-and-body tilt function in total darkness in which VPV variation is small relative to the magnitude of the change of retinal image orientation associated with the rotation of head-and-body (Bauermeister, 1964), indicates that along with the influence from the visual field, VPV constancy involves a major contribution of signals from the body-referenced mechanism. Changes in perceived head-and-body tilt (Witkin, 1949) and perceived head tilt in the presence of a tilted frame (Ebenholtz & Benzchawel, 1977) have been reported, and, since such effects would be a consequence of an interaction between the visual system and the body-referenced mechanism, they could be a sign of an additional contribution to a compensatory mechanism for head-and-body tilt.

Although the present experiments have been exclusively concerned with the influence of visual stimulation on VPV, there are several aspects of the present results that bear on the influence of the body-referenced mechanism: Not only do the individual subjects manifest a great deal of consistency in their susceptibility to visual influences as measured by the slope of the VPV-vs roll-tilt or equivalent roll-tilt responses across conditions of an experiment as described above, but they also manifest considerable individual consistency in dark values and the y-intercepts. Since the dark value is measured in the absence of any visual stimulation except for the short test line itself, it provides a measure of the operation of the body-referenced mechanism. Since the y-intercept is a measure of biasing in an erect visual field that actually depends on measurements with different retinal orientations (and presumably would tend to average them out), it may also be taken to reflect the operation of the body-referenced mechanism, and this is supported by the generally high correlations with the dark values. Witkin and Asch (1948) and Witkin (1949) have previously described large individual differences and considerable

[5] The term "configuration-independence" here refers to the finding that the combined influence on VPV of either two short lines or two long lines depends only on the sum of the roll-tilts of the two bilaterally symmetric lines and not on their separate roll-tilts, e.g., if the roll-tilts of two lines of a given length are −15° and +10°, the influence of the two presented together will be essentially indistinguishable from the influence of two lines of the same length whose roll-tilts are −5° and 0°; (see Fig. 6); a similar statement may be couched in terms of the VPVs generated by the lines (see Fig. 10). The term "mass action" refers to the finding that the influence on VPV as a deviation from the dark baseline or from the y-intercept increases with the deviation of the magnitude of the sum of the separate VPVs of the two lines or of their orientations, and not on the individual values themselves.

individual consistency of their subjects across tasks. The statistical analyses of our results for both the VPV values under induction by lines and in darkness provide strong and broad support for both of these aspects.

The identical inducing lines that were employed in the present experiments were reported to induce large influences on another aspect of the egocentric perception of space—the perception of elevation—as measured by the subject's setting of a small circular target in the median plane to an elevation that appeared to correspond to eye level (VPEL setting) (Li et al., 2001; Li & Matin, 1996; Matin & Li, 1992, 1994a, 1994b, 1994c, 1995a, 1995b, 1999, 2000, 2001; Post et al., 2003). The visual induction of changes in VPEL generated by changes in the parameters of orientation and length of the 1-line and 2-line stimuli follows quantitative variations that are nearly identical to those that we have found to hold for the induction of changes in VPV in the present experiments, both for roll-tilted lines and for pitched-from-vertical lines. Thus: (1) Within the range of roll-tilts and equivalent roll-tilts examined in the present experiments the deviation of VPEL from a baseline value (y-intercept) increases in opposite directions with opposite directions of deviation-from-vertical of the roll-tilt of the inducing line; the increase is nearly linear with the deviation-from-vertical of line orientation. (2) Induction by 1-line stimuli on VPEL approximates a negatively accelerated exponential with a length constant averaging 15.1° (close to the 17.1° length constant in Exp. 1 above for VPV). (3) For two lines with any combination of orientations VPEL manifests linear summation across a 50° bilaterally symmetric extent of the monocular visual field, with nearly complete summation for short lines with slope functions as in Fig. 10 equal to 0.99 (0.91 in Expt. 3c for VPV), and a close approach to averaging for long lines: 0.58 for real roll-tilt for VPEL and 0.61 for equivalent roll-tilt, (0.66 and 0.67 for real roll-tilt and equivalent roll-tilt respectively).

