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Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room

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Abstract. The effect of field size, velocity, and visual fixation upon the perception of self-body rotation and tilt was examined in a rotating furnished room. Subjects sat in a stationary chair in the furnished room which could be rotated about the body roll axis. For full-field conditions, complete 360° body rotation (tumbling) was the most common sensation (felt by 80% of subjects). Constant tilt or partial tumbling (less than 360° rotation) occurred more frequently with a small field of view (20 deg). The number of subjects who experienced complete tumbling increased with increases in field of view and room velocity (for velocities between 15 and 30° s^{-1}). The speed of perceived self-rotation relative to room rotation also increased with increasing field of view.

1 Introduction

Gravity is the most pervasive force that we encounter in our daily lives. Proper orientation of our bodies with respect to gravity is crucial for balance and motor coordination. Normally, congruent visual, vestibular (predominantly utricular), and somatosensory inputs are integrated to obtain a reliable estimate of orientation with respect to the gravity vector (see Howard 1982, for a review). In some circumstances, such as the microgravity of space or the artificial worlds of a virtual reality simulation, sensory information from the otoliths and the visual system can conflict. Discordant visual and vestibular sensory information has been associated with motion sickness and the similar nausea that sometimes accompanies a session in a flight simulator (simulator sickness).

The brain uses at least three visual cues in order to make a judgment about the direction of gravity (Howard and Childerson 1994): visual frame, visual polarity, and motion of the visual scene. The visual frame refers to sets of distinct horizontal and vertical lines and surfaces. In our environment, these are objects such as walls and ceilings, which are typically aligned with or perpendicular to gravity. Since the frame is normally aligned with gravity, tilt of the visual frame suggests a tilt of the gravity vector in the direction of the tilt of the frame. Perception of the true vertical is more accurate in the presence of a gravitationally aligned visual frame (Asch and Witkin 1948; Witkin and Asch 1948a). These authors found that when observers viewed a stationary tilted frame a vertical rod appeared tilted in the opposite direction. This was interpreted as reflecting an equivalent tilt in apparent body orientation in the opposite direction (Witkin 1949).

Objects such as people, plants, and furniture exhibit an intrinsic visual polarity with an identifiable top and bottom. Objects can also have an extrinsic visual polarity due to their relation to surfaces of support. When all polarised objects in a visual scene are tilted with respect to gravity by the same amount, the effect is a compelling illusion of self-tilt which can be referred to as polarity-induced self-tilt (Howard and Childerson 1994). When upright observers view the interior of a furnished room tilted in roll or pitch they experience an illusion of self-tilt in the opposite direction due to tilt of the polarised features of the room in addition to the visual frame outlined by the walls, floor, and ceiling (Klient 1937; Witkin and Asch 1948b).

The motion of a large rotating homogeneous field induces nystagmus and the illusion of self-motion. Rotation of a 130-deg-wide frontal plane visual display about the roll axis induces a perception of continuous self-motion (vection) in the opposite direction with a paradoxical sense of limited self-tilt with a mean value of 15° (Dichgans et al 1972). This tilt is due solely to the motion since the stimulus was a homogeneous array of dots and contained no cues to vertical. Using annular rings of dots, Held et al (1975) found that illusory self-tilt increased with field size and retinal eccentricity. The limitation on illusory self-tilt about the roll (and pitch) axis is believed to be due to the inhibitory role of the utricles which do not register any change in the gravitational field. Support for this theory comes from the fact that the induced self-tilt increases when the head is tilted 90° to the side, a position which places the utricles in a less sensitive position (Young et al 1975). Further support comes from the fact that people who have suffered total bilateral loss of vestibular function experience the illusion of complete full-body rotation under these conditions (Cheung et al 1989). Subjects also report complete 360° rotation when exposed to these stimuli during the microgravity phase of parabolic flight (Cheung et al 1990).

