Journal of Experimental Psychology:
Human Perception and Performance
2005, Vol. 31, No. 5, 1023–1038

0096-1523/05/$12.00 DOI: 10.1037/0096-1523.31.5.1023

Naive Optics: Acting on Mirror Reflections

Heiko Hecht
Johannes Gutenberg-Universität Mainz and
Massachusetts Institute of Technology

Marco Bertamini
University of Liverpool

Matthias Gamer
Johannes Gutenberg-Universität Mainz

It is known that naive observers have striking misconceptions about mirror reflections. In 5 experiments, this article systematically extends the findings to graphic stimuli, to interactive visual tasks, and finally to tasks involving real mirrors. The results show that the perceptual knowledge of nonexpert adults is far superior to their conceptual knowledge. Whereas conceptual errors include the assumption of left–right reversals in mirror images and often blatant extensions of the boundary of mirror space, the perceptual context prevents most such errors. However, a consistent bias to misjudge objects in mirrors too far to the outside is demonstrable in all cases including tasks with real mirrors. The authors present a 2-stage hypothesis consisting of an implicit bias of judging the mirror surface to be turned toward the observer's line of sight followed by a normalization that becomes explicit.

Keywords: mirror reflection, naive physics, intuitive physics, optics

This article is the third in a series on "naive optics" (Bertamini, Spooner, & Hecht, 2003; Croucher, Bertamini, & Hecht, 2002). Naive optics is embedded in naive physics (for a definition and an overview, see Proffitt, 1999; Smith & Casati, 1994) and, specifically, explores naive beliefs and perceptions about geometrical optics and related phenomena. Of particular interest is Fermat's law of reflection and the implication this law has for reflections on planar specular surfaces. We have found that people have a naive understanding of how mirrors behave, which is at odds with Fermat's law, which posits the equivalence of incident and exit angles.[1] Our commonsense conceptual and—to a lesser extent—perceptual understanding of reflection is limited and biased (Bertamini, Latto, & Spooner, 2003; Bertamini, Spooner, & Hecht, 2003; Croucher et al., 2002). Note that we are not referring here to the knowledge of the law of reflection itself, which most participants possess, but knowledge of what is made visible by a mirror. This lack of understanding is particularly intriguing given the vast amount of experience human observers have with mirrors. The current study addresses the question of whether human observers' understanding of mirrors is equally poor in all perceptual situations or whether more realistic presentation and action may reveal deeper knowledge. We answered the question in four steps. First, we introduced different tasks and richer stimuli, thereby going beyond paper-and-pencil and photographic stimuli to interactive displays and eventually to images in real mirrors. Second, we placed the observers at different vantage points with respect to the mirror surface. Third, we compared monocular viewing to stereo images of mirror objects. And finally, we introduced an interactive task in which observers could match the orientation of the mirror with a given relationship between environment and mirror image.

With a few notable exceptions, empirical work on the comprehension of geometrical optics is scarce. The exceptions include Loveland (1986), who discussed the process of learning the mirror's affordances from an ecological point of view, and Winer and collaborators (e.g., Winer, Cottrell, Karefilaki, & Chronister, 1996; Winer, Cottrell, Karefilaki, & Gregg, 1996), who studied the extromission belief in children and adults. The first in the current series of articles on naive optics (Croucher et al., 2002) investigated naive beliefs about the location of mirror reflections using paper-and-pencil tasks. When we asked participants to report where a person moving parallel to the surface of a mirror would first see her or his mirror image, we found that participants consistently overestimated how much the mirror would reflect. For instance, when walking toward a mirror hanging on a wall (on a path parallel to mirror and wall) participants stopped too early, before they had reached the edge of the mirror. The same results were found when participants were presented with schematic drawings from a bird's eye view and asked to indicate at what observer position on a given path the mirror image should first appear. Strangely, this overestimation error was not made when

Heiko Hecht, Psychologisches Institut, Johannes Gutenberg-Universität Mainz, Mainz, Germany, and Man Vehicle Laboratory, Massachusetts Institute of Technology; Marco Bertamini, Department of Psychology, University of Liverpool, Liverpool, United Kingdom; Matthias Gamer, Psychologisches Institut, Johannes Gutenberg-Universität Mainz, Mainz, Germany.

We thank Ivan Petrakiev and Jane Wu for their superb programming assistance. Erin Alexander and Leah Kaplan helped collect data for Experiments 1 and 2. Cornelius Muelenz assisted with data collection, analysis, and discussion of Experiments 4 and 5. We are grateful to Alice Spooner and John Pittenger for their insightful comments on a draft of this article.

Correspondence concerning this article should be addressed to Heiko Hecht, Psychologisches Institut, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, D 55099, Mainz, Germany. E-mail: hecht@uni-mainz.de

---

[1] Strictly speaking, Fermat's law states light travels along the fastest line, and the law of reflection can be deduced from Fermat's law.

imagining a situation in which the person climbs up or down a rope (a finding later replicated when observers imagined being in a glass elevator). These orientation-contingent conceptual errors were best explained with a left–right reversal hypothesis, which states that observers mistakenly believe a mirror reverses left and right. In actuality, when facing a mirror, objects to the left in the world of the observer appear to the left in the mirror. However, according to the left–right reversal hypothesis, objects on the left in the world are expected on the right in the mirror. This translation is equivalent to a 180° rotation about the midvertical axis of the mirror or of the observer. If this axis of rotation were fixed relative to the gravitational up and down, or the observer's head, this would explain why the early error was not present for up-down movements.

The second article (Bertamini, Spooner, & Hecht, 2003) replicated the results and confirmed that many observers hold the mistaken belief that a mirror should reverse left and right, because objects on the left were predicted to appear on the right in the mirror. However, this is only true for conceptual tasks. By that we mean that when observers are presented with images of mirror reflections seen from the proper station point, they can detect that mirrors do not reverse left and right. In the long controversy surrounding the issue of why mirrors invert left–right but not top–bottom, we agree with Morris (1993) and Gregory (1998), who have argued that the would-be reversal is caused by a reference assumption of the beholder, not by the optics of the mirror (see also Corballis, 2000; Gardner, 1990; Haig, 1993; Hofstadter & Dennett, 1981; Ittelson, Mowafy, & Magid, 1991; Rimbot, 1976).

