Perception, 2004, volume 33, pages 259 – 276

DOI:10.1068/p5190

Bias to experience approaching motion in a three-dimensional virtual environment

Clifford F Lewis¶
Department of Psychology, Kent State University, PO Box 5190, Kent, OH 44242-0001, USA
Michael K McBeath
Department of Psychology, Room 301, Technology Center, Arizona State University, Tempe, AZ 85287-1104, USA; e-mail: m.m@asu.edu
Received 2 August 2002, in revised form 26 July 2003

Abstract. We used two-frame apparent motion in a three-dimensional virtual environment to test whether observers had biases to experience approaching or receding motion in depth. Observers viewed a tunnel of tiles receding in depth, that moved ambiguously either toward or away from them. We found that observers exhibited biases to experience approaching motion. The strengths of the biases were decreased when stimuli pointed away, but size of the display screen had no effect. Tests with diamond-shaped tiles that varied in the degree of pointing asymmetry resulted in a linear trend in which the bias was strongest for stimuli pointing toward the viewer, and weakest for stimuli pointing away. We show that the overall bias to experience approaching motion is consi'stent with a computational strategy of matching corresponding features between adjacent foreshortened stimuli in consecutive visual frames. We conclude that there are both adaptational and geometric reasons to favor the experience of approaching motion.

1 Introduction

When viewers observe apparent motion in a picture plane, they show biases to experience movement in certain preferred directions (McBeath and Kaiser 1992; McBeath et al 1992; Morikawa and McBeath 1992; Probst et al 1995). Some of these biases have been shown to be a result of cognitive expectations, while others are a result of previous experience with movements that are more common in one direction than another. Some, but not all, of the biases may have adaptational benefits. In the present study, we examine whether a similar bias might also occur in the depth direction.

Three types of biases were demonstrated previously for two-dimensional images. McBeath and Kaiser (1992) found a gravitational bias. This bias caused the experience of apparent motion of a column of circles to be favored in the downward direction. Similarly, among randomly moving dots, coherent upward motion is more readily detected than downward motion (Probst et al 1995). Several explanations are possible for these findings. First, the visual system may develop biases based on previous experiences, such as the common experience that objects fall downward more often than they jump upward. Similarly, the bias may have an adaptational basis, due to evolved tendencies to experience motion in a way that is consistent with gravity and the laws of physics. A third possibility is that higher-level cognitive expectations might influence the experienced direction of motion. An expectation for motion consistent with gravitational principles might manifest itself as a downward bias during an otherwise ambiguous visual movement.

McBeath et al (1992) used similar methods to demonstrate a forward-facing bias. Triangles, arrows, stick figures of humans, and sketches of mice were all shown to result in biases to experience movements in directions the stimuli appeared to point or face. In addition, participants exhibited a bias to experience movement in the interpreted forward-facing direction of an ambiguous duck – rabbit figure (Jastrow 1899).

¶ Address for correspondence: 3269 Altamont Avenue, Cleveland Heights, OH 44118, USA; e-mail: cfl@alumni.cwru.edu

This manipulation ruled out geometric properties of the figures and nearest-neighbor correspondence as possible explanations, because the stimulus was identical regardless of the direction it was perceived to be facing. The findings suggest that cognitive expectations play a role in determining the perceived direction of motion.

McBeath and Morikawa (1997; Morikawa and McBeath 1992) demonstrated a leftward bias, and concluded that it was associated with reading direction. This bias was found to be consistent with the preponderance of leftward motion of text relative to successive fixation points when reading from left to right. It does not appear to be caused by cognitive expectations as in the case of the forward-facing bias. It also clearly seems to be a learned bias, rather than one that is innate. A horizontal bias has also been reported among randomly moving dots, with coherent rightward movement more readily detected than leftward movement (Probst et al 1995). This result, combined with their finding that upward movement is more readily detected than downward movement, suggests that the ability to detect movement could be lessened by a motion perception bias in the same direction.

From a theoretical standpoint, therefore, both learning and expectations have been shown to influence perception of two-dimensional picture-plane motion. In the present study we examine whether similar biases exist on the depth axis; that is, in the direction of approaching or receding motion. We use methods similar to those of McBeath et al (1992) to test for biases in the depth direction.

We anticipated that such biases might exist, on the basis both of adaptational value and of experiences. First, movement in depth is an important and common phenomenon in our three-dimensional world. In addition, our daily experiences with walking and driving, not to mention other means of locomotion, are nearly always in the forward direction. While receding motion is not uncommon, it seems likely that approaching motion is more prevalent. Previous researchers have theorized that frequent experience with forward movement may result in a learned preference for outward radial motion, which is consistent with an approaching stimulus (eg Ball and Sekuler 1980; Georgeson and Harris 1978). The finding of a bias in the depth dimension would lend support to this argument.

Another reason that we anticipated finding a bias for motion in depth was the adaptational importance of looming motion. The salience of looming motion begins at an early age (Ball and Tronick 1971). People also possess an acute ability to distinguish between objects headed directly toward them and objects that will miss them (Portfors-Yeomans and Regan 1996). From an adaptational perspective, if one sees an ambiguous movement in the depth direction, it makes sense to favor interpreting it as an approaching object, in order to be more prepared to take evasive action.

1.1 *Biases for radial motion*

Because of linear perspective, motion in depth is characterized in the retinal image by expanding or contracting radial motion. As early as 1911, researchers documented asymmetries in the perception of this type of motion (Wohlgemuth 1911). Wohlgemuth attributed the preference for outward movement to blurring as a result of fatigue, but this explanation has been ruled out because it also occurs with motion aftereffects (Scott et al 1966). Instead, these asymmetries are generally thought to result from either experience or a built-in predisposition to favor some types of movements.

While many studies have, indeed, revealed asymmetries in the perception of radial motion, they have yielded conflicting results regarding the direction of bias. Many experiments have shown a preference to perceive expanding or centrifugal motion, which is consistent with that experienced in forward motion. A number of other studies, however, have shown a preference for motion in the opposite direction. For example, the experience of movement in depth induced by rotating spirals is more realistic and more easily detected for inward centripetal motion (which is perceived to be receding) than it is for outward centrifugal motion (which is perceived to be approaching). Induced movements of static objects, and motion aftereffects of spirals, however, last longer and are more realistic for approaching motion than for receding motion (Reinhardt-Rutland 1983, 1994). Reinhardt-Rutland (1994) attributed the lesser realism of the approaching-motion stimuli to the lack of several cues that occur in real approaching stimuli, specifically the lack of rapid acceleration of the expanding image, and the lack of a terminal collision.

Georgeson and Harris (1978) found that displays consisting of both outward and inward motion simultaneously presented to peripheral vision gave an impression of drifting away from the fovea rather than toward the center. They attributed this drift to frequent experience with expanding patterns of motion. Expanding movements also appear to be faster than similar rotating or traversing movements, suggesting that the types of movement consistent with approaching motion are misjudged to be faster than other motions (Bex and Makous 1997; Geesaman and Qian 1996). Ball and Sekuler (1980) found that people responded to left or right motion away from the fovea more quickly than they responded to motion toward the fovea. Takeuchi (1997) reported that visual search time for an expanding target in a field of contracting distractors was independent of the number of distractors, but the same was not true for a contracting target in a field of expanding distractors.