The effects of visual frame and visual polarity have been investigated in tilted furnished rooms. Static tilt of a room in roll causes a compelling illusion of self-tilt (Klient 1937; Witkin and Asch 1948a, 1984b). Recently, Howard and Childerson (1994) built a full-sized rotating room to study the effects of visual polarity and visual frame on the sensation of self-tilt. When the cubic room was devoid of polarised objects, judgments of visual tilt of a vertical rod or of postural self-tilt were made with respect to either the surface nearest to horizontal or the nearest diagonal of the room. Thus judgments of subjective vertical, like the axes of room symmetry, exhibited a 45° periodicity with respect to rotation. When the room was furnished with polarised objects this ambiguity was removed and the axis of symmetry had a 360° periodicity. Subjects now tended to use only the nearest horizontal wall as their reference for subjective vertical, rather than the room diagonals. No subjects reported more than a 60° tilt. Thus, even in the presence of static polarised features, judgments in the stationary room exhibited a 90° periodicity.

The effect of motion of the visual field in conjunction with the effects of visual polarity and a visual frame on the sensation of self rotation in roll was studied for the first time by Howard and Childerson (1994). Visual frame and visual polarity potentiated the effect of motion stimuli such that, with a furnished room, 60% of subjects experienced a complete full-body rotation (ie a cartwheeling sensation). This confirmed earlier anecdotal reports of complete rotation in a furnished room (Klient 1937; Witkin 1949). This also demonstrated that the restraining influence of the otolith organs could be overcome by visual stimuli. The objectives of the present experiment are to determine the effects of field size, rotational velocity, and viewing strategy on the sensations elicited in the tumbling room.

2 Methods

2.1 *Subjects*

Thirty-five subjects (eighteen male, seventeen female, ages 18 to 51 years) were recruited and were paid for their participation in this study. Owing to the requirement to wear the field-restricting apertures, people who normally wore spectacles were excluded. Each subject participated in one session lasting approximately 1 h.

2.2 *Apparatus and stimulus*

The stimulus consisted of a furnished cubic room (length of each side was 2.1 m) with a rich assortment of visual polarity and visual frame cues to vertical (see figure 1). Descriptions of the construction, furnishing, and illumination of the room are given in Howard and Childerson (1994). The subject sat on a stationary chair supported by a boom

Figure 1. Photograph of the tumbling room used in this experiment (see section 2.2 for a description). A partial view of the furnished room through the open doorway is shown (the door was closed for the experiment).

protruding through the back wall of the room. The stationary chair extended above the head of the observer and was visible to the subject when he/she looked directly above, below, or to the side. The room could be rotated at constant velocity, clockwise or anticlockwise, about a horizontal axis passing through the roll axis of the subject's head.

The field of view (FOV) could be restricted by placing circular apertures over the eyes. Field sizes of 20, 50, 80, 100 deg, and full field were used. Actual field size with each aperture was measured and verified for each subject.

2.3 *Procedure*

The subject was strapped into the stationary chair with a five-point harness. Each subject was presented all combinations of FOV, rotational velocity, and visual fixation conditions (20 conditions: 5 FOVs × 2 velocities × 2 fixation conditions). For each field size the room was rotated at $15^\circ\ s^{-1}$ and $30^\circ\ s^{-1}$. Since previous work has shown no bias for clockwise or anticlockwise rotation (Howard and Childerson 1994) the direction of rotation was alternated for each subject across conditions. During acceleration of the room, subjects were instructed to close their eyes. When the room had reached constant velocity, subjects were instructed to open their eyes at the point where the room was oriented in its normal position. After four complete revolutions subjects were instructed to close their eyes while the room was stopped.

For each FOV and each speed of rotation two conditions were studied: head-fixed with centrally directed gaze, and head-free. In the head-fixed condition, subjects were instructed to keep their heads fixed straight ahead, and to fixate the centre of roll rotation located directly in front of them. In the head-free condition subjects were instructed to look slowly about the room including looking upwards and downwards such that they could see their bodies and the stationary chair as well as the room.