Bertamini, Spooner, and Hecht (2003) found a dissociation of conceptual and perceptual knowledge. When observers viewed manipulated scenes of rooms containing a mirror, left–right reversals were easily identified as unnatural. Thus, perceptual information about the scene was sufficient to recognize side reversals as unnatural. However, observers made quantitative errors and judged mirror images that contained more scenery than they should to be just as natural as canonical mirror images. We termed the implicit belief that the mirror contains more than it actually does the *boundary extension hypothesis*. The second article was not able to differentiate between boundary extension and an egocentric bias to misjudge the mirror surface as being tilted toward the observer's line of sight, termed the *egocentric mirror rotation hypothesis*. The reason for this lack of differentiation was the use of naturalness ratings as the only dependent measure in the perceptual experiments containing manipulated mirror images. A second reason may have been the exclusive use of pictorial stimuli. We discuss these theoretical implications at the end of the present article.

The systematic mistakes in predicting what is visible in a mirror are particularly interesting given (a) the large degree of familiarity that people have with planar mirrors; (b) the absence of any difficulty in appreciating the abstract principle of reflection (the equality of the two angles was already known to Euclid, c. 300 B.C.); and (c) the fact, recently documented by Higashiyama and Shimono (2004), that size and distance judgments for images in plane mirrors are fairly accurate.

The present article extends the assessment of visual understanding of mirror reflection to more involved perceptual tasks, to dynamic displays, and finally to the use of real mirrors. It also assesses performance with respect to different observer positions. The images used in previous studies were viewed from station points perpendicular to the mirror, prone to create magnification and minification effects (Lumsden, 1983). We determined whether there is a particular rift between naive conceptual and perceptual judgments of mirror reflections (Bertamini, Spooner, & Hecht, 2003) and to what extent implicit knowledge about laws of geometrical optics can be accessed when viewing conditions are more ecologically valid, such as in dynamic displays (e.g., Kaiser, Proffitt, Whelan, & Hecht, 1992). Finally, stationary images are inherently ambiguous, and size and distance relations are only specified when additional assumptions are made about the room's having rectangular shape, the regularity of the floor pattern, or the actual size (or distance) of the object. Thus, we set out to assess judgments of mirror reflections in renditions that were able to convey the information that is present in more ecological situations of mirror use. They were properly tailored to the position of the participant.

Experiment 1: Placing the Mirror Image in a Stationary Scene

Previously (Bertamini, Spooner, & Hecht, 2003; Croucher et al., 2002), we have presented observers with paper-and-pencil drawings that did not have a visually given viewpoint and with photograph-like images taken with an observer's line of sight roughly orthogonal to the mirror surface (head-on view). Here, a three-dimensional (3D) rendition of a large room was constructed such that the line of sight of the observer could be changed with respect to a large mirror hanging on the room's front wall. Specifically, the line of sight varied from orthogonal to the mirror surface (0°) to almost parallel (90°), as shown in Figure 1. An object propped up on a pole was always present in the room. For purposes of obtaining quantitative data on judged locations of mirror objects, participants were required to place the mirror image of a visible object in its correct location on the mirror surface. These changes in task and methodology allowed us to address the influence of line of sight in a systematic way.

Method

Observers. Seven Massachusetts Institute of Technology (MIT) students (3 women and 4 men) volunteered to participate in the experiment. They ranged in age from 19 to 30 years and had normal or corrected-to-normal vision.

Apparatus and stimuli. The stimuli were generated on a Silicon Graphics Indigo 2 Extreme workstation. The 20-in. (38 cm horizontal by 29 cm vertical) display screen had a resolution of 1280 × 1024 pixels and a refresh rate of 72 Hz (noninterlaced). The animation update rate was 36 frames per second. The observer was seated 31 cm away from the screen in a height-adjustable chair to align his or her line of sight with the center of the display screen; the display subtended 63° visual angle horizontally by 50° vertically.

We simulated a large empty room with a regularly textured floor. The room's front wall (15 m long) was decorated with a large (7.5 m horizontal × 2.8 m vertical) mirror vertically centered on the wall (see Figure 1). Side walls were partially visible; the rear wall was behind the observer. Ceiling height was 3 m. The observer's reference eye point (virtual camera 0°) was simulated to be 1.7 m above the ground and 1.75 m to the left of the horizontal midline of the mirror, with the observer's line of sight being perpendicular to the mirror plane. In this case the observer's mirror reflection was indicated by a schematic figure. The mirror subtended 18.4

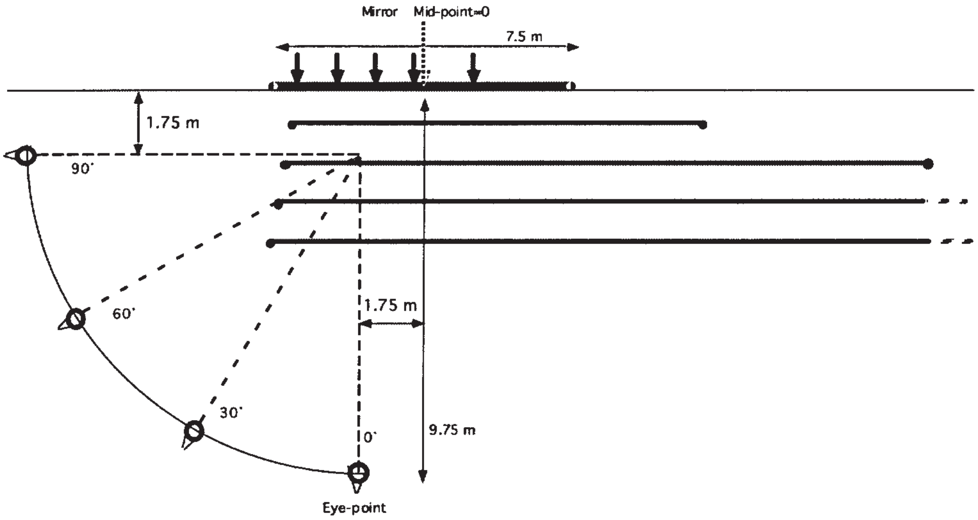


Figure 1. Top view of the stimulus space for Experiment 1. The thick solid line indicates the position of the mirror. The scene was simulated from the eye point of the observer at a normal standing eye height of 1.7 m. This eye point was rotated in a circle for different conditions. The lines with the black dots represent the range of locations of the visible sphere for the four distances from the mirror. Only one location was shown per trial. The mirror image was movable and had to be positioned by the participant. The black arrows on the mirror indicate the correct locations of the mirror images corresponding to the visible spheres. Note that to create the five mirror image positions with all spheres, the range of object locations in the room exceeds the boundaries of the figure (for 90° eye-point rotation and sphere distances from the mirror larger than 2 m).

cm horizontally on the display, which corresponded to a visual angle of 33°. Three additional observer positions (eye points) were used such that the simulated line of sight formed an angle with the mirror of 30°, 60°, or 90°. In these cases the horizontal subtense of the 7.5-m-wide mirror was 24°, 14°, and 5°, respectively.

