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Illusory scene distortion occurs during perceived self-rotation in roll

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Abstract

We report a novel illusory distortion of the visual scene, which became apparent during both: (i) observer rotation inside a furnished stationary room; and (ii) room rotation about the stationary observer. While this distortion had several manifestations, the most common experience was that scenery near fixation appeared to sometimes lead and other times lag more peripheral scenery. Across a series of experiments, we eliminated explanations based on eye-movements, distance misperception, peripheral aliasing, differential motion sensitivity and adaptation. We found that these illusory scene distortions occurred only when the observer perceived (real or illusory) changes in self-tilt and maintained a stable fixation.

Keywords: Vection; Tilt; Spatial; Distortion; Scene

1. Introduction

Self-motion can be registered and perceived through a number of senses, including vision, the vestibular sense, proprioception, somatosensation and audition (Dichgans & Brandt, 1978; Howard, 1982). Since the time of Mach (1975) it has been known that compelling visual illusions of self-motion (or vection) can be created by rotating large homogeneously textured displays around a stationary observer. However, in this specific situation, the nature of the induced vection depends on whether the display rotation occurs about the yaw, roll or pitch axis (Brandt, Dichgans, & Koenig, 1973; Cheung, Howard, Nedzelski, & Landolt, 1989; Cheung, Howard, & Money, 1990; Dichgans & Brandt, 1972, 1974, 1978; Dichgans, Held, Young, & Brandt, 1972; Held, Dichgans, & Bauer, 1975; Young, Oman, & Dichgans, 1975). Erect observers inside a homogeneously textured sphere rotating about the yaw (or vertical) axis typically experience 360° illusory self-rotations (in the opposite direction to the display motion). However, when such a display is rotated about the roll or pitch axis, erect observers report the following paradoxical experience. Continuous illusory self-rotation is coupled with illusory self-tilt of typically less than 20°—both in the opposite direction to the display motion (Dichgans et al., 1972; Held et al., 1975; Howard and Childersen, 1994; Howard, Cheung, & Landolt, 1989; Young et al., 1975). This limit to illusory self-tilt has been attributed to inputs from the gravireceptors (the otolith and somatosensory systems), which continue to indicate that the observer is erect. Support for this sensory conflict explanation has been provided by studies in which: (i) observers reported complete 360° self-rotations in roll when viewing rotating random-dot displays in the microgravity conditions of parabolic flight (Cheung et al., 1990; Young & Shelhamer, 1990); and (ii) patients with bilateral vestibular loss reported complete 360° self-rotations in roll when viewing similar displays in normal gravity conditions (Cheung et al., 1989).

In all the above experiments, the vection stimuli contained no information about the direction of gravity. Experiments conducted in I. P. Howard's laboratory have shown that the results are different when the rotating display contains a rich variety of information about the

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observer's orientation to gravity (Allison, Howard, & Zacher, 1999; Howard & Childersen, 1994; Howard, Jenkin, & Hu, 2000). In these experiments, observers sat inside a furnished room, which rotated 360° about the roll axis (known as the 'Tumbling Room' apparatus). This room provided: (i) a visual frame consisting of corners and surfaces that were normally vertical or horizontal; and (ii) a rich variety of familiar objects (such as furniture, pictures, and bookshelves), which acted as visual polarity cues to the direction of gravity. Individual objects provided intrinsic polarity cues because each had a recognizable 'top' and 'bottom' (such as a table, cup, or animal). Extrinsic polarity cues were created by the spatial relationships between these objects (such as a cup being supported by the table). Witkin and Asch (1948a, 1948b) had previously shown that a tilted furnished room could produce illusions of self-tilt. I. P. Howard and his colleagues extended these findings by demonstrating that the physical rotation of a furnished room about the roll or pitch axis could produce compelling 360° illusions of self-rotation in most erect observers.

The original goal of the present study was to compare the perceived speed and magnitude of the illusory self-rotation produced by rotating the tumbling room about the roll axis of a stationary observer (room-rotation trials) with that produced by rotating the observer inside a stationary room (chair-rotation trials). We were also interested in whether these conditions differed in the extent to which visual motion was allocated to self-motion rather than to scene motion. To this end, observers rated both the perceived amount of scene motion and perceived scene rigidity during room-rotation and chair-rotation trials. To foreshadow our results, we found that room-rotation and chair-rotation trials produced very similar ratings of self-rotation and scene motion. We were, however, surprised to find that significant distortions of the visual scene accompanied both real and illusory self-rotations, which were most noticeable on the textured pattern on the wall directly opposite to the observer. To our knowledge, our study is the first report of this type of apparent scene shearing/deformation during perceived self-rotation. The three experiments outlined below (and their controls) investigated the origins and phenomenology of these illusory scene distortions.

2. Experiment 1: Ratings of self-motion, room motion and room rigidity in a furnished tumbling room

2.1. Method

2.1.1. Observers

Nine males and three females (aged between 22 and 41 years) were paid for their participation in this study. Each participated in one session lasting approximately 1.5 h. None of the observers had any known ocular, ocular-motor or vestibular pathology. The use of human observers was approved by the York University Human Observers Review Sub-Committee.

2.1.2. Design

Three independent variables were examined: (i) Rotation Type—observers were either rotated at a constant velocity in a stationary room or were stationary while the room rotated about them at a constant velocity; (ii) Rotation Speed—five speeds of chair and room rotation were examined: 10°, 15°, 20°, 25°, 30°/s; and (iii) Viewing type—observers either binocularly or monocularly fixated a disc. The disc was the end of a short shaft, which protruded through the opposite wall of the room, on the axis of rotation. Three dependent variables were recorded. On each trial, observers rated: (i) the perceived speed of their (real/illusory) self-rotation; (ii) the perceived speed of any (real/illusory) scene motion; and (iii) the perceived rigidity of the room.

2.1.3. Apparatus and stimuli

The apparatus, shown in Fig. 1, was similar to that used by Howard and Hu (2001). The 8-foot cubic room was made from an aluminium frame lined with 1.27 cm thick foam plastic, and lit by a fixture placed in the centre of the ceiling. The four walls were covered in wallpaper which contained pictures of animals (roosters, pigs and cows). The following objects were firmly attached to the carpeted floor: an empty chair, a chair holding a seated mannequin, a table with knives, forks, spoons, cups, bowls and a basket glued to it's 'top' surface. One of the three walls visible to the observer contained a door. The other two walls had framed pictures, a bookshelf with objects on the shelves, and a clock firmly attached to them. The observer sat on a chair suspended from a boom protruding through the rear wall of the room. To reduce tactile sensations and to secure the observer during physical rotation: (i) padded plates supported the back, top and sides of the observer's head; (ii) thick, high density foam plastic lined the chair; (iii) a padded chestplate was strapped to the observer's chest; and (iv) straps secured the observer's torso, legs and feet to the frame of the chair. Both the room and chair could be rotated 360° at a constant velocity about a horizontal axis,

Fig. 1. Visual frame and visual polarity cues present in Experiment 1.

which was close to the roll axis of the observer's head.[1] The experimenter and the observer communicated through the microphones and headsets.