Subjects were instructed to attend to their perceptions of body orientation and movement during the trial. Subjects were informed that they may experience sensations of body tilt and rotation (vection). Response measures for each condition were the subject's percept of maximum body tilt and the perceived velocity of self-rotation (vection) relative to room rotation. After each condition, subjects reported the maximum degree of angular body tilt (0° – 360°) and the direction of the tilt. Visual alignment of a metal rod to the perceived orientation of the body axis with respect to gravity was used as an aid in making this determination. This report was taken with the subject seated in the room while it was stationary and upright. Velocity of the maximum sensation of self-rotation relative to the perceived room velocity was measured on a seven-point ordinal scale (see table 1).

Table 1. Seven-point scale used to make vection magnitude estimates. Subjects were required to estimate their perceived velocity, S, relative to the perceived velocity of the room, R. Thus, subjects were estimating the degree of saturation of the vection sensation.

Relative velocity	Value
Only room moving	0
$R \gg S$	1
$R > S$	2
$R = S$	3
$R < S$	4
$R \ll S$	5
Only subject moving	6

2.4 *Results*

The sensations experienced by our subjects can be classified into four types of responses (Howard and Childerson 1994). (i) In the 'constant-tilt response' subjects felt inclined about the roll axis at a constant angle opposite to the direction of the moving room. The 'none' response was a special case of constant tilt with tilt of 0°. (ii) In the 'alternating response' subjects felt that they were rotating opposite to the room but only to a certain limiting angle, at which point they suddenly perceived themselves to be upright or displaced somewhat in the opposite direction (ie changing tilt with a maximum tilt less than 360°). (iii) In the 'tumbling' response subjects felt that their bodies were completely rotating in roll and that at some time they felt completely inverted with respect to gravity (changing tilt with a maximum tilt of 360°). (iv) In a few instances, subjects felt as if they were lying supine or felt a lesser degree of inclination in pitch. Seven of the thirty-five subjects felt this supine tilt on at least one trial. This was termed the 'supine response' by Howard and Childerson (1994). No relation between occurrence of the supine sensation and FOV, velocity, or fixation conditions could be identified in these data. In our data the supine response was typically accompanied by a sensation of vection and, in instances of supine inclination of less than 90°, tilt in roll as well. These roll responses were qualitatively similar to the vection responses in the absence of the supine response and were included in the quantitative analysis of roll tilt angle and velocity.

The percentage of subjects who experienced complete 360° rotation increased significantly [$\chi^2(4, N = 700) = 79.195$, $p < 0.01$] with increasing field size of 20, 50, 80, 100 deg and full FOV (see figure 2). With full-FOV conditions 80% of subjects experienced complete illusory body rotation compared with 31% of subjects with a 20 deg FOV. Constant tilt and partial tumbling sensations were more frequent with small FOVs. The percentage of subjects who experienced tumbling was also significantly [$\chi^2(1, N = 700) = 4.236$, $p < 0.05$] influenced by the velocity of the room. It was found that at $15° \text{ s}^{-1}$ and $30° \text{ s}^{-1}$, 52.6% and 60.3% of subjects, respectively, experienced complete self-rotation (averaged across FOV and fixation conditions). Subjects also reported that the quality of the illusion changed with increasing field size and was most compelling with a full FOV.

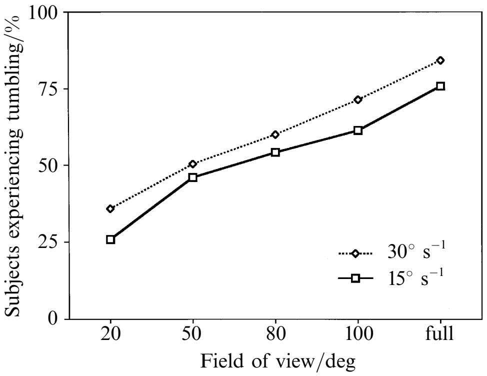

Figure 2. The increase in percentage of subjects who experienced the tumbling sensation is shown versus field size for two angular rotational velocities. The response is collapsed across viewing condition (head-fixed vs head-free). $N = 70$ observations.