However, there is one very important difference between the processing of VPV and VPEL: Whereas for lines in the frontoparallel plane, parallel roll-tilted lines on opposite sides of the median plane generate influences of the same sign on VPV and bilaterally symmetric roll-tilted lines (counterrolled lines) generate influences of opposite signs, for VPEL the opposite is true: parallel roll-tilted lines on opposite sides of the median plane generate influences of opposite sign and bilaterally symmetric roll-tilted lines generate influences of the same sign; these same differences hold true for lines of equivalent roll-tilt. This difference in processing the identical stimuli for the two perceptual dimensions of elevation and roll-tilt is an important indication of the visual system's ability to maintain perceptual constancy in both dimensions simultaneously, employing two different mechanisms for processing the same stimulus to do so (Matin & Li, 1994c).

4.5. Neural mediation of the visual influence on VPV

The strong similarities together with the important differences in visual influence on the two dimensions of egocentric space perception, as measured by VPV and VPEL, provides some support for the view that the neural processing for them both is common up to the point in higher level processing at which the sign reversal that separates them is generated; such a bifurcation point in processing is likely to lie beyond V1. Our recent report (Shavit, Li, Semanek, & Matin, 2004) of a significant correlation ($r = +0.45$) for sensitivity-to-induction by 2-line stimuli between the VPEL and VPV discriminations across 30 subjects supports this view of common lower level processing of the visual influence followed by separate higher level processing for the two discriminations.

The sensitivity of the setting of VPV to the orientation of the individual inducing line suggests connections to the properties of orientationally selective neural units in V1. Such connections offer the great theoretical advantage of suggesting a first stage in the neurophysiological and neuroanatomical substrate for processing these inducing stimuli. Although receptive fields in V1 are no larger than about 3° (Hubel & Wiesel, 1974, 1977), some V1 units have been reported in which the influence of length grows with negative acceleration to lengths up to as much as 16° (Gilbert, 1977), presumably as a consequence of horizontal summation across single neural units with the same orientation selectivity serving adjacent retinal areas (Gilbert & Wiesel, 1983; Ts'o, Gilbert, & Wiesel, 1986). This is consistent with the increase of summation of the VPV influence with line length we describe above where: (1) summation approximates a negatively accelerated exponential with a 17.1° length constant (Fig. 4), (2) summation between two lines laid end to end is as great as between two spatially separated lines (Figs. 4 and 5a), (3) linear summation (using algebraic quantities) is manifested between two line segments of any combination of orientations horizontally separated by 50° that are processed in the different hemiretinas of the same eye and thus in different cerebral hemispheres (Figs. 5,6,10).

Based on these considerations we proposed a 4-channel neuromathematical model that closely predicts the quantitative results of more than five sets of experiments measuring VPEL (Matin & Li, 2001). Two of the channels process orientation on one side of the median plane and two on the other side, with one of the two on each side processing cw retinal orientation and the other ccw orientation; the two cw channels reverse sign on opposite sides of the median plane as do the ccw channels. A very similar model, without the sign reversal across the median plane, predicts the present results with VPV (Matin & Li, 2002).

However, in recent work (Shavit, Li, & Matin, 2004), we have varied the global orientation of an array of short parallel lines and the orientation of the individual lines in the array (their local orientations) independently, and found that the influence on both VPV and on VPEL of the global orientation manifests an influence equal to that generated by the local orientation of a single continuous line of the same length where global and local orientations are identical. The orientation-selective neural units in V1 have only been reported to respond to local orientation but not global orientation, and we have suggested that the influence on both VPEL and VPV are a consequence of the retinotopic location information from the orientation-selective and/or non-orientation-selective neural units in V1 being passed on to a higher-level processor where the global orientation is generated. With this modification—utilization of the location information from the initial processing in V1 instead of the orientation information and the construction of global orientation by higher level processing—the previously proposed neuromathematical model continues to account for the previous results and for those involving the separation of local and global orientations as well.