2.1.4. Procedure

Prior to the experiment, observers were told that: "on 50% of the trials you will be rotated at a constant velocity inside a stationary room and on the remainder you will be stationary inside a rotating room. Your task is three fold. First, I want you to indicate how fast you appear to be moving (relative to a standard speed of '10', see below). Second, I want you to indicate how fast the room appears to be moving (relative to a standard speed of '10'). Finally, I want you to indicate to me how rigid the room appears over the course of the trial. If the room appears to be completely stationary or moving coherently then you should rate the room as being 100% rigid. If, however, parts of the room appear to be moving at different speeds, then you need to rate the perceived rigidity of the room at a lower value. A value of 0% would indicate that every part of the room appears to be moving at a different speed". Since the method of magnitude estimation was used, the first condition in each session provided the modulus for the observer's speed ratings (Stevens, 1957). The standard stimulus for this modulus was a physical rotation of the observer at 10°/s inside a stationary room (either clockwise or anticlockwise). After two full rotations, observers were told that they were to rate this speed of self-rotation as '10' (with '0' representing being stationary). Further, they were told that the speeds of self-rotation and room rotation they would experience later in the experiment should be rated relative to this standard (e.g. if their perceived speed of self-motion was twice as fast as the standard it should be rated as '20', etc.). At the beginning of each trial, observers were instructed to close their eyes. They were told to open their eyes 5s later, when the room/chair had reached a constant speed of rotation. After 30 s, observers were asked following questions in the following order:

Q1: "Do you feel that you are moving? How fast compared to 10?"
Q2: "Do you feel that the room is moving? How fast compared to 10?"
Q3: "How rigid do you perceive the room to be? From 0–100%"

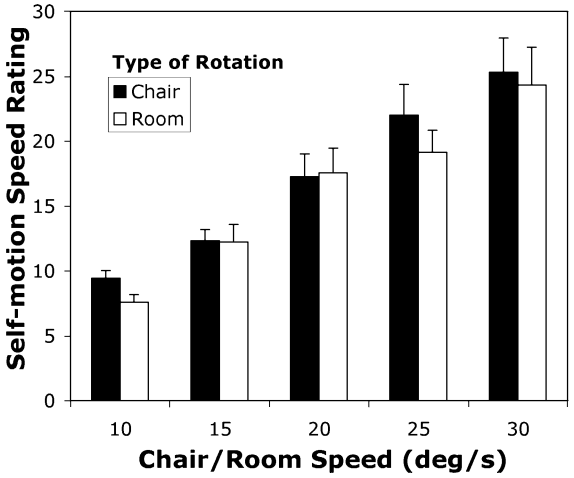

Fig. 2. Ratings of the perceived speed of self-rotation produced by either room or chair rotation (at 10–30°/s).

The order of the trials for each observer was fully randomised—the direction of chair/room rotation was randomly determined for each trial.[2] After five trials, the observers were re-exposed to the standard stimulus (i.e. the physical rotation of the observer at 10°/s) to prevent drifts in their speed ratings.

2.2. Results

Eleven of the 12 observers reported full 360° self-rotation about the roll axis during room-rotation trials. The remaining observer felt that she was rotating through 360° while lying on her back.[3] For most observers, illusory self-rotation started almost instantaneously after stimulus onset. Five observers experienced mild to significant motion sickness during this experiment. The symptoms were quite similar during room-rotation (illusory self-rotation) and chair-rotation (physical self-rotation) trials.

2.2.1. Perceived speed of self-rotation

A 2 (Rotation Type) × 5 (Rotation Speed) × 2 (Viewing type) repeated measures ANOVA was performed on the self-motion speed rating data (See Fig. 2). The main effect of Rotation Type failed to reach significance [$F(1,11) = 1.78$, $p > .05$]—indicating that the self-motion speed ratings produced by chair rotation in a stationary room were very similar to those ratings produced by rotating the room about the stationary observer. A significant main effect of Rotation Speed was found [$F(4,44) = 20.99$, $p = .0001$]—indicating that faster speeds of either room

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[1] While the axis of rotation was precisely aligned with the observer's vertical axis in the tumbling room experiments, it was slightly lower than eye level (by either 10–20 cm depending on the seated height of the observer). It was possible that this vertical offset could have generated optical artefacts in the observer's retinal flow, which were in turn responsible for the scene distortion findings described later in this paper. Contrary to this notion, we found that these illusory scene distortions persisted when observers were tested in a large rotating sphere (see Section 4.3.1 of this paper). In this control experiment, the observer's eyes were precisely aligned (both horizontally and vertically) with the roll axis.

[2] Previous research in the tumbling room found no bias for clockwise or anticlockwise rotations (Howard & Childersen, 1994).

[3] This interpretation would appear to resolve the dynamic visual-vestibular conflict, because the observer would not expect changing otolith inputs when rotating about a vertical roll axis. However, this appears to be a relatively rare percept (Howard & Childersen, 1994), presumably because it also introduces a salient static conflict (i.e. the gravireceptors indicate an upright posture as opposed to a supine one).

rotation or chair rotation, led to higher ratings of the speed of self-motion. However, the main effect of View Type failed to reach significance—indicating that self-motion speed ratings were not affected by whether the room was viewed monocularly or binocularly [$F(1,11) = .18$, $p > .05$]. No other 2- or 3-way interactions reached significance.

2.2.2. Perceived speed of scene motion

A 2 (Rotation Type) × 5 (Rotation Speed) × 2 (Viewing type) repeated measures ANOVA was performed on the scene speed rating data (See Fig. 3). A significant effect of Rotation Type was found [$F(1,11) = 6.35$, $p < .05$]—indicating that the perceived speed of scene motion produced by room rotation was significantly greater than that produced by chair rotation. Observers were more likely to (correctly) attribute a portion of the visual motion to the scene when the room was rotating than when they were rotating. However, modest (illusory) scene rotation was often perceived during observer rotation. As expected, a significant effect of Rotation Speed was found [$F(4,44) = 4.07$, $p < .01$]—indicating that faster room or chair rotations produced significantly higher ratings of the speed of scene rotation. There was no significant main effect of Viewing Type (monocular or binocular) on the speed of scene rotation [$F(1,11) = .11$, $p > .05$]. No 2- or 3-way interactions reached significance.