Analysis of variance showed a significant main effect of total FOV for both response measures—maximum angular tilt and vection magnitude—$F_{1,696} = 11.359$ and $F_{1,696} = 12.78$, respectively, $p < 0.01$. At large FOVs many subjects experienced complete self-rotation with no perception of motion of the room (saturated vection). Although the illusion of self-rotation, as reflected by both response measures, increased with field size in all subjects, there were significant intersubject variations in the degree of self-rotation experienced. Some subjects experienced compelling full 360° body rotations at small field sizes while others did not even at large field sizes. Although the mean magnitude of illusory self-tilt showed a near linear increase with FOV the self-tilt angle was not normally distributed about the mean (see figure 3). The angle of illusory self-tilt was bimodally distributed with one mode centred at small tilt angles (< 90°) and one at 360°. Instead of a linear increase in self-tilt with FOV, as FOV increased a greater proportion of subject responses switched to the 360° mode. This is the increase in percentage of subjects experiencing the tumbling sensation discussed earlier. This switch to the tumbling mode resulted in an increase in mean tilt angle.

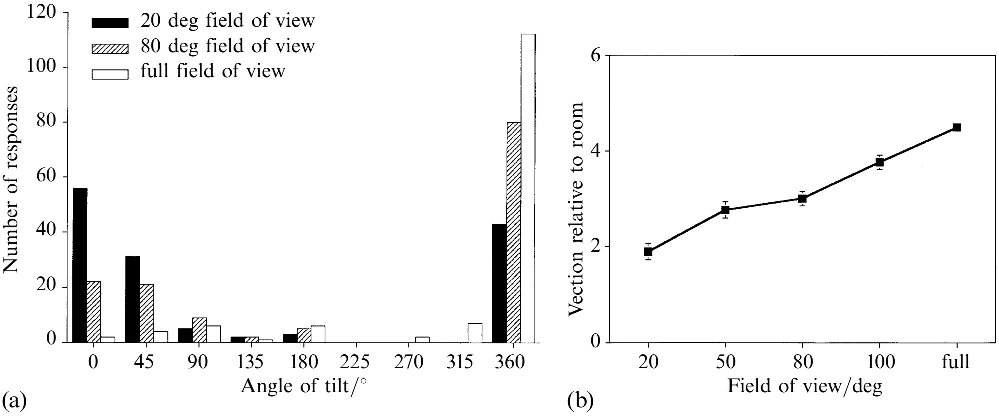

Figure 3. (a) Histogram of maximum angle of self-tilt experienced by the subject as function of field size for three different field sizes collapsed across viewing condition and room speed (resulting in 4 observations for each of the 35 subjects for each field-of-view condition). For each field-of-view condition the distribution of the 140 self-tilt angle responses is shown. Responses are grouped into 45° wide bins centred on the values shown on the abscissa. (b) The magnitude of the vection sensation (mean ± SE) as a function of field of view. A value of 6 meant that subject felt the room was stationary and attributed all motion to self-motion. A value of 0 meant that the subject experienced no sensation of self-motion and all motion was attributed to the room. No significant effects of viewing condition (head fixed vs head free) or angular velocity were found; hence the response is shown collapsed across velocity and viewing condition (resulting in 4 observations for each of the 35 subjects for each field-of-view condition).

The increase in self-tilt angle in the subset of subjects who never experienced tumbling showed a significant increase in self-tilt angle with increased FOV.

The speed of rotation of the room had a significant main effect on the angle of maximum illusory body tilt, which increased with increase in speed, $F_{1,696} = 2.994$, $p < 0.01$. As the speed of room rotation increased, the magnitude of illusory self-rotation also increased, keeping the relative measure of vection constant.

No significant effect of viewing condition (fixation versus free gaze) was found. This was despite sometimes large individual differences in the response as a result of being able to move the head and change gaze position. Some subjects felt that this made the illusion of self-rotation much more compelling while others felt that it attenuated the sensation. On average, the freedom to look about the room while the stimulus was being presented had no effect.