Note that the observer was 1.75 m in front of the wall with the mirror when the camera angle was 90°. Thus, the eye point was rotated in a circle with a radius of 8 m and whose origin was displaced 1.75 m to the left and to the front of the mirror's midline. The simulated observer positions are shown in Figure 1. All stimuli were designed such that a sphere (radius = 0.25 m) was always visible in the world. It was propped up by a small pole at 1.7 m above the ground, which corresponded to about one standing eye height. Each trial showed one sphere in one of the locations, whose range is indicated by the connected black dots in Figure 1. The locations were chosen such as to create mirror images that fell in exactly five locations as indicated by the black arrows. These locations were mostly to the left of the midline of the mirror as necessitated by the constraint that there should always be solutions to the problem, that is, the correct mirror image should always fall inside the mirror. The correct mirror image locations were positioned at −3.25 m, −2.25 m, −1.25 m, −.25 m, and +1.25 m from the mirror's midline, where negative values indicate positions to the left. These positions were not evenly spaced at the center to prevent occlusion of the observer's mirror reflection (schematic) in the 0° eye-point conditions.

Design. Three factors were fully crossed in a within-subjects design. Eye point had four levels. The eye point was rotated around a point 1.75 m in front of the mirror ranging from perpendicular to the mirror (0°) and two intermediate positions (30° and 60°) to parallel to the mirror (90°). Sphere distance had four levels: The sphere could be positioned at 1, 2, 3, and 4 m in front of the mirror. Finally, lateral displacement of the sphere in the world created five unique lateral offsets of the corresponding correct mirror image from the mirror's midline.

Procedure. All 80 stimuli were viewed binocularly, presented in different random orders for each observer. Observers could inspect the room with the mirror and the sphere as long as they pleased. Then they were instructed to press the left or right arrow key to move a visible mirror image of the sphere, which had the appropriate smaller image size compared with the sphere in the world, to the correct position. The sphere in the mirror was constrained to move along the mirror surface at the correct height. If the observer placed the mirror image outside the range of the mirror, it would turn black such that its position could still be specified. This fact was pointed out to the participants. The mirror image started out at a random position on the screen, including off-mirror placements. Once the participant had placed the mirror image to his or her satisfaction, a keypress initiated the next trial. To familiarize the observer with the task, five practice trials were given before the experiment. Observers were instructed to take short breaks whenever they needed.

Results

The distance (error) between the response and the correct image position was recorded. Positive errors indicate that the response was too far outward. We conducted a repeated measures analysis of variance (ANOVA) on signed errors, with lateral offset (five levels), sphere distance (four levels) and eye point (four levels) as factors.

The analysis revealed a significant main effect of eye point, $F(3, 18) = 19.92$, $p < .001$. Errors increased significantly as the eye point became more oblique (see Table 1). That is, oblique views on the mirror increased the bias to displace mirror images outwardly from their actual location. The bias was, however, present even in the straight-on views (eye-point = 0°), $t(6) = 5.39$, $p = .002$. This is confirmed by regression coefficients for judged position against actual position of the mirror image. Coefficients ranged from 1.15 (0°), over 1.03 (30°), and 0.88 (60°), to 0.61 (90°). That is, the slope coefficients decrease as a function of eye-point eccentricity.

Table 1
Average Judgment Errors for Each Eye-Point Condition Expressed in Meters and in Degrees of Visual Angle

	Judgment error (m)		Judgment error (degrees)	
Eye point	*M*	*SD*	*M*	*SD*
0°	0.34	0.17	2.80	1.04
30°	1.23	0.48	6.51	2.95
60°	1.94	0.97	6.07	2.36
90°	3.93	1.93	3.59	1.07

Potentially, this error measure may have exaggerated small differences at oblique viewing points. However, when we considered placement errors in terms of visual angles between actual and correct image placement (origin at observer's eye point), the significant main effect of eye point persisted, $F(3, 18) = 9.31$, $p < .001$. Metric errors increased with obliqueness of eye point, whereas angular errors first increased but then decreased at the extreme eye point of 90° (see Table 1).

The correct location of the mirror image (lateral offset) had no influence on the judgments, $F(4, 24) < 1$. The analysis revealed also a significant main effect of distance of the visible object from the surface of the mirror, $F(3, 18) = 21.59$, $p < .001$: The farther the sphere was from the mirror, the larger was the position error away from the observer. This was also true for errors in visual angle, $F(3, 18) = 9.87$, $p < .001$. Note that to produce a mirror image with the same position as a sphere farther from the mirror, the object had to be placed farther away from the observer. Thus, absolute lateral sphere position interfered with the task.

There was a significant interaction between eye point and lateral offset, $F(12, 72) = 4.93$, $p < .001$. This is illustrated in Figure 2. Straight-on views (eye point = 0°) caused small errors across the board. Lateral offsets accentuated the eye-point effect for the more oblique eye points. The same effect was found when considering placement errors in terms of visual angles, $F(12, 72) = 6.29$, $p < .001$. The ANOVA also revealed a significant interaction between eye point and sphere distance, as illustrated in Figure 3, $F(9, 54) = 10.05$, $p < .001$. Whereas sphere distance did not affect performance in head-on views, oblique viewing angles caused errors to increase with sphere distance. This effect seemed to be mainly due to the use of distance errors as the dependent variable, and it disappeared when we considered angular errors instead, $F(9, 54) < 1$. There were no significant interactions between lateral offset and sphere distance and between lateral offset, sphere distance, and eye point.