2.2.3. Perceived rigidity of the room

All 12 of our observers reported significant illusory scene distortions, which became apparent during both chair-rotation trials and room-rotation trials. This apparent shearing or deformation of the room had several manifestations. The most common form was that objects near to the point of fixation appeared to be rotating at different speeds to more peripheral objects. However, several observers reported that the left and right hand sides of the wall in front of them appeared to be moving in opposite directions. In some cases, this illusory shearing was also present as a motion aftereffect. We performed a 2 (Rotation Type) × 5 (Rotation Speed) × 2 (Viewing Type) repeated measures ANOVA on the room rigidity rating data (See Fig. 4). A significant main effect of Rotation Type was found for these ratings [$F(1,11) = 9.06$, $p < .01$]. While illusory scene distortions occurred during both room-rotation and chair-rotation trials, the facing wall appeared significantly less rigid during room-rotation trials than during chair-rotation trials. A significant main effect was also found for Rotation Speed [$F(4,44) = 12.81$, $p < .01$]—indicating that illusory scene distortions became more salient as the physical speed of the room or chair rotation increased. The main effect of Viewing Type failed to reach significance [$F(1,11) = 2.05$, $p > .05$]. No 2- or 3-way interactions reached significance.

2.3. Discussion

Room-rotation and chair-rotation trials in the tumbling room produced very similar perceptions of self-rotation about the roll axis (see also Allison et al., 1999; Howard & Childersen, 1994). While Howard and Childersen (1994) had found that 60% of observers perceived head-over-heals tumbling during room rotation, a later study by Allison and colleagues (1999) found that up to 80% of observers experienced complete tumbling when additional polarised objects were attached to the inside of the room. In our experiment, which contained even more visual polarity cues, for example a seated manikin, 92% of our observers experienced complete illusory tumbling during room-rotation trials. This provides further evidence that compelling visual information about orientation to gravity (visual motion, changing frame and visual polarity cues) can override conflicting non-visual information that the observer is stationary and aligned with gravity.

Interestingly, the perceived speed of self-motion was consistently underestimated in both room-rotation and chair-rotation trials. This was probably due, in part, to observers attributing a certain portion of the visual motion to scene motion rather than self-motion. While room-rotation trials produced higher ratings of scene speed, chair-rotation trials

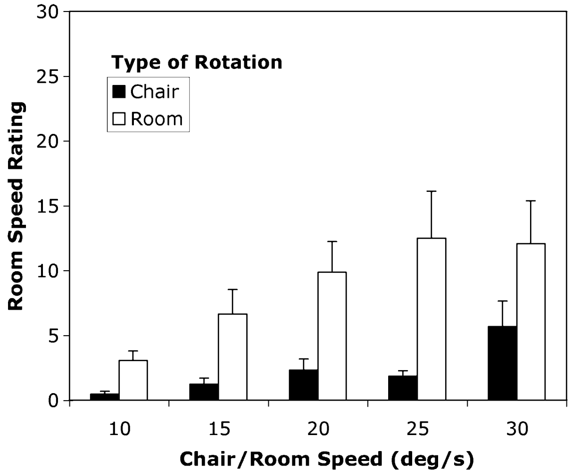

Fig. 3. Ratings of the perceived speed of room rotation produced by either room or chair rotation (at 10–30°/s).

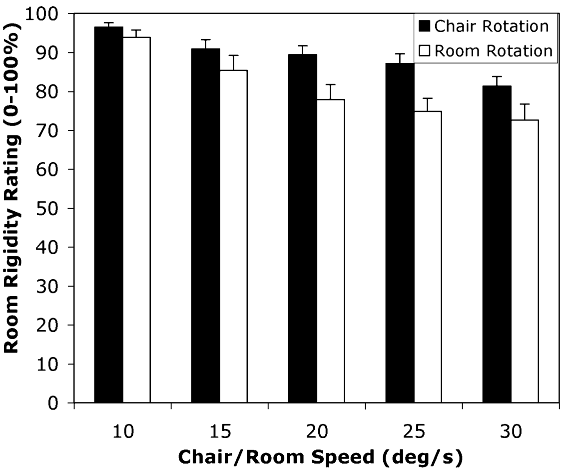

Fig. 4. Ratings of the perceived room rigidity during either room or chair rotation (at 10–30°/s).

also produced modest (illusory) scene motion. Thus, it appeared that some of the visual motion produced by self-motion was misattributed to the room.

However, the most important finding of this experiment was that both real and illusory self-rotations in the tumbling room produced significant perceptual distortions of the visual scene—which were most noticeable on the textured pattern on the wall facing the observer. This illusory scene distortion was present during binocular and monocular viewing in both chair-rotation and room-rotation trials.

2.3.1. Perceived tumbling control

A control experiment examined whether either the perception of self-rotation or large field visual rotation was required to experience these illusory scene distortions. The room and chair were rotated in the same direction at 30°/s. Seven of the 12 observers from Experiment 1 reported that both they and the room felt stationary and vertical throughout the trial. The remaining observers reported that, while they and the room appeared vertical throughout the trial, they felt that they were oscillating up-down and left-to-right, as if on a Ferris wheel. This "Ferris-wheel" illusion arises because the cyclic stimulation of the otolith organs produced by roll rotation is the same as that produced by rotation of an erect person about an eccentric axis (Schöne, 1984). Importantly, all 12 of the observers indicated that the room appeared fully rigid (i.e. with no detectable shear) during this control. In principle, the absence of illusory scene distortions in this specific situation could have been due to either: (i) the lack of perceived change in self-tilt; or (ii) the lack of any large field visual motion (relative to the observer).

2.3.2. Eye-movement control

Previous research has shown that: (i) the gain of torsional nystagmus is much smaller than the gain of horizontal or vertical nystagmus; and (ii) the relationship between torsional eye movements and roll vection is complex[4] (Cheung & Howard, 1991; Cheung, Money, & Howard, 1995; Thilo, Probst, Bronstein, Ito, & Gresty, 1999). Thus, in this second control experiment, we examined whether illusory scene distortions were related to the torsional eye movements induced by scene rotation. We tested five observers from the main experiment. Just before each trial, a camera flash produced the afterimage of a thin vertical line that subtended approximately 20°. Observers then fixated on the disc at the centre of the facing wall while either the chair or the room rotated at 30°/s. As in the main experiment, all five observers reported significant illusory scene distortions in both conditions. However, all observers clearly reported that their torsional eye-movements, as indicated by the apparent movements of the afterimage, were not related in either magnitude or timing to the apparent shearing of the room's wall.

3. Experiment 2: Does illusory scene distortion persist under impoverished visual conditions?

Experiment 2 further examined the two possible prerequisites for illusory scene distortions—perceived change in self-tilt and large field visual motion relative to the observer. We reduced the likelihood of 360° illusory self-rotation during room-rotation trials by turning the main room lights off. Instead observers viewed a linear array of LEDs attached to the facing wall. If significant perceived self-tilt change was required for illusory scene distortions, then these distortions should be markedly reduced under these conditions—because the visual frame was reduced to a single line and there were no visual polarity cues. Turning the main lights off during room-rotation and chair-rotation trials also allowed us to examine whether large-field visual motion was required for illusory scene distortion.