Scott et al (1966) demonstrated that motion aftereffect was longer for movement away from the fovea than for movement toward the fovea. In addition, they showed that this asymmetry disappeared after sufficient experience with both centrifugal and centripetal motion. This result supports the explanation that the asymmetry is a result of exposure to consistent forward motion, and that frequent exposure to stimuli consistent with backward motion can diminish the bias. In peripheral vision, a centrifugal bias also was found in second-order but not first-order motion (Dumoulin et al 2001).

Cells in the anterior superior temporal polysensory area (STPa) of the macaque monkey show preferred firing to motion that is radially outward. This area seems to be sensitive to approaching motion (radial expansion) more than it is to lateral motion (uniform translation) (Anderson and Siegel 1999).

Not all studies support preferences for approaching or centrifugal motion, however. Edwards and Badcock (1993), for example, measured thresholds for detection of coherent movement of dots in a field of randomly moving dots. They found that centripetal motion was detected more readily than centrifugal motion. The authors speculated that the type of motion studied was consistent with that detected by area PG of the parietal cortex, which seems to be specialized for detecting arm movements in the center of the visual field rather than self-motion (Steinmetz et al 1987). Raymond (1994) found that threshold for detecting motion of a dot in a small area was lower for motion toward the nose than for motion away from the nose.

If a spot is moving toward the fovea, it is perceived to be ahead of its actual position when a flash of light occurs at the fovea. In contrast, if the spot is moving away from the fovea, it is perceived to be behind its actual position. This finding is also interpreted to support a preference for movement toward the fovea rather than away (Mateef and Hohnsbein 1988; Mateef et al 1991). However, if the same procedure is performed when the motion is visible only within an aperture, the findings are reversed, replicating the results of Ball and Sekuler (1980). Mateef et al suggest that two different motion systems are involved, theirs involving detection of successive displacements while Ball and Sekuler's experiment accesses a process that detects continuous motion.

In summary, while asymmetries between approaching and receding motion have been found, the results whether observers favor one over the other are mixed. On the one hand, the adaptational importance of registering approaching or looming objects is consistent with a bias to experience approaching motion. Frequent experience with forward self-movement would also predict an approaching-motion bias. In contrast, the unusualness of backward or receding motion could make it more salient. In addition, the lack of peripheral vision in a virtual environment test display might produce approaching motion that is less convincing than receding motion, and hence lead to a preference for the latter. Our hypothesis was that one of these two biases would occur, so that observers would tend to favor either approaching or receding motion.

1.2 *Apparent motion as an instrument for determining biases*

In the present study, we used out-of-phase presentations of repeating patterns in order to present participants with an ambiguous direction of apparent movement. The technique of presenting an ambiguous stimulus for the purpose of studying visual biases has been used at least since the time of Helmholtz (1867/1962). This approach is based on the principle that even stimuli containing ambiguous information typically produce an unambiguous perceptual experience. The preferred perception often corresponds with that which is most familiar and consistent with frequent experience (Attneave 1971). We used two-frame apparent motion with a setup similar to that in McBeath et al (1992), but modified to produce ambiguous motion in depth. The experienced direction of movement depended, therefore, on perceptual and/or cognitive processes rather than on actual movement. This approach allowed us to manipulate properties of the stimulus, and to study the influence they might have on the perception of movement.

2 Experiment 1

In experiment 1, we hypothesized that a direction bias would exist for the perception of motion in depth. We tested this as a non-directional hypothesis. Second, we hypothesized that stimulus shape parameters would influence the magnitude of the bias, as was previously demonstrated for picture-plane stimuli by McBeath et al (1992). We predicted that this forward-facing bias would have the effect of shifting the bias toward approaching the viewer when the stimulus pointed toward the viewer, and shifting it toward receding when the stimulus pointed away. To test this hypothesis, we used three different patterns tiled to the inside wall of a three-dimensional virtual tunnel: triangles pointing toward the observer, triangles pointing away from the observer, and diamonds, designed to be neutral.

Our third hypothesis was based on the finding that the two-dimensional forward-facing bias was influenced by the degree to which triangles appeared to point. Stimuli that convey a stronger implication of directionality (ie long, thin triangles) have been found to cause a stronger bias than those that convey a weaker implication of directionality (shorter, fatter triangles) (McBeath et al 1992). We hypothesized that a similar effect would occur with a three-dimensional stimulus, such that more-pointed shapes would have a greater influence on the overall bias than would less-pointed shapes. To test this hypothesis, each of the three directional stimuli (toward, away, and neutral) were further modified to have either long or short lengths. The long stimuli had twice the length, and the same width, as the short stimuli. Thus, a total of six patterns were used in the experiment. A single pattern was used on each trial.

Finally, we hypothesized that the size of the display would affect the magnitude of any biases we might find. In order to test this hypothesis, we performed the same experiment with both a desktop monitor and a large-screen projection monitor. Visual angles were approximately the same for the large screen as for the small screen, but there were enough cues to the actual size and distance of the display (eg accommodation) to result in perception of a much larger tunnel. Our own experience was that the large-screen display appeared much more imposing, conveying a greater sense of immersion, and a stronger feeling of movement over larger distances. The distance to the large-screen display also reduced accommodation cue conflicts that existed in the smaller virtual display. For these reasons, we thought that the large-screen condition might produce different results from the small-screen.

2.1 *Method*

2.1.1 *Participants: Small-screen condition.* Nine male and nine female Kent State University undergraduates participated in the experiment to satisfy a general psychology course requirement. These undergraduates were asked to participate only if they were able to use both eyes together to experience depth. As an added precaution, we wrote a program to screen participants for stereo depth perception. The program displayed a pattern of five squares with equal retinal image sizes but differing disparities. If a participant was able to report the relative depths of the squares, he or she was considered to have adequate stereo vision. All participants were able to give the correct answer within a few seconds, and no one was excluded from the experiment as a result of this test. All squares in the test were 5.5 cm on each side on the small screen; 43.9 cm on the large screen. Two of the squares had uncrossed disparity corresponding to a position 7.6 cm behind the screen. Two others had crossed disparity corresponding to a position 7.6 cm in front of the screen. The fifth square had no disparity, corresponding to a position in the plane of the screen. Disparity on the small screen was 0.57 cm for squares in front of the screen, 0.00 cm for the square in the plane of the screen, and 0.41 cm for squares behind the screen. On the large screen, it was 4.72 cm for squares in front of the screen, 0.00 cm for the square in the plane of the screen, and 3.38 cm for squares behind the screen.

Large-screen condition. This condition involved a different physical setup, and was therefore run independently of the small-screen condition. The large-screen condition was run after all work in the small-screen condition was completed, and different participants were used in the two conditions. Five male students and fifteen female students participated in the experiment. All were Kent State University undergraduates who participated to satisfy a general psychology course requirement. Participants were screened with the same procedures that were used for the small-screen condition. No one was excluded from the experiment as a result of this screening procedure. We discarded data for two females because of problems running the experiments. We used data for the remaining eighteen participants. All participants in both the large-screen and small-screen conditions were naïve of the hypotheses being tested and had normal or corrected-to-normal vision.