Finally, it is worth noting that although V1 may be an early stage of processing of the visual influence on VPV and VPEL, important influences from the body-referenced mechanism may already play a role: Thus, a substantial percentage of V1 neurons has been reported to be sensitive to vestibular input and head orientation input (Denny & Adorjani, 1972; Grüsser & Grüsser-Cornehls, 1960; Horn, Stechler, & Hill, 1972; Jung, Kornhuber, & Da Fonseca, 1963; Tomko, Barbaro, & Ali, 1981). It appears likely that the relative weighting given to vision and the body-referenced mechanism works well over a large range of variation, in conformity with the large individual variations in susceptibility to the visual influence on VPV and VPEL measured psychophysically, and the neurophysiological findings in V1 raise the possibility that such relative weighting is begun as early as V1 or earlier.

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References

Asch, S. E., & Witkin, H. A. (1948a). Studies in space orientation. I. Perception of the upright with displaced visual fields. *Journal of Experimental Psychology, 38*, 325–337.

Asch, S. E., & Witkin, H. A. (1948b). Studies in space orientation. II. Perception of the upright with displaced visual fields and with body tilted. *Journal of Experimental Psychology, 38*, 455–477.

Bauermeister, M. (1964). Effect of body tilt on apparent verticality, apparent body position, and their relation. *Journal of Experimental Psychology, 67*, 142–147.

Beh, H., & Wenderoth, P. (1972). The effect of frame shape on the angular function of the rod-and-frame illusion. *Perception & Psychophysics, 11*, 5–37.

Beh, H., Wenderoth, P., & Purcell, A. T. (1971). The angular function of a rod-and-frame illusion. *Perception & Psychophysics, 9*, 353–355.

Bertini, M., Pizzamiglio, L., & Wapner, S. (1986). *Field dependence in psychological theory, research, and application*. Hillsdale, NJ: Lawremce Erlbaum Associates, Inc.

Chelette, T., Li, W., Esken, R., & Matin, L. (1995). Visual perception of eye level (VPEL) under high *g* while viewing a pitched visual field. *Annual Meeting of Aerospace Medical Association*, A55.

Denny, D., & Adorjani, C. (1972). Orientation specificity of visual cortical neurons after head tilt. *Experimental Brain Research, 14*, 312–317.

Dichgans, J., & Brandt, T. (1974). The psychophysics of visually induced perception of self-motion and tilt. In F. O. Schmitt & F. G. Worden (Eds.), *The neurosciences, third study program* (pp. 123–129). Cambridge, MA: MIT Press.

Dichgans, J., Held, R., Young, L. R., & Brandt, T. (1972). Moving visual scenes influence the apparent direction of gravity. *Science, 178*, 1217–1219.

DiZio, P., Li, W., Lackner, J. R., & Matin, L. (1997). Combined influences of gravitoinertial force level and visual field pitch on visually perceived eye level. *Journal of Vestibular Research, 7*, 381–392.

Ebenholtz, S. M. (1977). Determinants of the rod-and-frame effect: The role of retinal size. *Perception & Psychophysics, 22*, 531–538.

Ebenholtz, S. M. (1985). Absence of relational determination in the rod-and-frame effect. *Perception & Psychophysics, 37*, 303–306.

Ebenholtz, S. M., & Benzchawel, T. L. (1977). The rod and frame effect and induced head tilt as a function of observation distance. *Perception & Psychophysics, 22*, 491–496.

Ebenholtz, S. M., & Callan, J. W. (1980). Modulation of the rod and frame effect: Retinal angle vs. apparent size. *Psychological Research, 42*, 327–334.

Ebenholtz, S. M., & Glaser, G. W. (1982). Absence of depth processing in the large-frame rod-and-frame effect. *Perception & Psychophysics, 32*, 134–140.

Gibson, J. J., & Mowrer, O. H. (1938). Determinants of the perceived vertical and horizontal. *Psychological Review, 45*, 300–323.

Gilbert, C. D. (1977). Laminar differences in receptive field properties of cell in cat primar visual cortex. *Journal of Physiology, London, 268*, 391–421.