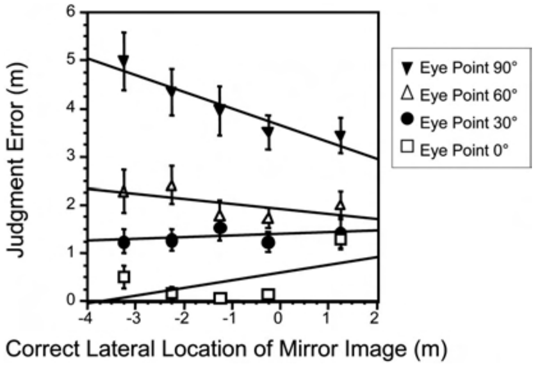


Figure 2. Experiment 1: Average errors made when positioning the mirror image plotted for each correct position in the mirror. Separate curves are plotted for each simulated eye point. Positive errors indicate an outward bias, that is, all mirror images were judged to be displaced outward from where they would naturally occur. The abscissa indicates lateral distance of the correct mirror image from the center line (0) of the mirror in meters. The horizontal subtense of the mirror ranged from −3.75 (left) to + 3.75 m (right). The solid lines represent linear regression lines for each eye-point condition. Error bars indicate standard errors of the mean.

Observers behaved similarly. Without exception, they showed a significant bias to place the mirror image too far to the outside. Average misplacements per observer ranged from 1.25 to 3.49 m. Also the size of the eye-point angle correlated perfectly with error magnitude for all but 1 observer. This person made slightly larger placement errors for 30° than for 60° while 0° was associated with his smallest and 90° with his largest error.

Discussion

We found a large effect of eye point on the ability to place the mirror image. Oblique viewing angles led to a shift of the image to the outside, that is, to the observer's right when the eye point was to the left of the mirror (outward bias). Something like a qualitative jump in bias can be detected: An eye point of 0° yielded small errors, maybe with the exception of the right-most target, whose mirror image was placed about 1.3 m to the right of its true location. The more oblique the eye point, the stronger this outward bias. Whereas for eye points up to and including 60° overestimation was almost constant, in the 90° condition the rightward displacement was stronger the more the true image should have been to the left of the mirror's midline. This could reflect a ceiling effect that was reached for 90° eye points. The average displacement toward the outside was more than half the width of the mirror for mirror images truly falling on the left side of the mirror. To avoid putting other mirror images outside the mirror (which hap-

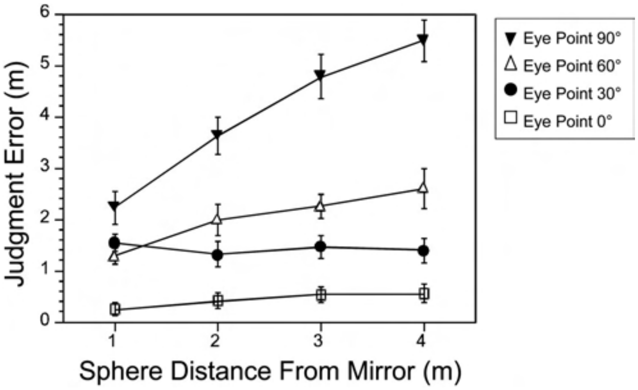


Figure 3. Experiment 1: Average errors made when positioning the mirror image plotted by distance of the visible sphere from the surface of the mirror. Positive errors indicate that mirror images were judged to be too far to the outside, as seen from the observer. Separate curves are plotted for each simulated eye point. The lines represent linear interpolations between the average values. Error bars indicate standard errors of the mean.

pened in one case: correct location 1.25 m away from the mirror's midline, top right data point in Figure 3), participants may have placed the mirror images more to the left than they might have had the mirror been larger. Nonetheless, the eye-point effect was robust: The outward bias increased continually in metric size with obliqueness of eye point, whereas in terms of visual angle, observers produced smaller errors at the 0° and the 90° position compared with the 30° and 60° positions.

The eye-point effect is possibly related to a general problem of the visual system with respect to imagining projective transformations (Pani, Jeffres, Shippey, & Schwartz, 1996) from oblique vantage points, but note that the bias was also significant in the head-on views. The outward bias that participants produced for oblique trials is compatible with results obtained by Croucher et al. (2002). In a paper-and-pencil task similar to the present 90° eye-point condition, participants marked the location where an object in front of and to the right of the midline of a mirror could first be seen by an observer who approached the mirror from the left. On average, observers were expected to see the object earlier than they actually could have. This corresponds to an outward displacement of the mirror object in the current task, where observer and object position in the world are given. However, unlike in paper-and-pencil conditions, our observers were rather accurate in the nonoblique trials. In addition, the large tolerance for misplacement of mirror images found in Bertamini, Spooner, and Hecht (2003) was not replicated. Errors were comparatively small but consistent. The interactive visual task seems to be responsible for the improved performance. MIT students may, also, be untypical in their physics training and in their ambition to figure out the correct solution. It is all the more surprising that they were not able to produce correct answers in the oblique trials.

Experiment 2A: Determining the Self-Reflection in a Head-On Moving Scene

Experiment 1 suggests that perceptual knowledge was activated by the graphic presentation of the stimulus. Is further activation possible? Dynamic information was not included in all previous displays. The observer's viewpoint remained stationary. If the activation of perceptual knowledge about mirrors depends on the observer's frame of reference, as is the case in some intuitive physics problems (see Kaiser et al., 1992), it might require a dynamic observation point to reveal such potential implicit knowledge not otherwise accessible. Experiments 2A and 2B investigated this possibility. The first focused on dynamic self-reflections, whereas the second investigated dynamic object reflection. Because most experience with mirrors is facing them frontally, and to compare the outcome to our previous studies, the observer in Experiments 2A and 2B was always simulated to translate on a line parallel to the mirror. The introduction of dynamic viewpoint information also allowed us to vary the plane of motion and thereby address a second unresolved issue: In a paper-and-pencil task that asked observers where they would first see themselves when moving horizontally or vertically along a wall with a mirror, Croucher et al. (2002) found that the bias to displace the mirror image disappeared with a vertical motion path, whereas for horizontal paths the point was judged sooner than would be the case. Asking for the same judgments within a dynamic visual scene should determine whether the horizontal–vertical anisotropy is universal or whether it was limited to conceptual tasks.