2.1.2 *Apparatus: Small screen.* All images were generated on a Silicon Graphics IRIS Indigo computer, and presented on a 46 cm diagonal (28.2 cm high × 36.5 cm wide), 1024 × 1280 pixel color monitor. The computer presented alternating left-eye and right-eye views at a rate of 60 s^{-1}. Participants wore CrystalEyes liquid-crystal-shuttered goggles from StereoGraphics Corp., which filtered the images so that the proper stereo views reached each eye.

The stimuli were presented on the monitor in a darkened room. A sheet of black poster board was placed in front of the display, with a cutout to show the stimulus while minimizing the distraction that the edges of the monitor might cause.

Participants were allowed to sit at a comfortable distance from the monitor, so the exact image angle varied somewhat. The typical viewing distance was about 50 cm, which resulted in visual angles of about 30 deg high × 40 deg wide.

Large screen. Images were generated by the same computer as that used in the small-screen condition. Instead of using the monitor, however, we projected the images onto a wall in a darkened room, using an Electrohome ECP 4100 large-screen projector. The projected image was 2.24 m high × 3.00 m wide. With participants seated 3.05 m from the wall, the projected image subtended visual angles of about 40 deg high × 52 deg wide.

The center of the image was 1.93 m above the floor, which was approximately 0.81 m above eye level.

Participants wore the same CrystalEyes liquid-crystal-shuttered glasses that were used in the small-screen condition. They were seated with the computer keyboard in their laps, and responded on the keyboard as in the previous experiments.

2.1.3 *Stimuli.* We used six stimuli, which we created using Silicon Graphics IRIS Graphics Library routines. A perspective view of a typical stimulus is shown in figure 1, and a front-on view as it appeared on the monitor is shown in figure 2.

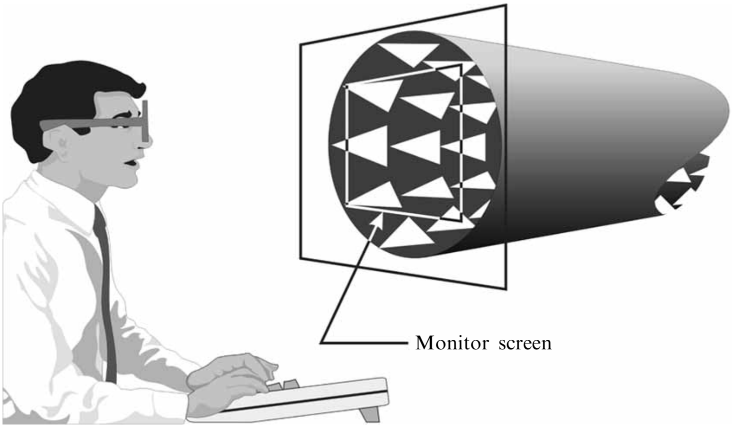

Figure 1. Perspective view of the short-away-triangle stimulus configuration. The outer diameter of the tunnel was larger than the monitor screen, so the effect was that of looking into the inside of the tunnel through a window. The near end of the tunnel was occluded by the edges of the monitor. Note that the outer surface of the tunnel was not visible to the participant. It is illustrated here as it was conceived by the authors, but it did not have an inherent shape.

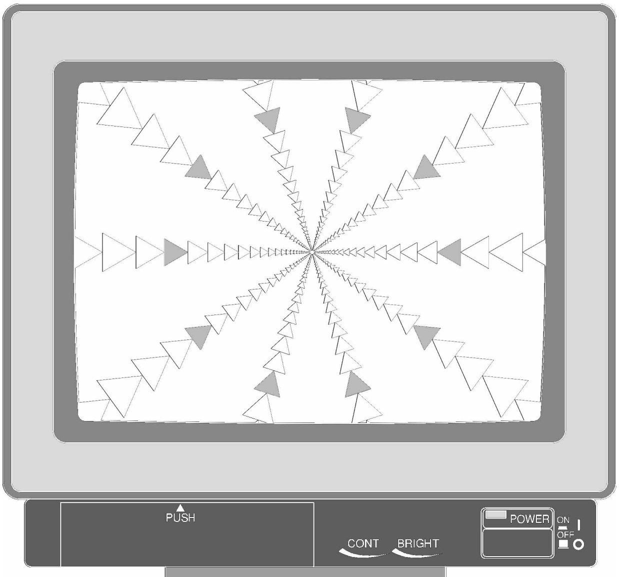

Figure 2. The short-away-triangle stimulus configuration as it appeared on the screen in experiment 1. All triangles were magenta, against a yellow background. With stereo imaging, the participant's experience was that of looking down a long tunnel tiled with the triangles. In the present illustration, one ring of triangles is shaded in light gray to clarify the meaning of the term 'ring'.

While looking through the stereo glasses, the participant's experience was that of looking through a window into the center of a long circular tunnel. The diameter of the tunnel was larger than the monitor screen, so that the end closest to the viewer was occluded by the boundaries of the monitor. This was necessary in order to make the direction of motion ambiguous; the tunnel had to have no visible beginning or end. The far end of the tunnel was visible as a small dot in the center, but any movement at this end was much smaller than the resolution of the monitor, so movement toward or away from this point remained ambiguous.

The inside of the tunnel was lined, like wallpaper, with a repeating pattern. Six different patterns were used: (i) short isosceles triangles that pointed away from the viewer; (ii) short isosceles triangles that pointed toward the viewer; (iii) short diamonds; (iv) long triangles (same base and twice the length of the short triangles) that pointed away from the viewer; (v) long triangles that pointed toward the viewer; and (vi) long diamonds. (Note that a single pattern was used on each trial.) The minor axes of the diamonds were the same width as the triangle bases, and the major axes were equal to the triangle heights. Virtual areas of the short triangles and diamonds were equal, as were the virtual areas of the long triangles and diamonds. Ten triangles or diamonds were arranged in a circle on the circumference of the tunnel, forming one ring. This pattern repeated for 200 rings along the length of the tunnel, receding into the depth of the monitor.

All of the dimensions given below for the stimuli are the virtual sizes (ie the coordinates that were used in the program code, which correspond to the sizes and positions that the objects would possess if they actually existed in real three-dimensional space). From these coordinates, the Graphics Library routines computed what sizes to display the images to give the appropriate impression of distance.

The display was programmed for a 15.8-deg vertical field of view and a viewing distance of 45.72 cm, so that the monitor screen served as a window 12.7 cm high × 15.875 cm wide, looking into the center of the tunnel. The tunnel was programmed to have a virtual inside diameter of 22.86 cm. With a diameter larger than the window, the outside of the tunnel was not visible. The triangles and diamonds were arranged on circles of the same diameter, to give the appearance of wallpaper. A given stimulus consisted of approximately 200 rings, each ring containing 10 triangles or diamonds arranged circumferentially, resulting in a total of about 2000 triangles or diamonds in the full tunnel-shaped pattern. All of the triangles or diamonds in a single stimulus display pattern were programmed to be the same size in virtual space, but the computer displayed the receding shapes as successively smaller, in accordance with linear perspective. The short triangles had virtual dimensions of 3.05 cm base × 30.5 cm long. Because of foreshortening, these triangles appeared to be much closer to equilateral on the monitor. This is consistent with similar distortions found in real stimuli (Norman et al 1996). The long triangles had the same bases as the short triangles, but were twice as long (virtual length 61.0 cm). The remaining shapes were diamonds, chosen to possess neutral directionality in that they appeared to point in both directions. Short diamonds were the same length as the short triangles, and the long diamonds were the same length as the long triangles. The short axes of the diamonds were the same lengths as the bases of the triangles. Side views of the six types of stimuli are illustrated in figure 3.