3.1. Method

The procedure was identical to that of Experiment 1.

3.1.1. Observers

Six males and four females (aged between 18 and 37 years) were paid for their participation. Each participated in one session lasting approximately 1.5 h. Five of the observers had participated in Experiment 1.

3.1.2. Design

Three independent variables were examined in this experiment: (i) Lighting Type—observers viewed either the room under full lighting ("Room-on") or only the rod with either 4 LEDs ("Part-rod-on") or 8 LEDs ("All-rod-on"); (ii) Rotation Type—observers were either rotated in the stationary room or the room was rotated about them; and (iii) Rotation Speed—the chair or room rotated at 10° or 30°/s. In all conditions, observers fixated a centrally located shaft protruding through opposite wall of the room. As in Experiment 1, observers provided three ratings during each trial: (i) the perceived speed of their (real/illusory) self-rotation; (ii) the perceived speed of any (real/illusory) scene motion; and (iii) the perceived rigidity of the scene.

3.1.3. Apparatus and stimuli

The basic apparatus was the same as that used in Experiment 1, with the following modifications (see Fig. 5). First, a linear array of eight LEDs was mounted on the wall of the room facing the observer so that it rotated with the room. Either four or all eight of the LEDs were turned on in trials when the main room light was turned off. One LED was located 30° below the centre of the facing wall, one was at the centre, and the others were 3.75°, 7.5°, 11.25°, 15°,

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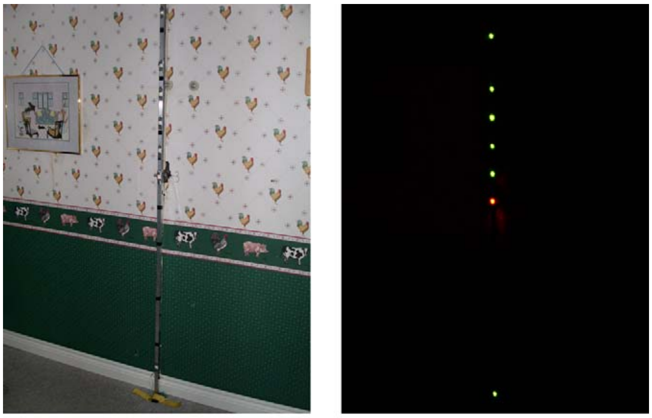
[4] Finke and Held (1978) reported that more ocular torsion occurred during perceived scene motion than during roll vection. However, Cheung and Howard (1991) failed to find any relationship between the onset and offset of roll vection and optokinetic torsional nystagmus. In conflict with both of these findings, Thilo and colleagues (1999) have recently found that torsional nystagmus was enhanced during roll vection.



Room Lights On Room Lights Off

Fig. 5. Room lights on ("Room-on") and Room lights off ("All-rod-on") views of the tumbling room. A 7.5 ft rod was placed inside the room with 8 LEDs (the red LED coincides with the shaft location). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

22.5°, and 30° above the centre. When only the four LEDs were turned on, they were at the centre and 3.75°, 7.5°, and 11.25° above the centre of the facing wall. The table, two chairs, and the manikin were removed from the room so that they did not obscure the view of the LEDs.

3.2. Results

In Experiment 1, 92% of the observers experienced 360° illusory self-rotations about the roll axis during room-rotation trials. In Experiment 2, only 60% of the observers reported 360° illusory self-rotation under full-lighting conditions, presumably because the chairs, table, and manikin had been removed. Repeated measures ANOVAs—3 (Lighting Type) × 2 (Rotation Type) × 2 (Rotation Speed)—were performed on each of the dependent measures. The results of these three separate analyses are outlined below.

3.2.1. Perceived speed of self-rotation

We found significant main effects of Lighting Type [$F(2,18)=18.05$, $p<.01$] and Rotation Type [$F(1,9)=24.64$, $p<.01$], as well as a significant interaction between Lighting Type and Rotation Type [$F(2,18)=15.26$, $p<.01$]. These findings were interpreted as indicating that: (i) with the room lights on, the self-motion speed ratings made during chair-rotation were similar to those made during room-rotation; (ii) the self-motion speed ratings made during room-rotation were significantly slower when the room lights were turned off; and (iii) the self-motion speed ratings made during chair-rotation were similar irrespective of whether the room lights were on or off (see Fig. 6a). We also found a significant main effect of Rotation Speed [$F(1,9)=75.82$, $p<.01$] and a significant interaction between Rotation Type and Rotation Speed [$F(1,9)=5.67$, $p<.05$]. We interpreted these findings as follows: increasing chair rotation speed from 10° to 30°/s produced a greater increase in self-motion speed ratings than the same increase in room rotation speed.

3.2.2. Perceived speed of scene motion

As in Experiment 1, significantly more scene motion was perceived during room rotation than during chair rotation [Rotation Type: $F(1,9)=23.6$, $p<.01$]. We also found that faster physical speeds of room or chair rotation produced significantly faster perceived speeds of scene motion [Rotation Speed: $F(1,9)=8.2$, $p<.05$]. A significant 2-way interaction between Rotation type and Rotation Speed [$F(1,9)=6.73$, $p<.05$] indicated that these increases in perceived scene motion were greater for room-rotation trials than for chair-rotation trials. Finally, we found a significant 2-way interaction between Lighting Type and Rotation Type [$F(2,18)=5.10$, $p<.05$]. This was interpreted as indicating