Gilbert, C. D., & Wiesel, T. N. (1983). Clustered intrinsic connections in cat visual cortex. *Journal of Neuroscience, 3*, 1116–1133.

Gogel, W. C., & Newton, R. E. (1975). Depth adjacency and the rod-and-frame illusion. *Perception & Psychophysics, 18*, 163–171.

Goldstein, A. G., & Chance, J. E. (1965). Effects of practice on sex-related differences on performance on Embedded Figures. *Psychonomic Science, 3*, 361–362.

Grüsser, O. J., & Grüsser-Cornehls, V. (1960). Mikroelektrodenuntersuchungen zur Konvergenz vestibularer und retinaler afferenzen an einzelnen Neuronen des optischen Cortex der Katze. *Pflugers Archiv, 270*, 227–288.

Held, R., Dichgans, J., & Bauer, J. A. (1975). Characteristics of moving visual areas influenceing spatial orientation. *Vision Research, 15*, 357–365.

Higashiyama, A., & Koga, K. (1998). Apparent body tilt and postural aftereffect. *Perception & Psychophysics, 60*, 331–347.

Horn, G., Stechler, G., & Hill, R. M. (1972). Receptive fields of units in the visual cortex of the cat in the presence and absence of bodily tilt. *Experimental Brain Research, 15*, 113–132.

Howard, I. P. (1982). Human visual orientation. New York: John Wiley.

Howard, I. P., & Childerson, L. (1994). The contribution of motion, the visual frame, and visual polarity to sensation of body tilt. *Perception, 23*, 753–762.

Howard, I. P., & Templeton, W. B. (1966). Human spatial orientation. New York: John Wiley.

Hubel, D. H., & Wiesel, T. N. (1974). Uniformity of monkey striate cortex: A parallel relationship between field size, scatter, and magnification factor. *Journal of Comparative Neurology, 158*, 295–306.

Hubel, D. H., & Wiesel, T. N. (1977). Functional architecture of macaque monkey visual cortex. *Proceedings of the Royal Society, London B,, 198*, 1–59.

Hudson, T., Li, W., & Matin, L. (1997). Individual differences in cognitive styles and perception. *Eastern Psychological Association, 68*, 80.

Hudson, T., Li, W., & Matin, L. (submitted for publication). The field-dependence/independence cognitive style does not control the spatial perception of elevation.

Jung, R., Kornhuber, H. H., & Da Fonseca, J. S. (1963). Multisensory convergence on cortical neurons: Neuronal effects of visual, acoustic and vestibular stimuli in the superior convolutions of the cat's cortex. *Progress in Brain Research, 1*, 207–240.

Kendall, M. G. (1955). Rank correlation methods. London: C. Griffin.

Koffka, K. (1935). Gestalt psychology. NY: Harcourt Brace.

Li, W., Dallal, N., & Matin, L. (2001). Influences of visual pitch and visual yaw on visually perceived eye level (VPEL) and straight ahead (VPSA) for erect and rolled-to-horizontal observers. *Vision Research, 41*, 2873–2894.

Li, W., & Matin, L. (1996). Visually perceived eye level is influenced identically by lines from erect and pitched planes. *Perception, 25*, 831–852.

Li, W., & Matin, L. (1998). Change in visually perceived eye level without change in perceived pitch. *Perception, 27*, 553–572.

Li, W., & Matin, L. (2002). Decomposition of the influence of the frame. III. The whole is less than the sum of its parts. *2nd Annual Meeting of Vision Sciences Society, 2*, 181.

Li, W., & Matin, L. (in press). The rod-and-frame effect: The whole is less than the sum of its parts. *Perception*.

Linn, M. C., & Peterson, A. C. (1985). Emergence and characterisation of sex differences in spatial ability: A meta-analysis. *Child Development, 56*, 1479–1498.

Matin, L., & Fox, C. (1989). Visually perceived eye level and perceived elevation of objects: Linearly additive influences from visual field pitch and from gravity. *Vision Research, 29*, 315–324.

Matin, L., & Li, W. (1992). Visually perceived eye level: Changes induced by a pitched-from-vertical 2-line visual field. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 257–289.