Because of linear perspective, visual angles subtended by the shapes varied with distance. For the purpose of illustration, dimensions and visual angles are given here for the closest possible ring that could be seen completely on the screen (virtual distance = 82 cm from viewer). The actual screen size of the base of a triangle at this distance would measure 3.8 cm. Assuming a 46 cm viewing distance, the base would subtend a visual angle of 4.7 deg. The length of the short triangle (30.5 cm on

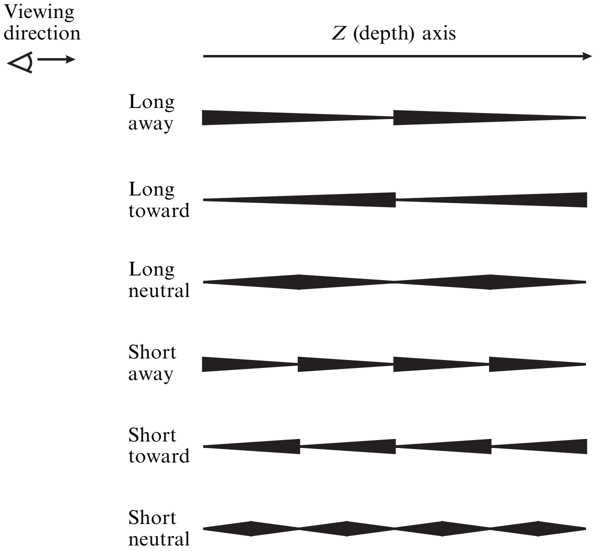

Figure 3. The six types of triangles and diamonds used in experiment 1. Each stimulus was a circular tunnel wallpapered with one of these shapes. A ring consisted of ten triangles or diamonds arranged in a circle around the inner circumference of the tunnel. This pattern repeated along the Z axis to make a total of 200 rings receding in depth, as shown in figures 1 and 2.

the Z axis) would measure 3.8 cm on the screen, for a visual angle of 4.7 deg. A long triangle would measure 6.0 cm, subtending a visual angle of 7.5 deg. (Note that a just-visible away-pointing triangle at the very top of the screen would have a horizontal line for the base, and would point straight downward on the screen. The base-to-tip length reported above would be measured on the screen as the vertical distance below the base.) The far end of the tunnel had a screen diameter of 0.09 cm, with a visual angle of 0.11 deg.

The rings of shapes were equally spaced at a virtual distance of 30.5 cm for the short triangles and diamonds, and 61.0 cm for the long triangles and diamonds. This resulted in the shapes touching each other tip-to-tail. (Pilot experiments had shown that an absence of space between rings was necessary in order to eliminate an overpowering effect in which the stimulus appeared to move in accordance with the expansion or contraction of the closest ring of shapes.)

All shapes were magenta-colored (RGB value $=$ 210, 60, 90). The tunnel wall behind the pattern appeared on the screen as a solid yellow (RGB value $=$ 210, 180, 50) background, with a small black hole at the far end. The overall appearance was of a receding yellow tunnel, with the triangular pattern wallpapered on the inside of the tube.

The words "Look here" appeared in white characters centered on the tunnel axis, 508 cm virtual distance behind the screen (aligned approximately with the 16th ring of short triangles, or 8th ring of long triangles). Since there were no tunnel features on the central axis, and it was easy to be distracted by the walls of the tunnel, we found that the words were more compelling to look at than a fixation cross.

For the stereo display, the convergence distance was programmed to be in the plane of the screen (equal to the viewing distance of 45.7 cm). Having convergence in the plane of the screen prevented any problems with mismatched features and negative disparity at the edge of the monitor. Clipping planes, which specified the near and far boundaries of the images, were 43.2 cm for the near clipping plane and 6096 cm for the far clipping plane. Thus, the near clipping plane was in front of the monitor screen.

The far end of the tunnel was at a finite distance, which could have provided a cue for the direction of movement if motion at that end could be discerned. With linear perspective, this movement was about 0.002 cm, or less than 0.1 min of arc, which was on the same order of magnitude as the threshold for movement detection (Johansson 1978; Nakayama 1985). It was also approximately one tenth the pixel resolution of the monitor. While these movements were very small, it is conceivable, with the computer's anti-aliasing feature, that the direction of movement could have been discerned by a person attending to this feature of the display. However, attention during the experiment was directed to other parts of the display that had larger and more salient movements, and we believe it was unlikely that far-end movement could have influenced the perceived direction. While inspecting the display, we were not consciously aware of any movement at the far end.

The centers of projection were 2.54 cm apart in the small-screen version of the program, which was the largest disparity that could be fused comfortably. This parameter, often called eye spacing, actually controls the amount of disparity in the display. The manufacturer recommends choosing a value that results in a maximum disparity of approximately 1.5 deg, in order to allow the images to be fused easily. It is normal for the value to differ from the physical distance between the eyes (Lipton 1997). In the small-screen display, disparities ranged from 0.0 cm in the plane of the screen to 5.8 cm at the far end of the tunnel. At a viewing distance of 50 cm, this resulted in a maximum visual angle of 6.6 deg. Most likely, we were able to use such a large disparity because attention was generally directed away from the far end of the tunnel.

The exact same program was used in both the large-screen and the small-screen conditions, except that the distance between centers of projection was decreased to 0.89 cm for the large-screen condition in order to calibrate the disparity for the size of the display. This reduction was necessary to compensate for the increased visual angle between images on the large screen. Disparities on the large screen ranged from 0.0 cm in the plane of the screen to 16.7 cm at the far end of the tunnel. At a viewing distance of 305 cm, this resulted in a visual angle of 3.1 deg.

On the large screen, the triangles in the closest possible fully visible ring would have a base of 30.7 cm. At the top of the screen, the viewing distance would be approximately 361 cm, resulting in a visual angle of 4.9 deg. (Note that the added distance to the top of the screen is taken into account in this calculation; the same dimension directly in front of the viewer would subtend a visual angle of 5.8 deg.) The length of a short triangle would be 30.7 cm, with a visual angle of 4.3 deg. The length of a long triangle would measure 48.5 cm, with a visual angle of 7.0 deg.

2.1.4 *Procedure.* Participants were instructed to maintain eye fixation on the words at the center of the tunnel, and to avoid looking at the walls of the tunnel.

Participants were first given five practice trials to make sure they understood the procedure. This was sufficient practice for all participants to understand the procedure. No feedback was given on the accuracy of responses.

On each trial, a tunnel tiled with one of the patterns (either toward, away, or neutral; long or short) was displayed on the screen. After 3.0 s, the same pattern was redisplayed in a new position, displaced a small distance in depth from the original position. This displacement caused the participants to experience apparent motion between the beginning tunnel position and the final position. Because the shapes repeated along the length of the tunnel, the subjective direction of motion was ambiguous. Participants responded on the computer keyboard to indicate whether the direction of apparent motion that they experienced was toward or away from them.