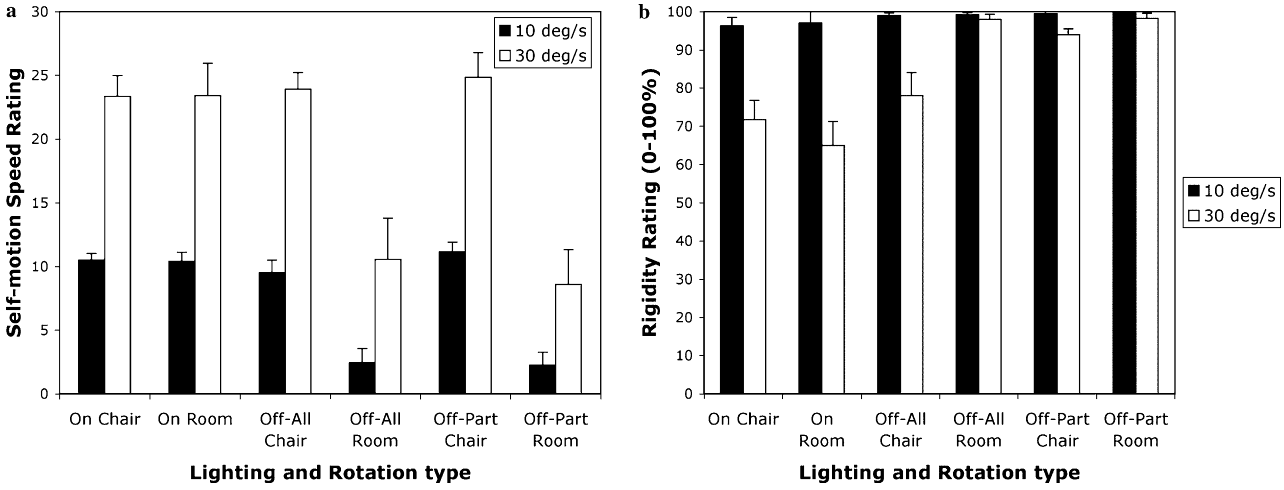


Fig. 6. Ratings of the perceived speed of self-rotation and perceived LED display rigidity during either "room" or "chair" rotation (at 10–30°/s). In the "On" lighting conditions, observers could see the whole room (the ceiling, the carpeted floor, the wallpapered wall and the straight rod with its 8 LEDs). In the "Off-All" lighting conditions, observers could only see the 8 LEDs on the straight rod. Finally, in the "Off-part" conditions, observers could only see the 4 central LEDs on the straight rod (i.e. closest to the shaft).

that: (i) during room rotation, more scene motion was perceived when the room lights were on than when they were off; and (ii) during chair rotation, the perceived amount of scene motion was similar for all three lighting conditions.

3.2.3. Perceived rigidity of the room and LEDs

Illusory scene distortions were found to persist in this second experiment. As in Experiment 1, the magnitude of these distortions was found to increase significantly with the speed of room/chair rotation [Rotation Speed: $F(1,9) = 30.39$, $p < .01$—See Fig. 6B]. We also found a significant main effect of Lighting Type [$F(2,18) = 19.6$, $p < .01$], a significant 2-way interaction between Lighting Type and Rotation Type [$F(2,18) = 15.16$, $p < .01$] and a significant 3-way interaction between Lighting Type, Rotation Type and Rotation Speed [$F(2,18) = 11.29$, $p < .01$]. Post-hoc contrasts were used to interpret these findings. In this experiment, significant distortions of the room or LED display were only produced by 30°/s rotations of room or chair ($p < .05$). As expected, significantly more distortion was observed when the room lights were turned on than when only the LEDs were visible ($p < .05$). When the room lights were on, similar magnitudes of scene distortion were found during room and chair rotations ($p > .05$). However, when the room lights were off, only chair rotation produced detectable shear of the LED display ($p < .05$). Finally, significantly more distortion occurred when all eight LEDs were turned on than when only four were on ($p < .05$).

3.3. Discussion

Contrary to the notion that large-field visual motion stimulation was required to produce scene distortions, significant shearing of the LED display occurred during chair rotation at 30°/s. Importantly, during room rotations (at 30°/s), illusory scene distortions were observed only with the room lights turned on. The failure of observers to perceive significant shear of the LED display during room rotation in the dark was consistent with the proposal that illusory scene distortions require observers to perceive significant changes in their orientation with respect to gravity. According to this account, negliable distortion of the LED display was found during room rotation because the room's visual frame and visual polarity cues were no longer visible. However, illusory distortion of the LED display occurred during chair rotation, because vestibular and somatosensory stimuli generated 360° sensations of self-rotation. The necessity for perceived change in self-tilt also explains the lack of scene distortion when both the room and the observer were physically rotated together at 30°/s in Experiment 1. In this case there was no *perceived* change in the observer's orientation to gravity.

4. Experiment 3: Does illusory scene distortion require stable fixation?

In the two previous experiments, observers fixated a disc at the centre of the facing wall, which coincided with the centre of room rotation. Experiment 3 examined whether illusory scene distortions would persist when observers either fixated other locations in the tumbling room or were allowed to look around its interior. We examined the following fixation conditions: (i) stable fixation on the centre of the facing wall, as in Experiments 1 and 2; (ii) stable fixation on peripheral locations, which would require horizontal and vertical tracking eye-movements as well as torsional nystagmus; and (iii) continuously alternating fixation. Experiment 3 also examined the effects of fixation type and location on the illusory self-tilt produced by rotating the well-lit room about stationary observers. We examined only the effects produced by room rotations.

Allison et al. (1999) previously found that the illusions of self-tilt induced by the tumbling room were similar both when the observer maintained a central fixation and when he/she looked slowly about the room. However, fixating a stationary object which is nearer to the observer than the large rotating display has been shown to reduce vection onset latency (Becker, Raab, & Jürgens, 2002; Fushiki, Takata, & Watanabe, 2000; Howard & Howard, 1994). Furthermore, while some studies have failed to find an effect of fixation on vection magnitude (Dichgans & Brandt, 1978), others have found that a stationary fixation target increases vection speed under certain conditions (DeGraaf, Wertheim, Bles, & Kremers, 1990; Howard & Howard, 1994).

4.1. Method

4.1.1. Observers

Four males and four females (aged between 22 and 41 years) were paid for their participation. Each observer participated in one session lasting approximately 1.5 h. Seven of the 8 observers had participated in either Experiment 1 or 2.

4.1.2. Design

Two independent variables were examined: (1) Rotation Speed—the chair or room rotated at 10° or 30°/s; and (2) Fixation Type—observers fixated a spot (i) at centre of the facing wall; (ii) 30° 'above' the centre; (iii) 30° to the 'left' of centre; (iv) 30° from centre along a radius at 45°; or (v) they continuously changed fixation between these spots. These directions refer to locations when the room was upright. Observers provided two ratings for each trial: (i) the perceived rigidity of the room; and (ii) the range of their perceived self-tilt during the course of the trial.

4.1.3. Apparatus and stimuli

The apparatus was the same as that used in Experiment 2, with the following modifications. All conditions involved only room rotation. The room, which contained only its carpeted floor, wall-paper and wall hangings, was always viewed under full lighting conditions. Three fixation spots were placed on the wall facing the observer. Each consisted of a small black dot (0.7 cm diameter) inside a larger white dot (1.3 cm in diameter).

4.1.4. Procedure

The procedure was similar to that used in Experiments 1 and 2, with the following modifications. First, observers were provided with no information about the likelihood of room or chair rotation. Second, after 30 s, observers were asked these three questions in the following order:

Q1: "How rigid do you perceive the room to be? With 100% being completely rigid and 0% being completely non-rigid (all of the objects across the visual field appear to be moving independently of each other)".
Q2: "Are you tumbling fully head over heals?"
Q3: "How far are you tilting from vertical? What is the range of your perceived change in body tilt?"

4.2. Results

Separate repeated measures ANOVAs—2 (Rotation Speed) × 5 (Fixation Type)—were performed on each of the dependent variables.