Matin, L., & Li, W. (1994a). The influence of the orientation of a stationary single line in darkness on the visual perception of eye level. *Vision Research, 34*, 311–330.

Matin, L., & Li, W. (1994b). Spatial summation among parallel lines across wide separation (50°): Spatial localization and the Great Circle Model. *Vision Research, 34*, 2577–2598.

Matin, L., & Li, W. (1994c). Mirror symmetry and parallelism: two opposite rules for the identity transform in space perception and their unified treatment by the Great Circle Model. *Spatial Vision, 8*, 469–489.

Matin, L., & Li, W. (1995a). Multimodal basis for egocentric spatial localization and orientation. *Journal of Vestibular Research, 5*, 499–518.

Matin, L., & Li, W. (1995b). Light and Dark adaptation of visually perceived eye level controlled by visual pitch. *Perception & Psychophysics, 57*, 84–104.

Matin, L., & Li, W. (1999). Averaging and summation of influences on visually perceived eye level between two long lines differing in pitch or roll-tilt. *Vision Research, 39*, 307–329.

Matin, L., & Li, W. (2000). Linear combinations of signals from two lines of the same or different orientations. *Vision Research, 40*, 517–527.

Matin, L., & Li, W. (2001). Neural model for processing the influence of visual orientation on visually perceived eye level (VPEL). *Vision Research, 41*, 2845–2872.

Matin, L., & Li, W. (2002). The influence of individual roll-tilted lines and their combinations on perceived vertical (VPV): Experiments and theory. *25th European Conference on Visual Perception*. In *Perception. Vol. 31*. (p. 30).

Matin, L., Li, W., & Hudson, T. (1999). Monocular discrimination between a pitched-from-vertical and roll-tilted line from the same nodal plane. *Investigative Ophthalmology & Visual Science, 40/4*, S43.

Mittelstaedt, H. (1986). The subjective vertical as a function of visual and extraretinal cues. *Acta Psychologica, 63*, 63–85.

Mittelstaedt, H. (1988). The information processing structure of the subjective vertical. A cybernetic bridge between its psychophysics and its neurobiology. In H. Marko, G. Hauske, & A. Struppler (Eds.), *Processing structures for perception and action* (pp. 217–263). Weinhein: Verlag Chemie.

Mittelstaedt, H. (1992). Somatic versus vestibular gravity reception in man. In B. Cohen, D. L. Tomko, & F. E. Guedry (Eds.), *Sensing and controlling motion, vestibular and sensorimotor function. Annals of the New York Academy of Sciences* (Vol. 656, pp. 124–139). New York Academy of Sciences.

Mittelstaedt, H. (1997). Interaction of eye-, head-, and trunk-bound information in spatial perception and control. *Journal of Vestibular Research, 7*, 283–302.

Poquin, D., Ohlmann, T., & Barraud, P. A. (1998). Isotropic visual field effect on spatial orientation and egocentric localization. *Spatial Vision, 11*(3), 261–278.

Post, R. B., Teague, J. M., Welch, R. B., & Hudson, T. E. (2003). Visually perceived eye level with reversible pitch stimuli: Implications for the great circle and implicit surface models. *Perception, 32*, 1073–1092.

Rock, I. (1954). The perception of the egocentric orientation of a line. *J. Experimental Psychology, 48*, 367–374.

Schöne, H. (1964). On the role of gravity in human spatial orientation. *Aerospace medicine, 35*, 764–772.

Shavit, A. Y., Li, W., Semanek, D., & Matin, L. (2004). Individual differences in sensitivity to induction-by-line: Covariation between perceived elevation (VPEL) and perceived vertical (VPV) [Abstract]. *Journal of Vision, 4*(8), 383a, Available from http://journalofvision.org/4/8/383/ doi:10.1167/4.8.383.

Shavit, A. Y., Li, W., & Matin, L. (2004). Influences of global and local orientations of line segments on perceived eye level. Abstracts of the 45th Annual Meeting. *Psychonomic Society, 9*, 112–113.