On the first presentation of a pattern, the displacement was small, at 20% of ring spacing. (Ring spacing is defined as the virtual distance, from tip to tail along the

Z axis, between one circular arrangement of triangles and the next, identical, circle.) This small initial displacement was calculated to produce a nearly unambiguous direction of movement. On subsequent trials with the same pattern, the displacement was increased by an additional 8% of ring spacing. This process continued until the observer reported experiencing movement in the opposite direction. The displacement on this trial was recorded as the first reversal point, and on subsequent trials displacement was decreased by 7% of ring spacing until another reversal point was obtained. This procedure continued according to a standard interleaved staircase procedure (Cornsweet 1962; Levitt 1971; McBeath 1990b; Meese 1995), until a total of eight reversals were recorded for each pattern. The size of the increment in displacement from one trial to the next was decreased by one percentage point (starting with 8% of ring spacing) after each reversal. Altogether, eight reversals were recorded for each stimulus, and an average was taken of the last seven reversal points to measure the strengths and directions of any biases we might find. The initial displacement direction was counterbalanced across participants and stimuli. The six patterns (toward, away, or neutral; long or short) were interleaved and presented once in random order within each round of trials.

2.2 *Results*

Results are plotted in figure 4 as a function of screen size, stimulus length, and pointing direction. All statistical tests were done with an a priori alpha level of 0.05. We performed a two-tailed t test of the mean reversal point, comparing it with a theoretical mean of 50% of ring spacing (the point of no bias). The test showed a significant bias to experience approaching motion ($t_{215} = 25.474$, $p = 0.000$). The mean reversal point for the six stimuli combined was 62.19% of the spacing between rings, with $s = 7.032$ (where an unbiased response would be at 50%). We also performed a $2 \times 3 \times 2$ (screen size × pointing direction × length) ANOVA. The results were significant only for pointing direction ($F_{2,204} = 13.19$, $p = 0.000$). We did not find effects for screen size or stimulus

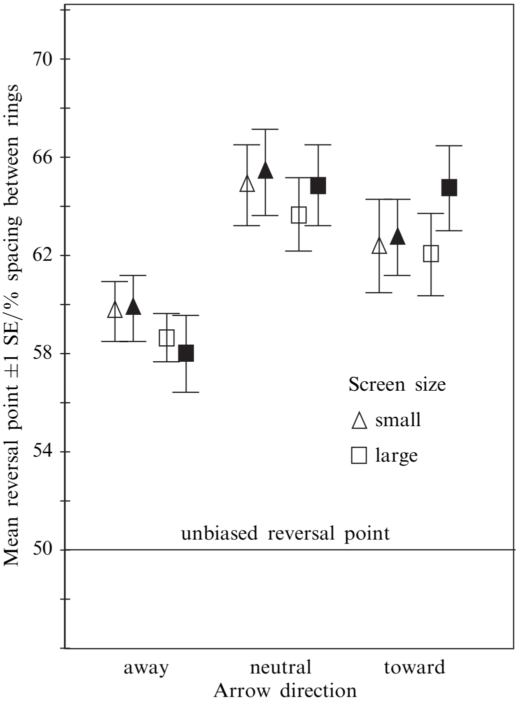

Figure 4. Mean reversal point as a function of screen size, stimulus length, and pointing direction in experiment 1. An unbiased participant would exhibit a mean reversal at 50% of ring spacing. Open shapes represent short stimuli. Filled shapes represent long stimuli. Triangles represent the small display screen, squares the larger one. All conditions produced significant biases to experience approaching motion.

length, or interactions of screen size with pointing direction or length. Nor did we find an interaction between screen size, pointing direction, and length. ($F < 1$ for all of the above.)

We performed a posteriori pairwise t tests for the direction the stimulus pointed, using a Bonferroni correction for three comparisons (alpha $= 0.017$) to maintain a familywise alpha level < 0.05. We found significant differences between triangles pointing toward the viewer and those pointing away ($t_{142} = 5.367$, $p = 0.000$) and also between neutral diamonds and triangles pointing away ($t_{142} = 3.608$, $p = 0.000$). We did not find a significant difference between neutral diamonds and triangles pointing toward the viewer ($t_{142} = 1.448$, $p = 0.150$, ns). Even for triangles pointing away from the viewer, however, the overall directional bias was significant in the direction of approaching motion. ($\bar{X} = 59.01$, $t_{71} = 13.66$, $p = 0.000$.) The effect on directional bias due to shape is consistent with the direction that the triangles appear to face.

2.3 *Discussion*

The approaching-motion biases seen here are larger than any biases that were found previously for two-dimensional apparent motion (McBeath and Kaiser 1992; McBeath and Morikawa 1997; McBeath et al 1992; Morikawa and McBeath 1992). If no directional bias existed, the mean reversal point should have occurred near the midpoint (50% of ring spacing). Instead, the mean reversal point for the six stimuli combined was 62.19% of the ring spacing. This means that, on average, the image had to move 12.19% of the ring spacing beyond the neutral reversal point before it was judged to be a receding movement. In other words, images that shifted beyond the neutral reversal point should have appeared to be receding, but a significant number were judged to be approaching at displacements up to 62% of the ring spacing. Our first hypothesis was thus confirmed. We suspect that the bias was so large because of frequent experience with approaching motion. However, it also could have been larger because the entire display induced the perception of motion in the virtual environment, whereas only one row of shapes was used in the 2-D movement studies. It is also possible that foreshortening of the retinal image determined the size of the bias. (See section 4.1.)

We found that the direction that the triangles pointed affected the magnitude of the depth bias, confirming our second hypothesis. Triangles pointing away from the observer weakened the impression of approaching motion, resulting in a smaller bias than those found for diamonds and triangles pointing toward the viewer. However, this effect was not strong enough to overcome the overall bias to experience approaching movement.

A forward-facing bias, associated with triangles pointing toward the viewer, would be expected to result in an even stronger approaching-motion bias than that found with neutral diamonds. However, we did not obtain a significant difference between these two classes of stimuli. This result is similar to an earlier finding by McBeath et al (1992), experiment 1, in which the leftward bias obtained for the neutral stimulus was not significantly different from that obtained for the leftward-pointing arrow. One possible explanation is that the bias for both the neutral stimulus and that for the toward-pointing triangles could be at a ceiling for the magnitude of bias in the approaching direction. A second possibility is that only those objects perceived to point away exerted enough influence to overcome the approaching-motion bias. A third possibility is that the shape of the neutral stimulus was not as neutral as it was designed to be. One result of foreshortening in the perspective view is that the half of the diamond pointing toward the observer is always larger than the half pointing away. Although the use of stereo vision helps viewers perceive the diamonds to be more symmetrical, the retinal images are not entirely neutral. This distortion could cause the diamonds to be perceived as pointing somewhat toward the viewer. The influence of stimulus shape is explored further in experiment 2.

One unexpected result was the lack of difference between long and short stimuli. These two sets of stimuli produced nearly identical results, on average. This result might have occurred because the ring spacing was also doubled for the longer stimuli, so that the amount of movement was the same percentage of the stimulus length in both long and short stimuli. Because it was necessary to arrange the stimuli tip-to-tail, it was not possible to change the length of the stimuli without changing the ring spacing. Thus, it is possible that the motion information that was interpreted was similar, despite the differences in the size of the objects.