4.2.1. Perceived rigidity of the room

We found a significant main effect of Fixation Type on room rigidity ratings [$F(4,28) = 23.1$, $p < .01$] (see Fig. 7a). Post-hoc contrasts revealed that illusory scene distortions were significantly more likely to occur: (i) with stable fixation than with continuously changing fixation ($p < .05$); and (ii) with central, as opposed to peripheral stable fixation ($p < .05$). As in Experiments 1 and 2, we also found that the magnitude of illusory scene distortions increased significantly with the speed of the room rotation [$F(1,7) = 21.97$, $p < .01$]. Finally, we found a significant two-way interaction between Fixation Type and Rotation Speed [$F(4,28) = 17.77$, $p < .01$]. This interaction was interpreted as indicating that: (i) there was very little effect of Fixation Type on rigidity ratings during room rotations at 10°/s (i.e. the room appeared rigid or nearly rigid for all of the fixation conditions tested at this velocity); and (ii) while alternating fixation produced negligible scene shear during room rotations at 30°/s, peripheral fixation produced modest scene shear and central fixation produced marked scene shear.

4.2.2. Perceived tilt range during room rotation

Consistent with the findings of Allison et al. (1999), the main effect of Fixation Type failed to reach significance for the self-tilt range data [$F(4,28) = .5$, $p > .05$] (see Fig. 7b). While, on average, faster speeds of room rotation produced larger ranges of perceived self-tilt, this main effect also failed to reach significance [$F(1,7) = 3.49, p > .05$]. The interaction between Fixation Type and Rotation Speed also did not reach significance [$F(4,28) = 1.81, p > .05$].

4.3. Discussion

While compelling illusory self-rotation was found in all the fixation conditions (central, peripheral or continuously changing), stable fixation proved to be essential for illusory scene distortions. These findings, when taken together with those of the previous experiments, indicate two independent requirements for illusory scene distortions—stable fixation and perceived self-tilt change. It is perhaps because of these two specific requirements that these surprising distortions have not been reported in earlier vection studies using large homogenously textured rotating spheres or disks.

Previous research has shown that: (i) sensitivity to motion and the strength of the motion aftereffect decline significantly with increasing retinal eccentricity (e.g. Burr, Morrone, & Vaina, 1998; Habak, Casanova, & Faubert, 2002; Nakayama, 1990; Van de Grind, Verstraten, & Zwamborn, 1994); and (ii) drifting gratings can appear to move more slowly when presented to peripheral vision (Johnston & Wright, 1986). Differential motion sensitivity, differential motion adaptation and peripheral aliasing accounts of our scene shearing effect would all predict that

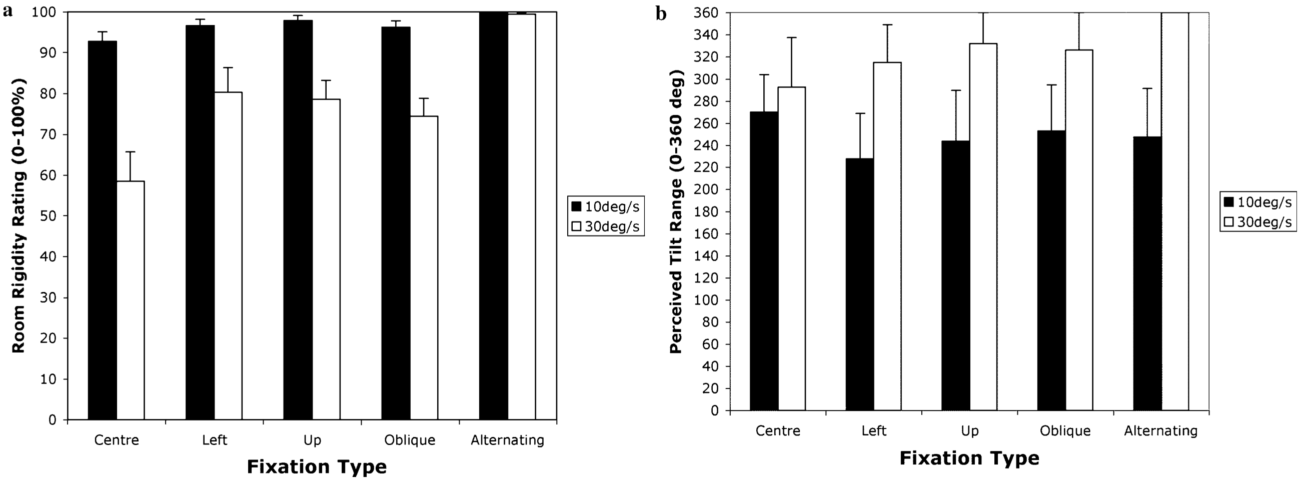


Fig. 7. Ratings of the perceived room rigidity (a) and the perceived tilt range (b) during room rotation (at 10° or 30°/s). Observers fixated on either the shaft (Centre), on a spot to the 'left' of the shaft (Left), on a spot 'above' of the shaft (Up), on a spot at an oblique angle to the shaft (Oblique), or in a continuously alternating fashion on each of these spots (Alternating).

these distortions should be more salient when stable central fixation is maintained throughout the trial, as was in fact found in the present experiment. However, none of these three accounts can explain our finding that significant scene shearing occurred only when observers perceived significant changes in their self-tilt (see Experiment 2).

4.3.1. Equidistant scene distance control

We also examined whether the illusory scene distortions observed in Experiments 1–3 arose because different parts of the room were at different physical distances from the observer. The egocentric distance of any point on the facing wall increased with increasing distance from the wall's centre. Therefore, the angular velocity of these points would also have increased with increasing distance from the centre. This could have caused the central region of the far wall to appear to rotate more rapidly than the surrounding regions. Accordingly, scene distortions should disappear when observers are rotated inside a large sphere, since all parts of the scenery are equidistant.[5] We examined this hypothesis by placing three of our observers from the main experiment inside a 9-foot diameter large sphere lined with randomly positioned black dots [see Howard and Childersen (1994) for a description of this apparatus]. Contrary to this differential distance account, we found that all three observers still reported significant illusory scene distortions during either chair rotation or sphere rotation at 30°/s, although the perceived magnitude of these distortions was less than that found in the tumbling room (presumably due to the reduced perceived range of self-tilt).