Method

Observers. Seven MIT graduate students (3 men and 4 women) volunteered for the study. They ranged in age from 18 to 26 years (average = 22.8 years). They were not informed about the purpose of the study until after the experiment. None of them had participated in earlier mirror experiments.

Apparatus, stimuli, and design. The display consisted of the 3D rendition of a room similar to a picture gallery. The walls were 3 m high with no ceiling. An indefinitely long wall was hung with photographs. The observer was simulated to look straight at the wall and to move parallel to it, thus maintaining a constant distance from the wall. Short side walls protruded from the main wall to form niches. A mirror was placed parallel to and 3 m in front of the long wall, which made the room look 3D. It consisted of a white 2 × 2 m board with a brown frame. It showed no reflections. A still frame of the room is shown in Figure 4. The observer's viewpoint started 6 m to the left of the mirror's center and was then translated to the right (or vice versa from right to left). In addition, the whole scene was rotated by 90° such that the viewpoint started 6 m below (or above) the mirror's center and was moved upward (or downward). The task was to press a button when a reflection of the observer should appear or disappear in the mirror. Sagittal distance from the mirror was either 4 or 8 m.

A computer with a 1000 MHz Pentium III processor and an NVIDIA G-force2 graphics card was used for the experiment. The displays were generated using a custom-made 3D graphics environment (Virtual Reality Utilities, which uses Python and OpenGL). A 20-in. (38 cm horizontal by 29 cm vertical) Sony Trinitron monitor presented the animation at a display rate of 72 Hz, a refresh rate of 72 Hz (noninterlaced), and a resolution of 1280 × 1024 pixels. The observer's line of sight was centered with respect to the monitor. Viewing distance was 40 cm, which created a horizontal visual angle of approximately 50° (and somewhat smaller in the vertical cases). Stimuli were viewed binocularly.

The design was fully crossed and consisted of the factors initial observer position (at −6 and +6 m lateral displacement from mirror center), distance from mirror (4 and 8 m), scene orientation (horizontal and vertical, in which the entire display was rotated by 90°), and eye height of the observer (sitting = 0.8 m, and standing = 1.6 m), resulting in a total of 16 trials. This block was presented once with the appearance task, to press a button when the observer would first see himself or herself in the mirror had it produced a mirror image, and once with the disappearance task, which consisted of pressing a button when the mirror image would disappear. To avoid long trials, the initial observer position was adjusted in the second block to be closer to the mirror. Within blocks, trials were presented in random order. Blocks were counterbalanced together with the two blocks from Experiment 2B.

Procedure. The observers sat comfortably in a chair in a darkened and quiet room, and their viewing distance was 40 cm. Their heads were not restrained, but they were asked not to move the chair during the experiment and not to lean forward. Observers had five practice trials, and more on request, to become familiar with the task and the controls. Observers were instructed to look at the scene as many times as they liked before making a judgment. They were told that the simulation corresponded to their being moved laterally either in a push chair or while standing, or to moving vertically in an elevator. The respective button should be pressed at exactly the moment of mirror image appearance or disappearance.

Results

The misconception that the observer's image should appear earlier than it does, which was so prominent in paper-and-pencil

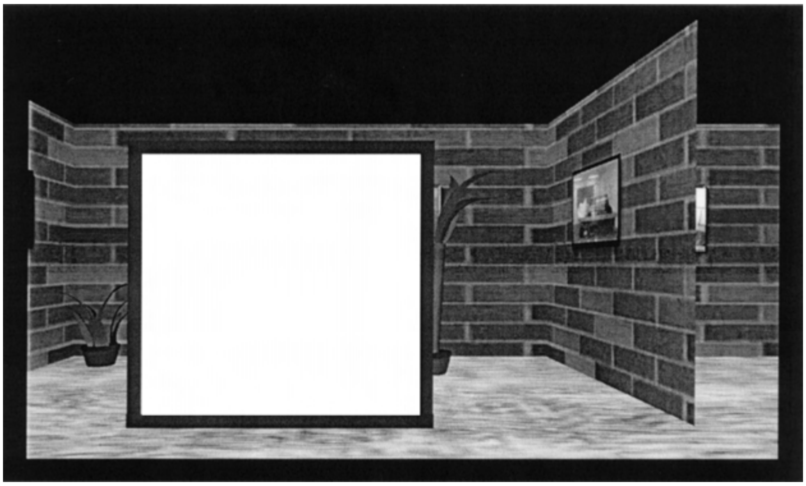


Figure 4. Still frame of the film sequence used in Experiment 2A. The observer's viewpoint was translating parallel to the mirror. The current frame was taken while the observer was simulated to move from right to left a little before reaching the edge of the mirror's frame.

tasks (Bertamini, Spooner, & Hecht, 2003), was minimal in the dynamic task. However, it was measurable. Because some of the students in the present experiment were well trained in formal physics, we first inspected individual performance, which yielded high variance. Participant 1 (no college physics or math classes) produced large errors of 2 to 4 m, indicating that the image was judged to appear too early and to remain too long. This error was approximately halved for vertical orientations. Participant 2 was accurate for horizontal trials and exhibited a small error (1 m) in vertical trials, in which the image was judged to appear a little too late and disappear too early. Participant 3 was accurate for horizontal trials and made small inconsistent errors (of about 0.5 m) in the vertical cases. Participant 4 was remarkably accurate with average errors within 0.25 m. Participant 5 exhibited early errors only in the appearance task, about 1.5 m horizontal and 0.7 m vertical. The same was the case for Participant 7 with somewhat smaller errors. Participant 6 only did the appearance task and showed early error of about 1 m in horizontal trials only. Participants 2 through 7 had taken several math and physics or engineering classes. Overall, appearance produced larger errors than disappearance, and horizontal produced larger error than vertical. The mean lateral position errors are presented in Figure 5. A negative error indicates early response. Note that most errors were in the same direction as those obtained before in conceptual or visual tasks. The mirror was judged to capture more than it actually does.