We also found no difference between the large-screen and the small-screen images. This might have been because there was not a large difference in the image angles between the large screen and the small screen. Nonetheless, results from both the screen-size and triangle-length manipulations show that the two major biases (approaching and forward-facing) are robust with respect to screen size and dimensions of the image. Observers consistently favored approaching motion mediated in the direction that the triangle patterns faced.

3 Experiment 2

The results of experiment 1 supported the hypothesis that the shape of the stimulus influenced the magnitude of the bias to experience approaching motion. The stimulus consisting of triangles pointing away from the viewer resulted in a bias that was weaker than the biases that were found for the other stimuli. The away triangles were the only ones to significantly mediate the strength of the approaching-motion bias. We performed experiment 2 in order to systematically explore the effect of stimulus shape by more finely varying the degree of asymmetry of diamond-shaped stimuli.

3.1 *Method*

3.1.1 *Participants.* Seven male and eleven female Kent State University undergraduates participated in the experiment to fulfill a general psychology course requirement. All participants were naïve to the hypotheses being tested, had normal or corrected-to-normal vision, and were screened for stereo perception in the same manner as that used in experiment 1.

3.1.2 *Stimulus.* The seven stimuli were based on the short neutral diamond of the previous experiment. The degree of asymmetry was varied in seven increments ranging from a triangle pointing away from the observer (replicating the short-away triangle of experiment 1) to a symmetrical diamond (replicating the neutral diamond of experiment 1), to a triangle pointing toward the observer (replicating the short-toward triangle of experiment 1). Four other asymmetric diamonds were created between these extremes—two weighted to point toward the viewer and two weighted to point away. The stimuli formed a seven-item continuum with equal area, height, and length, as illustrated in figure 5.

3.1.3 *Apparatus.* The apparatus was the same as that used for the large-screen condition in experiment 1.

3.1.4 *Procedure.* The seven stimuli were presented in random order with an interleaved staircase procedure, as in the previous experiment. Participants responded on the keyboard to indicate the direction of apparent motion.

3.2 *Results*

The mean reversal points for each of the seven stimuli are plotted in figure 6. In this figure, the symmetrical diamond stimulus is numbered 0, with negative numbers indicating stimuli weighted on the side pointing away from the viewers and positive numbers indicating stimuli weighted on the side pointing toward the viewers. The least-squares

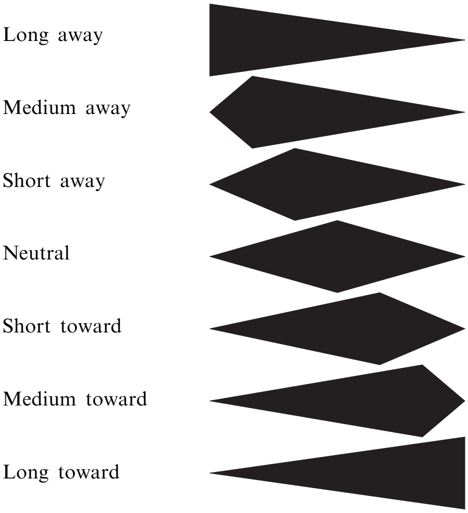

Figure 5. Stimulus shapes used in experiment 2, a continuum of seven asymmetric diamonds ranging in directionality. All of the shapes have the same length, height, and area. As in the previous experiment, the shapes were arranged to give participants the experience of looking down a long tunnel tiled with one of the shapes.

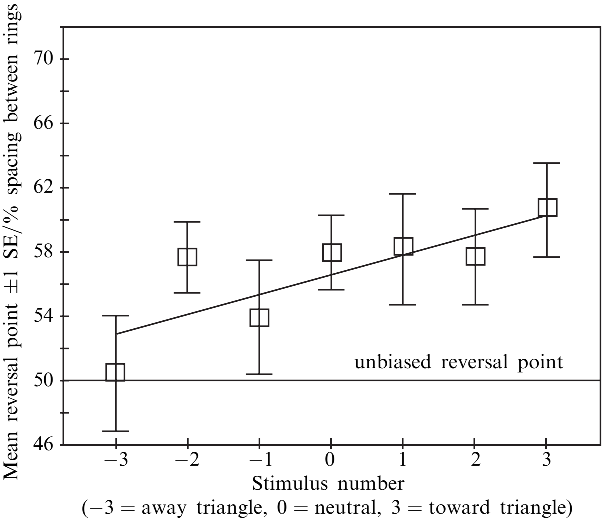

Figure 6. Mean reversal point as a function of shape directionality in experiment 2. The bias was in the approaching direction for all shapes. The linear trend supports that experienced direction of motion was correlated with extent of shape directionality.

regression line in the figure shows a positive slope as the stimulus is weighted more toward the viewer, with a Pearson *r* coefficient of 0.200. A trend analysis shows a significant linear trend ($F_{1,17} = 15.573$, $p = 0.001$).

The symmetrical diamond stimulus (stimulus 0 on the graph), which was a replication of the short neutral diamond of experiment 1, had a mean reversal point of 57.5% of ring spacing. This is lower than the mean from experiment 1 (63.65), but this difference was not significant ($t_{34} = 1.976$, $p = 0.056$, ns). Stimulus 3 from experiment 2, which was a replication of the short-toward triangle of experiment 1, had a mean reversal position of 60.56% of ring spacing, which is not significantly different from the mean of stimulus 3 in experiment 1 (61.99) ($t_{34} = 0.404$, $p = 0.689$, ns). Stimulus (−3) from experiment 2, which was a replication of the short-away triangle of experiment 1 (stimulus 1), is significantly different at the $\alpha = 0.05$ level ($t_{34} = 2.239$, $p = 0.032$), but is not significant when a Bonferroni probability correction is used. The mean for stimulus (−3) was 50.111% of ring spacing, compared with 58.63% for stimulus 1 of experiment 1.

3.3 *Discussion*

The results of this experiment further confirm that viewers have a general bias to experience approaching over receding motion. It also provides additional support that the direction that stimulus elements point systematically mediates the strength of approaching-motion bias. The extent to which stimuli point toward or away from the observer linearly influences the size of the bias to experience approaching motion. In the extreme case in which stimulus triangles unambiguously face toward the viewer, the bias to experience approaching motion is nearly canceled out by the bias to experience motion in the direction in which the triangles point.

The increasing function of bias shown in figure 6 may be linear as shown, but is also consistent with other nonlinear, monotonic increasing functions. For example, the findings also are consistent with observers exhibiting a categorical response concerning direction that stimuli point. Observers may be grouping the neutral diamond stimulus with the three triangle stimuli that point toward them, and interpreting them all with approximately equal directionality pointing toward themselves. Then each of these stimuli could contribute an approximately equal effect enhancing the percept of approaching motion. At some amount of pointing away, the effect may categorically reverse so that it diminishes the percept of approaching motion. This could explain why the results for the symmetrical diamond appear to be more similar to the toward triangle in both experiments. Additional research could help clarify the extent that strength of pointing direction is processed categorically.

4 General discussion

Our findings support a robust bias to experience approaching motion when a three-dimensional stimulus is used. The bias is stronger than those observed previously for leftward and downward motions (McBeath and Kaiser 1992; McBeath et al 1992; Morikawa and McBeath 1992). The findings confirm our hypotheses that biases exist in depth, and that the shape of the stimulus influences the bias in a way that is consistent with the direction the stimulus is pointing.