3 Discussion

This study confirmed the finding that rotation about the roll axis of a visual scene rich in visual frame and polarity cues induces a sensation of 360° rotation in the majority of subjects (Howard and Childerson 1994). Thus, these visual cues are able to override the conflicting otolithic and somatosensory information, which correctly indicates an invariant gravity vector. We have found that this sensation is potentiated by increasing field size and rotational velocity. Held et al (1975) used stimulus displays arranged in concentric rings to show that the magnitude of illusory body tilt due to roll vection increases with stimulus size and eccentricity. This effect probably accounts for at least part of the increased magnitude of tilt and vection that we observed with increasing FOV. As FOV increases, the area increases and more and more of the peripheral retina is stimulated. Thus, it is impossible to separate the effects of eccentricity and area in our data.

The effects of the visual polarity and visual frame cues could also have been potentiated by increases in FOV. For example, owing to the geometry of the room, a FOV of less than 50 deg made it impossible to see all four corners of the opposite wall simultaneously. Thus the effectiveness of the visual frame cue could be diminished. Similarly, fewer polarised objects were visible in the field at any one time with a smaller FOV. If the visual system used a weighted sum of polarity cues then a reduced number of polarised objects would be expected to elicit a weaker sensation. Review of the literature on these issues was of little help although Witkin (1949) has proposed that the illusion of tilt induced by a rotated visual scene increases with the amount of detail in the scene.

Even while experiencing complete tumbling, many subjects felt that the room was still moving appreciably. Witkin (1949) also described 'partial vection' where the perceived speed of an observer was less than the objective speed of the room, with the remainder attributed to rotation of the room. Vection magnitude has been found to be greater for rotation about an Earth vertical axis than an Earth horizontal axis, regardless of body posture (Howard et al 1987). This suggests that the otolith organs restrain vection for rotation about axes that are not parallel to the gravity vector. This cannot be the full explanation for the lack of saturated vection since partial vection and vection dropouts are common for yaw rotation about an Earth vertical axis. Presumably this is due to the ambiguity of the visual stimulus and the lack of any supporting cues to observer motion.

Freedom to move the head potentially allowed subjects to increase the effective FOV (although the instantaneous FOV would remain the same). The percentage of subjects who experienced full tumbling, and the maximum tilt angle and tilt velocity results for the subject pool as a whole did not vary between the head-fixed and head-free conditions. Thus, the increase in effective FOV due to the head motion did not increase the tilt or vection sensations. Witkin (1949) found that looking down at the stationary chair increased the probability of experiencing self-motion. He attributed this to a motion contrast effect in that if the illusory motion results from the changing relationship between the body and the room, visualising the body as well as the moving surround would add to this contrast and to the illusion. Howard and Howard (1994; see also Brandt et al 1975) have shown that stationary objects in the foreground can facilitate vection in the yaw plane by introducing relative motion-contrast. Vection latency decreases and vection magnitude increases when stationary objects are in view. From these motion-contrast effects, it would be expected that the ability to turn the head and view the stationary chair would increase vection. However, in all conditions, a stationary part of the body or of the visual aperture was visible. For the fixation condition the circular aperture would not contribute any relative motion. However, since the aperture moved with the head, there would be relative motion between the aperture and the stimulus in the head-free condition.

Another possibility is that freedom to move the head and eyes allows the subject to pursue portions of the stimulus. Small moving stimuli exhibit the Aubert – Fleischl phenomenon in which objects appear to move more slowly if tracked with the eyes (Fischer and Kornmüller 1930). A similar effect has been reported for vection where the apparent speed of vection increased with fixation versus pursuit (de Graaf et al 1991). These results must be interpreted with caution since this increase was found only when the two stimuli were sequentially presented and not when presented on separate trials (see also Dichgans and Brandt 1978). The fact that fixation conditions in the present study often had large effects for individuals but no effect on average suggests that the effects for each individual may depend upon individual gaze strategy.