A five-factor repeated measures ANOVA, with task, distance, direction, scene orientation, and eye height as factors, was conducted on the lateral position errors (in meters). Participant 6 was excluded from the ANOVA because only one block was collected. The analysis revealed a significant main effect of task, $F(1, 5) = 7.93$, $p = .037$: The appearance task led to large early errors, whereas the disappearance task led to minimal errors. There were no other significant main effects or interactions: For scene orientation, vertical displays tended to produce somewhat smaller errors than horizontal observer motion, but not significantly so, $F(1, 5) = 3.52$, $p = .119$, and for distance, close observer positions tended to produce smaller errors than far positions, $F(1, 5) = 3.62$, $p = .099$. When we considered angular errors as a dependent variable, this tendency for distance disappeared, $F(1, 5) = 2.34$, $p = .19$. Direction (whether the motion started from the left or from the right) and eye height failed to produce any discernible effects. Analysis using *t* tests revealed that the errors, albeit small, differed significantly from perfect performance. Lateral position, $t(5) = 5.61$, $p < .001$, as well as errors expressed in angular deviation, $t(5) = 5.77$, $p < .001$, were significantly larger than 0. This means that observers indicated their mirror image would appear on average 0.4 m before they reached the edge of the mirror, which was equivalent to a mirror rotation toward them by 3.6°. Individual errors ranged from would-be mirror rotations of 7° toward the observer to 1° away from the observer. Six out of the 7 participants produced errors compatible with mirror rotations toward them.

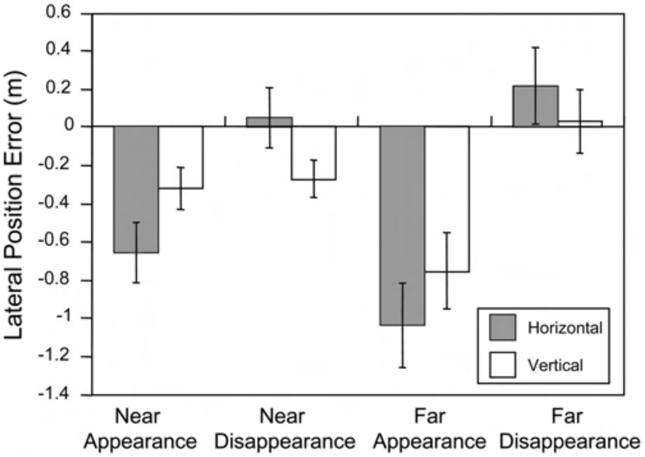


Figure 5. Average position errors obtained in Experiment 2A, including all participants. Negative errors indicate that the button was pressed too early. Error bars indicate standard error of the mean.

Discussion

Participants' responses were different from the paper-and-pencil performance in the equivalent task (Croucher et al., 2002). We found no evidence of left–right reversal, and the errors were smaller. When the judgments were expressed in terms of mirror rotations toward the observer, the average errors amounted to only about 3.6°, which is an order of magnitude smaller than obtained in paper-and-pencil tests. For example, when those errors were expressed in terms of mirror rotation, they averaged 34° in the "see yourself first" task (Bertamini, Spooner, & Hecht, 2003).

Thus, the visual simulation from the observer's station point decreased the size of the bias. However, the dynamic translation of the observer's viewpoint did not improve performance on top of the stationary graphic scene. Dynamic information was not able to make the bias disappear. Also, the superiority of vertical motion did not persist in the dynamic displays. The larger bias in horizontal conceptual tasks is likely to be an outcome of the imagery process observers engage in when confronted with schematic drawings, which is consistent with a recent suggestion by Jones, Bertamini, and Spooner (2004).

Experiment 2B: Determining the Object's Reflection in a Moving Scene

The experiment was structurally identical to Experiment 2A with the exception that the first appearance (or disappearance) of the mirror image position of an object and not of the observer had to be judged. Whereas the task in Experiment 2A had only one correct solution (the observer becomes visible when aligned with the edge of the mirror), judging the appearance (or disappearance) of an object in the mirror allows for a large range of correct positions. The object can be placed in numerous lateral positions in front of the mirror while remaining visible to the observer and, at the same time, yielding a mirror image that should also be visible. This range of object locations made the task harder. It was examined under the same conditions of a dynamic viewpoint translation. The object was close enough to the mirror to be visible throughout most of the observer's motion.

Method

Observers. The same 7 observers as in Experiment 2A participated. Three of them were administered Experiment 2B before Experiment 2A.

Apparatus, stimuli, and design. The scene was supplemented with a duck wearing a pointed hat, whose tip had to be treated as the reference point. The duck was confined to positions 1 m in front of the mirror. Lateral object position varied such that it produced lateral displacements of the duck from the respective edge of the mirror by 0.25, 0, and −0.25 m. Denoting the midline of the mirror (2 m wide) as the 0 point, lateral object positions were thus 1.25, 1, and 0.75 on either side. The other factors were direction (initial observer placement at −6 and +6 m lateral or vertical displacement from mirror center and subsequent translation to the opposite side), scene orientation (horizontal and vertical motion), task (see first vs. see last). In the appearance task, the object was placed near the same side of the mirror from which the observer started, and in the disappearance task, the object was placed at the opposite side of the mirror from which the observer started. Observers had to press a button when they thought they would see the duck first appear in the mirror or last see it before disappearance, respectively. This pairing of direction with task prevented correct observer positions of more than 1.5 m beyond the edge of the mirror. The design was fully crossed. Unlike in Experiment 2A, the observer's simulated distance from the mirror was constant at 6 m at one standing eye height of 1.6 m, or an equivalent displacement from the side wall (vertical floor) for vertical motion. The 24 unique stimuli were shown in two blocks, one containing appearance trials, the other containing disappearance trials.

Procedure. The procedure was identical to that of Experiment 2A, except that participants were required to indicate when they would first or last see the reflection of the duck rather than themselves.