The design of the present study does not allow us to verify the origins of these biases, but they are consistent with our predictions based on experience with forward self-motion and the salience of looming motion. They are also consistent with the cognitive expectations associated with a forward-facing motion bias.

Our results are consistent with an adaptational explanation based on experience and expectations. There are several reasons for people to assume that ambiguous motion is coming in their direction, including the preponderance of approaching motion, the importance of avoiding looming objects, and the value of being conservative in estimating the timing of approaching objects. Research has confirmed that adaptation to motion can impair the accuracy of judgments of time to collision in a driving task (Gray and Regan 2000). Biases, especially learned ones, could also lead to misjudgments of time to collision, and hence accidents, but presumably the cost of error is much less in the direction of reacting too soon.

4.1 *Geometric considerations*

The biases observed in this experiment are consistent with the findings found in earlier work for two-dimensional biases. However, the use of a three-dimensional virtual environment adds a potential confound that could provide an alternate mechanistic explanation for an approaching-motion bias. When we observe shapes receding in depth, the foreshortened perspective view leads to an asymmetry that is present both in virtual and real environments. In both cases, the closer half of an object subtends a larger retinal angle than does the more distant half.

Figure 7a illustrates the effects of foreshortening when the stimulus is translated 50% of the ring spacing. The figure shows a perspective drawing of one line of triangles. The black triangles show the initial positions, and the translucent white triangles superimposed on the black triangles show the final positions.

Figure 7b shows that the white triangle position that is optically midway between two black triangles corresponds almost exactly with the reversal point we found for the away triangles in experiment 1. Thus, it would be possible for our finding of a bias to experience approaching motion to be a result of this geometrical constraint.

The effect of removing stereo vision from the display has been investigated in a separate study, and was shown to result in a much smaller bias, although still statistically significant. On average, the reversal point was at 52.51% of ring spacing for a two-dimensional radial expansion, compared with 62.19% obtained in the present experiment. The results are to be reported elsewhere (Addie 2003). We conclude, therefore,

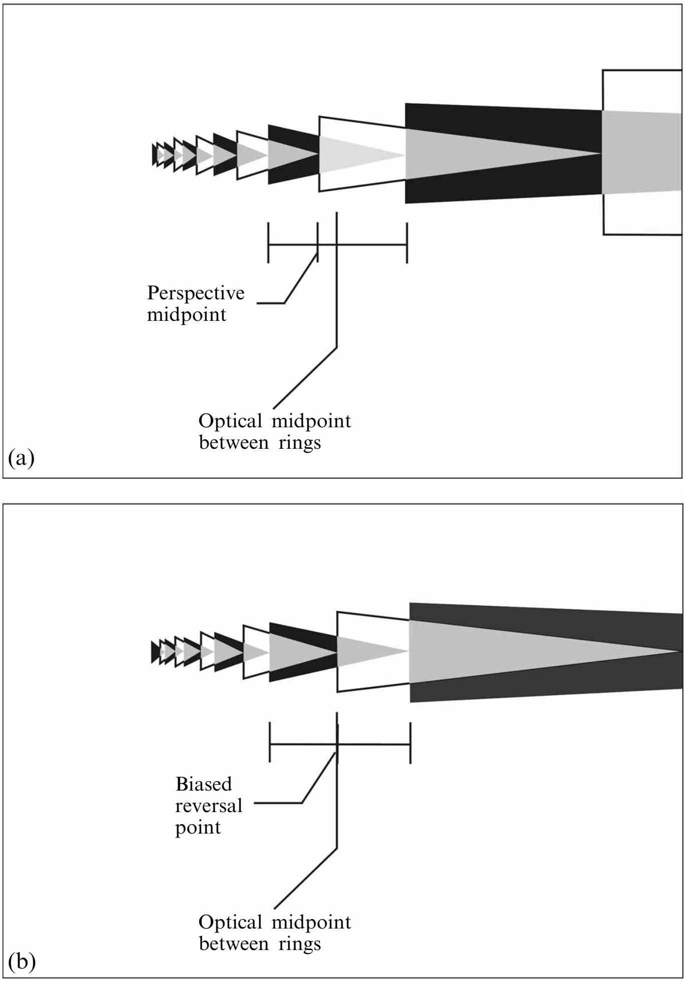

Figure 7. Feature matching in the perspective view. White triangles represent final position; black triangles represent initial position. (a) Unbiased (50% ring spacing). Owing to perspective foreshortening, the final position of any ring of triangles is closer to the initial position of the ring behind it than it is to the initial position of the ring in front of it. (b) 62% Ring spacing. This final position, which corresponds with the bias we obtained for triangles pointing toward observers, is an equal optical distance from the initial positions of both the rings behind it and in front of it.

that the observed bias is found only in the virtual three-dimensional environment and does not result from two-dimensional artifacts.

4.2 *Implications of the approaching-motion bias*

The biases found in this study may have notable consequences. For example, subtle errors by drivers in judging movement of approaching vehicles could make the difference between success and failure in avoiding a collision (Gray and Regan 1999, 2000; Schiff and Detwiler 1979). Similar errors in judgments of ball movement in high-speed ball games could result in mistakes by players and judges (McBeath 1990a; McBeath et al 1995).

Biases might cause errors in judging distance or velocity, or they might help to compensate for errors caused by the use of other heuristics. For example, the parameter τ, which has been proposed as an heuristic that observers and animals use to estimate time to contact, assumes a constant velocity (Lee and Reddish 1981; Lee et al 1983). If velocity is not constant, it will result in a timing estimate that is too short for accelerating motion, or too long for decelerating motion. A bias in the direction of approaching motion might increase error in some cases, but given a range of stimulus variability and perceptual noise, such a bias would generally tend to give observers more time to react and avoid collisions. In short, the benefits of being overly reactive in interpreting motion as approaching likely outweigh the costs of not being reactive enough.

Knowledge of directional biases might also be valuable in the design of virtual environments and simulator displays to obtain the most reliable and believable displays possible. Many cues for motion are present in real-life images. For example, a chrome bumper or brass doorknob reflects features from nearby objects. A realistic representation of movement in an image containing these components would require images with distorted reflections of the moving objects (Kersten 1997). Even the most sophisticated of computers is not able to display all of the motion cues present in a real environment, so it is necessary to select the most useful ones when displaying apparent motion (Kaiser and Montegut 1997). The results of this experiment demonstrate that a textured surface in depth can be shifted by more than 50% of the smallest texture elements and it will still tend to produce a sense of approaching motion. When the perception of receding motion is desired, smaller motion steps in the receding direction would be necessary.

5 Conclusions

We have shown that observers have a robust bias to experience approaching motion in depth when the direction of motion is ambiguous. The magnitude of the bias is mediated by the shape of the stimulus elements, with the strength of approaching motion increasing as a function of how much the stimuli appear to point toward the observer. For stimuli pointing away from the observer, the bias to experience approaching motion is weakened, but it remains significant. The approaching-motion bias and the mediating effect of stimulus shape are also robust with respect to display size. Observers favor approaching motion with both small and large screen displays.

There are several adaptational reasons for people to assume that ambiguous motion is approaching them, including the preponderance of approaching motion, the importance of avoiding approaching objects, and the value of being conservative in estimating the timing of approaching objects. The finding is also consistent with geometric aspects of the retinal image. The geometric explanation supports that observers judge the direction of apparent motion on the basis of where the final object came from, rather than on the basis of where the initial object went. In summary, it appears that there are both adaptational and geometric reasons to favor the experience of approaching motion in depth.