Sherman, J. (1969). Problem of sex differences in space perception and aspects of intellectual functioning. *Psychological Review, 74*, 290–299.

Spinelli, D., Antonucci, G., Goodenough, D., Pizzamiglio, L., & Zoccolotti, P. (1991). Psychophysiological mechanisms underlying the rod-and-frame illusion. In S. Wapner & J. Demick (Eds.), *Field dependence-independence: Cognitive style across the life span* (pp. 37–60). Hillsdale, NJ: Lawremce Erlbaum Associates, Inc.

Streibel, M. J., Barnes, R., Julness, G. D., & Ebenholtz, S. M. (1980). Determinants of the rod-and-frame effect: Role of organization and subjective contour. *Perception & Psychophysics, 27*, 136–140.

Tomko, D. L., Barbaro, N. M., & Ali, F. N. (1981). Effect of body tilt on receptive field organization of simple visual cortical neurons in unanestetized cats. *Experimental Brain Research, 43*, 309–314.

Trousselard, M., Cian, C., Nougier, V., Pla, S., & Raphel, C. (2003). Contribution of somesthetic cues to the perception of body orientation and subjective visual vertical. *Perception & Psychophysics, 65*, 1179–1187.

Ts'o, D. Y., Gilbert, C. D., & Wiesel, T. N. (1986). Relationships between horizontal interactions and functional architecture in cat striate cortex as revealed by cross- correlation analysis. *Journal of Neuroscience, 6*, 1160–1170.

Wapner, S., & Demick, J. (1991). *Field dependence-independence: Cognitive style across the life span*. Hillsdale, NJ: Lawremce Erlbaum Associates, Inc.

Weiner, M. (1955). Effects of training in space orientation on perception of the upright. *Journal of Experimental Psychology, 49*(5), 367–373.

Wenderoth, P. (1977). An analysis of the rod-and-frame illusion and its variants. In R. H. Day & G. V. Stanley (Eds.), *Studies in perception* (pp. 95–141). Perth: Univesity of Western Australia Press.

Wenderoth, P. (1982). Fine's frame and perceived tilt. *Perceptual and Motor Skills, 54*, 763–766.

Wenderoth, P., & Beh, H. (1977). Component analysis of orientation illusions. *Perception, 6*, 57–75.

Wertheimer, M. (1912). Experimentelle Studien Uber das Sehen von Bewegung. *Zeitschrift fur Psychologie, 61*, 161–262.

Witkin, H. A. (1949). Perception of body position and of the position of the visual field. *Psychol Monograph, 63*(7), 1–46.

Witkin, H. A. (1977). *Cognitive styles in personal and cultural adaptation. Heinz Werner Lecture Series* (Vol. XI). Clark University Press.

Witkin, H. A., & Asch, S. E. (1948). Studies in space perception. IV. Further experiments on perception of the upright with displaced visual fields. *Journal of Experimental Psychology, 38*, 762–782.

Witkin, H. A., Dyk, R. B., Faterson, H. F., Goodenough, D. R., & Karp, S. A. (1962). *Psychological differentiation*. New York: Wiley & Sons.

Witkin, H. A., & Goodenough, D. R. (1977). Field dependence and interpersonal behavior. *Psychological Bulletin, 84*(4), 661–688.

Witkin, H. A., & Goodenough, D. R. (1981). *Cognitive styles: essence and origins. Psychological issues, Monogr. 51*. (whole monogr: x+1-141pp.) International Universities Press.

Witkin, H. A., Karp, S. A., & Goodenough, D. R. (1959). Dependence in alcoholics. *Quarterly Journal of Studies on Alcohol, 20*, 493–504.

Witkin, H. A., Lewis, H. B., Hertzman, M., Machover, K., Meissner, P. B., & Wapner, S. (1954). *Personality through perception*. New York: Harper & Brothers.

Zoccolotti, P., Antonucci, G., & Spinelli, D. (1993). The gap between rod and frame influences the rod-and-frame effect with small and large inducing displays. *Perception & Psychophysics, 54*, 14–19.