4.3.2. Shearing phenomenology

In follow up research, we measured the onset latencies of the illusory scene distortions produced by the tumbling room. The scene shearing latencies (of four experienced observers) from the beginning of visual or physical motion stimulation were similar and quite short for both room-rotation trials ($M = 2.04$ s; $SD = 0.76$ s) and chair-rotation trials ($M = 2.28$ s; $SD = 0.38$ s). To provide a more systematic description of these scene distortions, our four observers used a three-button switch to continuously indicate the timing, direction and magnitude of these effects in separate control trials. As the observer's task was more difficult in this control experiment (it required continuous monitoring of the scene distortion time course and magnitude), we decided to use a simpler stimulus to generate the illusion (i.e. than the fully lit room). Specifically, our observers reported distortions of the LED display during chair rotation in the dark.[6] All observers reported a configural distortion of the LED bar array. Typically the peripheral portion of the display appeared to 'slip' so that its position appeared to lag behind the position of the central portion (positional lag of the peripheral portion of the LED display with respect to the centre). However, the magnitude of this positional lag was time varying and at times was replaced by a positional lead for some observers. Two observers reported that the positional lag was larger in magnitude and lasted longer than the positional lead of the periphery. The remaining observers predominantly saw shearing of the display that alternated between a peripheral positional lag and central-peripheral alignment. Note that these alternations between peripheral lag and peripheral lead (or alignment) were accompanied by corresponding apparent accelerations or decelerations of the periphery with respect to the centre. The timing of these alternations was such that scene distortions for all four observers appeared to peak when they approached 90° from true vertical. This suggests that the shearing effect might have oscillated above and below detectable levels, or alternated between veridical and illusory deformation, as the observer's perceived orientation with respect to gravity changed.

5. General discussion

The present study found that the 360° illusory self-rotations produced by rotating a furnished room around the stationary observer's roll axis were very similar to the sensations of self-rotation produced by rotating the observer inside the stationary room. In these two situations, the presence or absence of cyclic stimulation of the otolith organs should have reliably indicated whether or not the observer was rotating. However, observers appear to have ignored the conflicting information from the otolith organs during room rotation trials, due to the presence of the rich visual scene containing many familiar (polarised) objects. Since normal visual scenes do not rotate with respect to gravity, our observers preferred to perceive the familiar visual scene as remaining vertical throughout these trials. Nevertheless, they did experience marked illusory distortions of the visual scene—both when the room rotated and when they were rotated inside the stationary room. Thus, while adopting the assumption that the room does not rotate about a horizontal axis, observers reported experiences that violated the assumption that natural scenes, such as a room, are rigid.

The most common description of these illusory scene distortions was that scenery near fixation appeared to be rotating at different speeds to more peripheral scenery. However, several observers reported that these distortions also manifested themselves as the 'left' and 'right' hand sides of the facing wall appearing to move in opposite directions. In both cases, the perceived magnitude of the distortions ebbed and flowed throughout the trial. In a few cases, observers even reported that these illusory scene distortions were also present as motion aftereffects.

The findings of all three experiments and their controls strongly suggested that a compelling perception of self-tilt change was essential for the generation of illusory scene distortions. In Experiment 1, the rotation of a richly fur-

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[5] Such an account would, however, have difficulty explaining the current findings that both perceived self-tilt change and stable fixation were require to elicit scene shearing.

[6] While still significant, the scene shearing effects produced by observer rotation in the dark (relative to the LED display) were not quite as salient as those generated in a fully lit room.

nished room produced 360° perceptions of self-rotation and scene distortions in a stationary observer that were very similar to those produced by the rotation of the observer in the stationary room. However, in Experiment 2, when only the LED array was visible, chair rotation alone produced significant perceptions of self-tilt change and scene distortions. A further control experiment indicated that during chair rotation, illusory distortions of the LED display peaked when the observer approached 90° from the true vertical. The final evidence was provided by the following control: when the well-lit room and the observer were rotated together in the same direction at 30°/s, none of the observers reported either sensations of self-tilt change or scene shearing. Thus, it appeared that the perception of self-tilt change, as opposed to the occurrence of physical self-tilt change, was required for the production of these illusory scene distortions.

We also found that observers needed to maintain stable fixation throughout the trial in order to experience illusory scene distortions. In all three experiments, significant scene distortions occurred when observers fixated on a stationary target located at the centre of the roll rotation. However, no significant scene distortion occurred when observers continuously changed fixation to different parts of the room throughout the trial. Thus, it is seems likely that the irregular eye-movements in this condition either averaged out or masked the illusory scene distortions.

The illusory scene distortions observed during perceived self-rotation in the present experiments were somewhat similar to those reported previously by Palmisano and Gillam (1998). In this earlier vection study, observers sat inside a rotating drum and viewed the stripe pattern (0.2 cpd) on its inner wall through two 25° diameter holes in a nearer mask (each hole was located 75° to either the left or right of straight ahead). Even though the stripes on the drum wall were all physically rotating about the observer's vertical axis, binocular far-peripheral exposure caused many observers to report that the stripes viewed through the two holes were rotating about separate axes. Palmisano and Gillam argued that vection was impaired in these binocular far-peripheral conditions, because the localised scene distortions biased observers to perceive object, as opposed to self-, motion.

Unlike the local scene distortions reported in the Palmisano and Gillam study, the global scene distortions in the present study had little effect on observers' real/illusory perceptions of tumbling in roll. When the room was fully furnished and well lit, all observers reported compelling 360° illusions of self-rotation during room rotation trials—despite salient scene distortions. Even when these scene distortions were eliminated by having observers continuously change their fixation, there was no significant increase in reported self-rotation. Natural scenes rarely show global distortions. Even when distortions occur, they are most likely due to combinations of object and self-motions (e.g. jumping in a bouncing castle). This might explain why the illusory scene distortions found in the present study appeared to be quite compatible with compelling perceptions of head-over-heals tumbling.

Our control experiments revealed that none of the following factors could fully account for these illusory scene distortions: (i) failure of torsional eye-movements to adequately compensate for the effects of perceived self-rotation (shearing was not related to the motion of a flash-induced afterimage); (ii) differential scene distances (shearing occurred in the equidistant rotating sphere); and (iii) differences in motion sensitivity over the visual field or differential adaptation of motion detectors (the shearing effect required a perceived change in self-tilt). An anonymous reviewer suggested that efference copy theory could explain the illusory scene distortions. This explanation assumes that: (i) retinal image motion is interpreted in terms of a generalised efference copy signal that encodes eye-motion in space; and (ii) the observer will perceive motion whenever the retinal image motion does not match the reference signal (Wertheim, 1994). According to this explanation, illusory scene distortions were produced because the central and peripheral reference signals (derived from the optic flow) differed in magnitude. We have two main reservations about this account. While there is evidence that the central and peripheral retina have different effectiveness/efficiency in generating such signals (DeGraaf & Wertheim, 1988), we are not aware of any evidence that multiple motion reference signals are used simultaneously in different parts of the visual field. Furthermore, it is not clear why the illusion should depend on apparent posture according to this particular explanation.