Acknowledgment. This study was supported in part by a grant from Interval Research Corporation, Palo Alto, CA. It is based on Clifford F Lewis's Master's thesis.

References

Addie J, 2003 *Spatial Multi-sensory Interaction: Auditory Capture of Visual Apparent Motion* Master's thesis, Arizona State University, Tempe, AZ, USA

Anderson K C, Siegel R M, 1999 "Optic flow selectivity in the anterior superior temporal polysensory area, STPa, of the behaving monkey" *Journal of Neuroscience* **19** 2681 – 2692

Attneave F, 1971 "Multistability in perception" *Scientific American* **225**(6) 63 – 71

Ball K, Sekuler R, 1980 "Human vision favors centrifugal motion" *Perception* **9** 317 – 325

Ball W, Tronick E, 1971 "Infant responses to impending collision: Optical and real" *Science* **171** 818 – 820

Bex P J, Makous W, 1997 "Radial motion looks faster" *Vision Research* **37** 3399 – 3405

Cornsweet T N, 1962 "The staircase-method in psychophysics" *American Journal of Psychology* **75** 485 – 491

Dumoulin S O, Baker C L, Hess R F, 2001 "Centrifugal bias for second-order but not first-order motion" *Journal of the Optical Society of America A* **18** 2179 – 2189

Edwards M, Badcock D R, 1993 "Asymmetries in the sensitivity to motion in depth: A centripetal bias" *Perception* **22** 1013 – 1023

Geesaman B J, Qian N, 1996 "A novel speed illusion involving expansion and rotation patterns" *Vision Research* **36** 3281 – 3292

Georgeson M A, Harris M G, 1978 "Apparent foveofugal drift of counterphase gratings" *Perception* **7** 527 – 536

Gray R, Regan D M, 1999 "Adapting to expansion increases perceived time to collision" *Vision Research* **39** 3602 – 3607

Gray R, Regan D M, 2000 "Risky driving behavior: A consequence of motion adaptation for visually guided motor action" *Journal of Experimental Psychology: Human Perception and Performance* **26** 1721 – 1732

Helmholtz H von, 1867/1962 *Treatise on Physiological Optics* volume 3 (1962, New York: Dover); English translation by J P C Southall for the Optical Society of America (1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (first published in 1867, Leipzig: Voss)

Jastrow J, 1899 "The mind's eye" *Popular Science Monthly* **54** 299 – 312

Johansson G, 1978 "Visual event perception", in *Handbook of Sensory Physiology* VIII *Perception* Eds R Held, H Leibowitz, H-L Teuber (Berlin: Springer) pp 675 – 711

Kaiser M K, Montegut M J, 1997 "Of red planets and indigo computers: Mars database visualization as an example of platform downsizing" *Behavior Research Methods, Instruments, & Computers* **29** 48 – 53

Kersten D, 1997 "Inverse 3-D graphics: A metaphor for visual perception" *Behavior Research Methods, Instruments, & Computers* **29** 37 – 46

Lee D N, Reddish P E, 1981 "Plummeting gannets: a paradigm of ecological optics" *Nature* **293** 293 – 294

Lee D N, Young D S, Reddish P E, Lough S, Clayton T M H, 1983 "Visual timing in hitting an accelerating ball" *Quarterly Journal of Experimental Psychology A* **35** 333 – 346

Levitt H, 1971 "Transformed up – down methods in psychoacoustics" *Journal of the Acoustical Society of America* **49** 467 – 477

Lipton L, 1997 *StereoGraphics Developers' Handbook* (San Rafael, CA: StereoGraphics Corp.)

McBeath M K, 1990a "The rising fastball: Baseball's impossible pitch" *Perception* **19** 545 – 552

McBeath M K, 1990b *Velocity of Apparent Motion in Three-dimensional Space* doctoral dissertation, Stanford University, Stanford, CA, USA

McBeath M K, Kaiser M K, 1992 "Visual bias for gravitationally downward motion" *Investigative Ophthalmology & Visual Science* **33** 1143

McBeath M K, Morikawa K, 1997 "Forward-facing motion biases for rigid and nonrigid biologically likely transformations" *Perceptual & Motor Skills* **85** 1187 – 1193

McBeath M K, Morikawa K, Kaiser M K, 1992 "Perceptual bias for forward-facing motion" *Psychological Science* **3** 362 – 367

McBeath M K, Shaffer D M, Kaiser M K, 1995 "How baseball outfielders determine where to run to catch fly balls" *Science* **268** 569 – 573

Mateef S, Hohnsbein J, 1988 "Perceptual latencies are shorter for motion towards the fovea than for motion away" *Vision Research* **28** 711 – 719

Mateef S, Yakimoff N, Hohnsbein J, Ehrenstein W H, Bohdanecky Z, Radil T, 1991 "Selective directional sensitivity in visual motion perception" *Vision Research* **31** 131 – 138

Meese T S, 1995 "Using the standard staircase to measure the point of subjective equality: A guide based on computer simulations" *Perception & Psychophysics* **57** 267 – 281

Morikawa K, McBeath M K, 1992 "Lateral motion bias associated with reading direction" *Vision Research* **32** 1137 – 1141

Nakayama K, 1985 "Biological image motion processing: A review" *Vision Research* **25** 625 – 660

Norman J F, Todd J T, Perotti V J, Tittle J S, 1996 "The visual perception of three-dimensional length" *Journal of Experimental Psychology: Human Perception and Performance* **22** 173 – 186

Portfors-Yeomans C V, Regan D, 1996 "Cyclopean discrimination thresholds for the direction and speed of motion in depth" *Vision Research* **36** 3265 – 3279

Probst T, Loose R, Niedeggen M, Wist E R, 1995 "Processing of visual motion direction in the fronto-parallel plane in the stationary or moving observer" *Behavioural Brain Research* **70** 133 – 144

Raymond J E, 1994 "Directional anisotropy of motion sensitivity across the visual field" *Vision Research* **34** 1029 – 1037

Reinhardt-Rutland A H, 1983 "Induced movement-in-depth: Relative location of static stimulus and direction of asymmetry" *Perceptual & Motor Skills* **57** 255 – 258

Reinhardt-Rutland A H, 1994 "Perception of motion in depth from luminous rotating spirals: directional asymmetries during and after rotation" *Perception* **23** 763 – 769

Schiff W, Detwiler M L, 1979 "Information used in judging impending collision" *Perception* **8** 647 – 658

Scott T R, Lavender A D, McWhirt R A, Powell D A, 1966 "Directional asymmetry of motion aftereffect" *Journal of Experimental Psychology* **71** 806 – 815

Steinmetz M A, Motter B C, Duffy C J, 1987 "Functional properties of parietal visual neurons: Mechanisms of directionality within the visual field" *Journal of Neuroscience* **7** 177 – 191

Takeuchi T, 1997 "Visual search of expansion and contraction" *Vision Research* **37** 2083 – 2090

Wohlgemuth A, 1911 "On the aftereffects of seen movement" *British Journal of Psychology: Monographs* **1** 1 – 117

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 33 2004

www.perceptionweb.com