Results

As in Experiment 2A, observers performed well on the task as presented in this experiment as compared with paper-and-pencil presentations of the task. However, they revealed a consistent bias. On average, the lateral error was 0.77 m on trials where the first appearance of the duck's mirror image had to be judged, which was equivalent to observers' pressing the key 1,538 ms too early. This error was significantly different from correct performance, $t(6) = 4.53$, $p < .001$. It corresponds to a mirror rotation toward the observer's line of sight by 4.05°. On the other hand, when the task was to indicate where the mirror image would disappear, judgments were late by 0.8 m (1,610 ms), $t(6) = 3.76$, $p < .001$. This corresponds to a mirror rotation also toward the observer of 4.2°. The values ranged from 3.3° of average error to 6.6°. Note the fact that the observer without formal college physics produced the largest mirror rotation values error of 6.6°.

A four-factor repeated measures ANOVA with initial observer position, scene orientation, task, and object placement as factors was conducted on lateral positioning errors. The analysis revealed a significant effect for object placement only, $F(2, 10) = 18.83$, $p < .001$. As shown in Figure 6, objects associated with solutions where the observer had to pass the edge of the mirror (duck position of 1.25 or −1.25) produced larger errors than objects associated with solutions before the observer passed the mirror's edge (duck positions of 0.75 and −0.75 m). Note that the lateral positions of 1 and −1 corresponded to the mirror's lateral edges. No other main effects, interactions, or trends were found. Note that in this ANOVA, other than in Figure 6, the errors were signed according to the rotation hypothesis, that is, the errors of early judgments in the appearance task and late judgments in the disappearance task were of the same sign and did not differ in magnitude.

Discussion

As before, the errors were small but consistent. As with the self-reflections, the mirror images of objects were also judged to be displaced in an outward direction. Observers misjudged their own location where they should start or stop seeing the mirror reflection of the object in the room that was also visible. The errors disappeared or even reversed when the object was on the outside positions, which may indicate a reluctance to delay the response or an unwillingness to accept that one's own image should appear in the mirror before the object.

These results, together with the results from Experiments 1 and 2A, paint a clear picture. The bias that can be found in conceptual tasks is reduced but not eliminated by visual simulations from the correct viewpoint. The addition of animation did not seem to provide information beyond that. The nature of the bias is such that mirror images are thought to appear before they actually do.

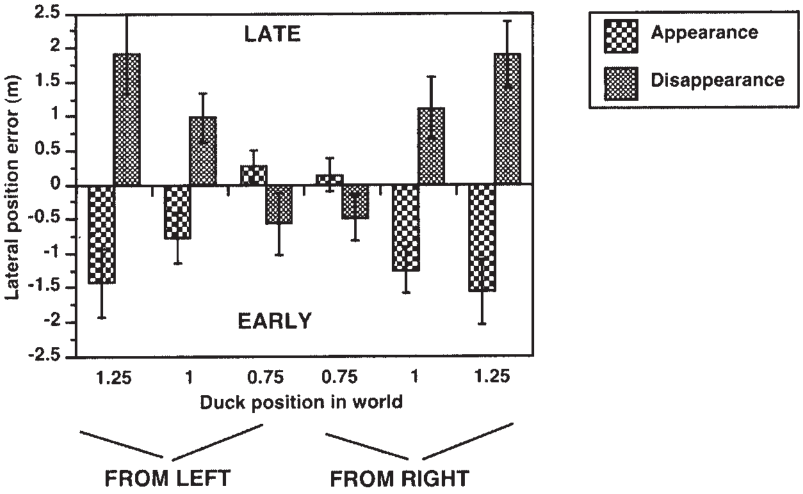


Figure 6. Experiment 2B: Average judged positions where the duck's mirror image should appear or disappear from view. In appearance trials this position was generally judged to be early—negative errors indicate that the button was pressed too early. Duck position is given in lateral distance from the midline of the mirror (in meters). The duck was always 1 m in front of mirror, the observer 6 m. Error bars indicate standard error of the mean.

Experiment 3: Judging the Naturalness of an Oblique Moving Scene

The failure of dynamic information to access implicit knowledge about mirror reflections above and beyond stationary and viewpoint-specific illustration may be due to the explicit nature of the task. Consequently, in Experiment 3 we replaced the explicit task with an implicit naturalness rating. In some cases, such as in the C-shaped tube task (Kaiser et al., 1992), naturalness judgments based on visual animation of the scenes previously depicted in paper-and-pencil tasks improved naive understanding of simple mechanics problems. Such visual knowledge that is not consciously accessible may also be present in our understanding of mirror reflections. We thus devised a task with animated scenes that refrained from asking directly about reflection angles and image positions. We hypothesized that if additional implicit knowledge about mirror reflection is activated in a dynamic scene at all, it should be detectable with this method.

As in Experiment 2B, dynamic scenes were presented. However, to produce scenes that varied in objective naturalness, objects rather than the observers were simulated to move in front of the mirror. The dynamics of the mirror reflection was manipulated in various impossible ways. The mirror image was shifted to the observer's left or right compared with the appropriate mirror image, or it covered a smaller or a larger range than adequate. Participants were asked to rate the naturalness of the event while watching the moving object as well as its moving mirror image.

Method

Observers. Seven MIT students (3 women and 4 men) volunteered to participate in the experiment. They ranged in age from 18 to 30 years and had normal or corrected-to-normal vision. Four observers had also participated in Experiment 1. For two of them, Experiment 3 was conducted first.

Apparatus, stimuli, and design. The same computer, visual scene, and viewing distance were used as in Experiment 1. The following changes were made to the design. Most important, the scene was animated, with the sphere moving from left to right parallel to the wall containing the mirror. The sphere always moved with a speed of 2 m/s. The path of the sphere was either 1 or 2 m from the wall (sphere distance), and the scene was viewed at 0°, 30° or 60° (eye point), where 0° is orthogonal to the mirror. A new factor, condition, was introduced, consisting of five different manipulations of the mirror image. First, the image could occur in its correct canonical. Second, the image could be shifted outward to the observer's right by 0.6 m. In eye-point angles larger than 0°, this would cause an outward displacement of the mirror image. That is, the sphere's image would—on its way to the observer's right—appear too late and disappear too late. The inverse was true for the sphere's moving to the left. Third, the sphere could be shifted to the left by −0.6 m. This resulted in the sphere's appearing and disappearing too soon on its way to the right, and too late when moving to the left. Fourth, a larger path than possible was compressed into the mirror (boundary extension). In this case, the sphere appeared too early and disappeared too late. Note that the reflected scene always maintained its canonical size. The compression factor was 20%. Finally, the mirror could present an image contracted by 20%, and dilated to fill the mirror (boundary contraction). In this case, the mirror image would appear too late and disappear too soon.