One possible explanation for the present findings was that scene shearing represented an effort by the visual system—made exclusively during perceived self-motion—to correct for eccentricity based differences in motion sensitivity. According to this notion, the visual system might have artificially increased the perceived speed of scenery in the retinal periphery—the goal being to make the global motion pattern more consistent with the perception of self-rotation. In principle, this compensation process might be quite useful during typical self-motions in roll, which tend to have short durations and small amplitudes. However, it might fail when the perceived self-motion has longer durations or larger amplitudes, producing the types of illusory scene distortion found in the current experiments. When the compensation is adequate, no shearing should be perceived; when it fails, the latent sensitivity differences should be manifest and the peripheral retinal motion should appear to lag the central motion. A critical question with this and any other mechanism based on central versus peripheral difference in sensitivity or scaling is what causes the distortion to ebb and flow as the subject experiences changes in self-tilt? We speculate that perhaps the compensation mechanism is optimized for head rotations that accompany upright human locomotion and fails to adequately compensate for self-motion in unusual postures, such as earth-horizontal. Note that compensation would not be necessary when the observer perceived only scene (or object) motion, because in this case, there would have been no expectation that the visual stimulation would be globally consistent.

In conclusion, it appears that both the perception of self-rotation in roll and stable fixation were prerequisites for a novel illusion—illusory scene shearing. Under these specific conditions, the perception of 360° self-rotation appears to alter the way in which we see the world around us. While the illusory scene distortions reported in this paper would be unlikely to occur during terrestrial locomotion, the prerequisites for this illusion should arise commonly during visually controlled flight—for example, when a pilot executes a banking manoeuvre in order to align his/her aircraft with a fixated environmental landmark. Thus, the descriptions of this illusory scene distortion and its aetiology should have a direct application in terms of improving flight safety.

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References

Allison, R. S., Howard, I. P., & Zacher, J. E. (1999). Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. *Perception, 28*, 299–306.

Becker, W., Raab, S., & Jürgens, R. (2002). Circular vection during voluntary suppression of optokinetic reflex. *Experimental Brain Research, 144*, 554–557.

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research, 16*, 476–491.

Burr, D. C., Morrone, M. C., & Vaina, L. M. (1998). Large receptive fields for optic flow detection in humans. *Vision Research, 38*, 1731–1743.

Cheung, B. S., & Howard, I. P. (1991). Optokinetic torsion: Dynamics and relation to circular vection. *Vision Research, 31*, 1327–1335.

Cheung, B. S. K., Howard, I. P., & Money, K. E. (1990). Visually induced tilt during parabolic flights. *Experimental Brain Research, 81*, 391–397.

Cheung, B. S., Howard, I. P., Nedzelski, J. M., & Landolt, J. P. (1989). Circularvection about earth horizontal axes in bilateral labyrinthine-defective subjects. *Acta Otolaryngologica, 108*, 334–336.

Cheung, B. S., Money, K. E., & Howard, I. P. (1995). Dynamics of torsional optokinetic nystagmus under altered gravitoinertial forces. *Experimental Brain Research, 102*, 511–518.

DeGraaf, B., & Wertheim, A. (1988). The perception of object motion during smooth pursuit eye movements: adjacency is not a factor contributing to the Filehne illusion. *Vision Research, 28*, 497–502.

DeGraaf, B., Wertheim, A., Bles, W., & Kremers, J. (1990). Angular velocity, not temporal frequency determines circular vection. *Vision Research, 30*, 637–646.

Dichgans, J., & Brandt, T. (1972). Visual-vestibular interaction and motion perception. In J. Dichgans & E. Bizzi (Eds.), *Cerebral control of eye movements and motion perception*. Basal, New York: S Karger.

Dichgans, J., & Brandt, T. (1974). The psychophysics of visually induced perception of self-motion and tilt. In F. O. Schmidt & F. G. Worden (Eds.), *The neurosciences* (Vol. 3). Cambridge, MA: MIT Press.

Dichgans, J., & Brandt, T. (1978). Visual-vestibular interactions and motion perception. In R. Held, H. W. Leibowitz, & H. L. Teuber (Eds.), *Handbook of sensory physiology* (Vol. 8). Berlin: Springer.

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

Finke, R. A., & Held, R. (1978). State reversals of optically induced tilt and torsional eye movements. *Perception and Psychophysics, 23*, 337–340.

Fushiki, H., Takata, S., & Watanabe, Y. (2000). Influence of fixation on circular vection. *Journal of Vestibular Research, 10*, 151–155.

Habak, C., Casanova, C., & Faubert, J. (2002). Central and peripheral interactions in the perception of optic flow. *Vision Research, 42*, 2843–2852.

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

Howard, I. P. (1982). *Human visual orientation*. Chichester, Sussex: John Wiley.

Howard, I. P. Cheung, I. P., & Landolt, J. (1989). Influence of vection axis and body posture on visually-induced self-rotation and tilt. In *Advisory Group for Aerospace Research and Development Conference Proceedings* (Vol. 433, pp. 15-1–15-8).

Howard, I. P., & Childersen, 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.

Howard, I. P., & Hu, G. (2001). Visually induced reorientation illusions. *Perception, 30*, 583–600.

Howard, I. P., Jenkin, H. L., & Hu, G. (2000). Visually-induced reorientation illusion as a function of age. *Aviation, Space and Environmental Medicine, 71*, 1–5.

Johnston, A., & Wright, M. J. (1986). Matching velocity in central and peripheral vision. *Vision Research, 26*, 109–1099.

Mach, E. (1975). *Grundlinien der Lehre von den Bewegungsempfindungen [Basic principles for the study of motion perception]*. Leipzig: Engelmann.

Nakayama, K. (1990). Properties of early motion processing: Implications for sensing egomotion. In R. Warren & A. H. Wertheim (Eds.), *Perception & Control of Self-motion*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Palmisano, S., & Gillam, B. J. (1998). Stimulus eccentricity and spatial frequency interact to determine circular vection. *Perception, 27*, 1067–1077.

Schöne, H. (1984). *Spatial orientation*. Princeton, NJ: Princeton University Press (pp 122-124).

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review, 64*, 153–181.

Thilo, K. V., Probst, T., Bronstein, A. M., Ito, Y., & Gresty, M. A. (1999). Torsional eye movements are facilitated during perception of self-motion. *Experimental Brain Research, 126*, 495–500.

Van de Grind, W. A., Verstraten, F. A. J., & Zwamborn, K. M. (1994). Ensemble models of the movement aftereffect and the influence of eccentricity. *Perception, 23*, 1171–1179.

Wertheim, A. H. (1994). Motion perception during self-motion: The direct versus inferential controversy revisited. *Behavioural and Brain Sciences, 17*, 293–355.

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

Witkin, H. A., & Asch, S. E. (1948b). Studies in space orientation IV. Further experiments on 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.

Young, L. R., & Shelhamer, M. (1990). Microgravity enhances the relative contribution of visually-induced motion sensation. *Aviation Space and Environmental Medicine, 61*, 525–530.