One discrepancy between our data and those of Howard and Childerson (1994) is in the proportion of subjects who experienced tumbling. We found that with unrestricted field of view 80% of our thirty-five subjects experienced complete full-body tumbling while the earlier study found only 60% of thirty subjects. A possible explanation for this is the age distribution of the subject pool. The majority of the subjects in the earlier study were middle-aged whereas our subject pool had a bias towards younger subjects with a mean age of 25 years. A similar sized group of school-aged children all exhibited complete 360° body rotation (A Howard, personal communication). In our data we found that the perceived velocity of rotation was significantly ($p < 0.01$) affected in a negative direction by age in regression of magnitude of perceived velocity on age and field size. Generalisation of this result is not possible, however, since the age range of our present study was restricted and the study included predominantly young adult subjects.

Roll axis rotation of a scene rich in polarity and frame cues can induce a sensation of complete 360° body rotation. We have shown that the sensation of motion induced by such a scene increases with increase in field size. Virtual reality and aerospace simulators use similar displays to simulate motion. By using a large FOV, these systems can use visual stimuli to overcome the restraining influence of vestibular and somatosensory cues to maintain the illusion of self-motion. A difficult problem in these systems is the synchronisation of the scene to motion of the head. Proper synchronisation prevents sensory conflict during head motion and leads to a realistic simulation. Although desirable for a realistic simulation, this study suggests that a head-slaved display would not necessarily result in a more compelling illusion of whole-body motion than a display viewed with head-fixed.

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References

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

Brandt T, Wist E, Dichgans J, 1975 "Foreground and background in dynamic spatial orientation" *Perception & Psychophysics* **17** 497 – 503

Cheung B, Howard I P, Money K E, 1990 "Visually induced tilt during parabolic flight" *Experimental Brain Research* **81** 391 – 397

Cheung B, Howard I P, Nedzelski J, Landolt J, 1989 "Circular vection about horizontal axes in bilateral labyrinthine-defective subjects" *Acta Otolaryngologica* **108** 336 – 344

Dichgans J, Brandt T, 1978 "Visual-vestibular interaction: Effects on self-motion perception and postural control", in *Handbook of Sensory Physiology* volume III, Eds R Held, H Leibowitz, H Teuber (Berlin: Springer) pp 755 – 796

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

Fischer M H, Kornmüller A E, 1930 "Optokinetisch ausgelöste Bewegungswahrnehmungen und optokinetischer Nystagmus" *Journal für Psychologie und Neurologie (Leipzig)* **41** 273 – 308

Graaf B de, Wertheim A, Bles W, 1991 "The Aubert – Fleischl paradox does appear in visually induced self-motion" *Vision Research* **31** 845 – 849

Held R, Dichgans J, Bauer J, 1975 "Characteristics of moving visual areas influencing spatial orientation" *Vision Research* **15** 357 – 365

Howard I P, 1982 *Human Visual Orientation* (Chichester, Sussex: John Wiley) pp 412 – 442

Howard I P, Cheung B, Landolt J, 1987 "Influence of vection axis and body posture on visually-induced self-rotation and tilt", in *Advisory Group for Aerospace Research and Development Conference Proceedings* **433** 15-1 – 15-8

Howard I P, Childerson L, 1994 "The contribution of motion, the visual frame, and visual polarity to sensations of body tilt" *Perception* **23** 753 – 762

Howard I P, Howard A, 1994 "Vection: the contributions of absolute and relative visual motion" *Perception* **23** 745 – 751

Klient H, 1937 "Versuche über die Wahrnehmung: I. Über Bewegung" *Zeitschrift für Psychologie* **141** 9 – 44

Witkin H A, 1949 "Perception of body position and the position of the visual field" *Psychological Monographs 6* (whole No 7) 1 – 63

Witkin H A, Asch S E, 1948a "Studies in space orientation: III. Perception of the upright in the absence of a visual field" *Journal of Experimental Psychology* **38** 603 – 614

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

Young L R, Oman C M, Dichgans J M, 1975 "Influence of head orientation on visually induced pitch and roll sensation" *Aviation Space and Environmental Medicine* **46** 264 – 268