Procedure. The sphere entered the scene on the left side of the wall and moved parallel to the mirror. The mirror image was always rendered, albeit in wrong locations. The mirror image of the sphere was no longer represented when it fell outside the mirror. Once the sphere had reached the end of the room, it reversed direction and moved to the left. This back-and-forth motion continued until the observer had made a naturalness judgment using the mouse to pop up an appropriately labeled menu containing the scores from 0 to 9. The scale was labeled *naturalness*, the 0 score was labeled *impossible* and the 9 *natural* while 1 to 8 were not labeled. A key had to be pressed to advance to the next trial. To familiarize the observer with the task and to anchor the naturalness scale, we administered 15 practice trials to represent the full range of stimuli. Thirty trials were presented in different random orders for each observer.

Results

A repeated measures ANOVA, with sphere distance (two levels), condition (five levels), and eye point (three levels) as factors, was conducted on naturalness ratings for the scenes. The analysis revealed a significant main effect of condition, $F(4, 24) = 6.81$, $p < .001$, and nonsignificant main effects of eye point, $F(2, 12) = 0.28$, $p = .76$, and sphere distance, $F(1, 6) = 1.03$, $p = .348$. To explore the significant effect of condition, a series of contrasts were examined for the naturalness ratings produced in each condition. Boundary extension was judged to be just as natural as the canonical cases, and shifts to the right (or to the left) were judged less natural than both canonical, $F(1, 6) = 11.45$, $p = .015$, and boundary-extended renditions, $F(1, 6) = 12.11$, $p = .013$. Shifts to the left did not differ significantly from shifts to the right. The ANOVA revealed a significant interaction between condition and eye point, $F(8, 48) = 5.43$, $p < .001$; see Figure 7. In particular, more oblique eye points resulted in greater naturalness ratings when the mirror image was shifted to the right (outward), while they did not in other conditions, $F(1, 6) = 20.53$, $p < .004$. Especially with a 60° eye point, the right-shifted trials look almost as natural as the canonical ones. All other interactions were nonsignificant.

As to be expected from naturalness ratings, the variability between conditions and observers was rather large. Standard deviations were, on average, 2.8 units on the naturalness scale, and they were consistent across display condition and observers (range = 2.1 to 3.1). When we looked at the two conditions that received the highest naturalness ratings for each observer, one observer preferred boundary extension above canonical scenes (and both over everything else), and for one both were tied in first place. Three observers preferred canonical events over boundary extension ones (and both over everything else). For one observer boundary contraction and extension took places one and two, and for the remaining observer the order of naturalness was canonical first and contraction second. In other words, canonical and boundary extended events were judged as most natural by the majority of observers.

Discussion

For orthogonal mirror orientations, boundary extension mirror reflections looked slightly more natural than the canonical cases, but not significantly so. Boundary reduction was judged to be equally natural. The other cases of laterally shifted mirror images looked significantly less natural. In other words, compression and dilation of the mirror space appeared perfectly natural, whereas shifts of the mirror images were easily spotted as unnatural. These effects were somewhat smaller for oblique mirror orientations: An outward shift of the visible mirror image produced higher naturalness ratings the more the eye point was rotated out of the orthogonal position. An undue outward shift of the mirror image only caused a decline in naturalness for a 0° eye point. This interaction effect suggests that only when oblique to the mirror (eye point larger than 0°) does the image look better when it is placed too far to the outside, as seen from the observer. In other words, observers detected a shift of the mirror image as unnatural when the mirror is orthogonal but not when it is oblique. This corroborates the results of Experiments 1 and 2.

The Nature of Mirror Space

At this point, let us attempt to interpret the data by integrating the different mirror scenarios we have used. To do so, let us focus on the relationship between localization error and eye point of the observer. One can express errors in terms of misjudged observer position, misjudged mirror image position, or misjudged mirror orientation with respect to the observer. Thus far, we have chosen to express errors in the former two terms. Now let us focus on mirror orientation. This approach is illustrated in Figure 8. The top left panel shows the standard situation. The top right panel shows how the mirror image shifts to the right when the mirror is turned toward the observer's line of sight. In other words, if a mirror image has to be placed on the basis of a real-world object, and it is placed too far to the right, this is tantamount to misjudging the mirror to be rotated toward the observer. We call this the *egocentric mirror rotation hypothesis*. Obviously, this will not work if the mirror is already perpendicular to the line of sight, but in all other cases, it could be mistaken as rotated more toward the line of sight than it actually is. Note that for an observer to the left of the mirror's midline, the egocentric mirror rotation hypothesis would

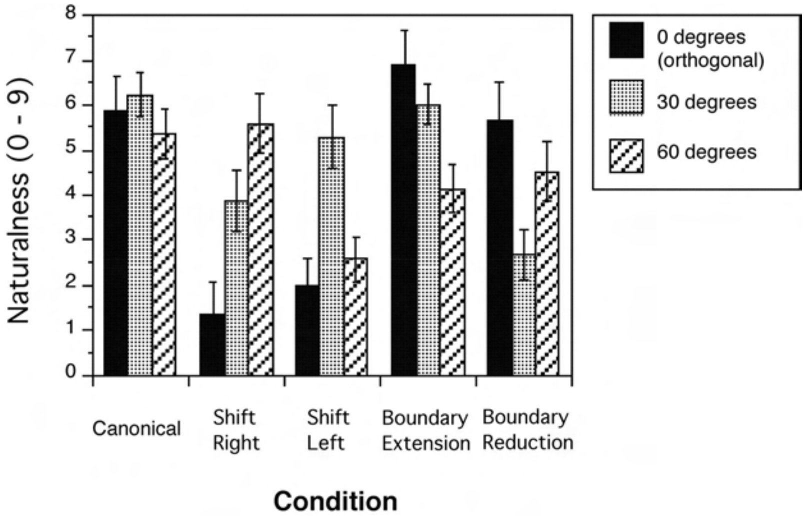
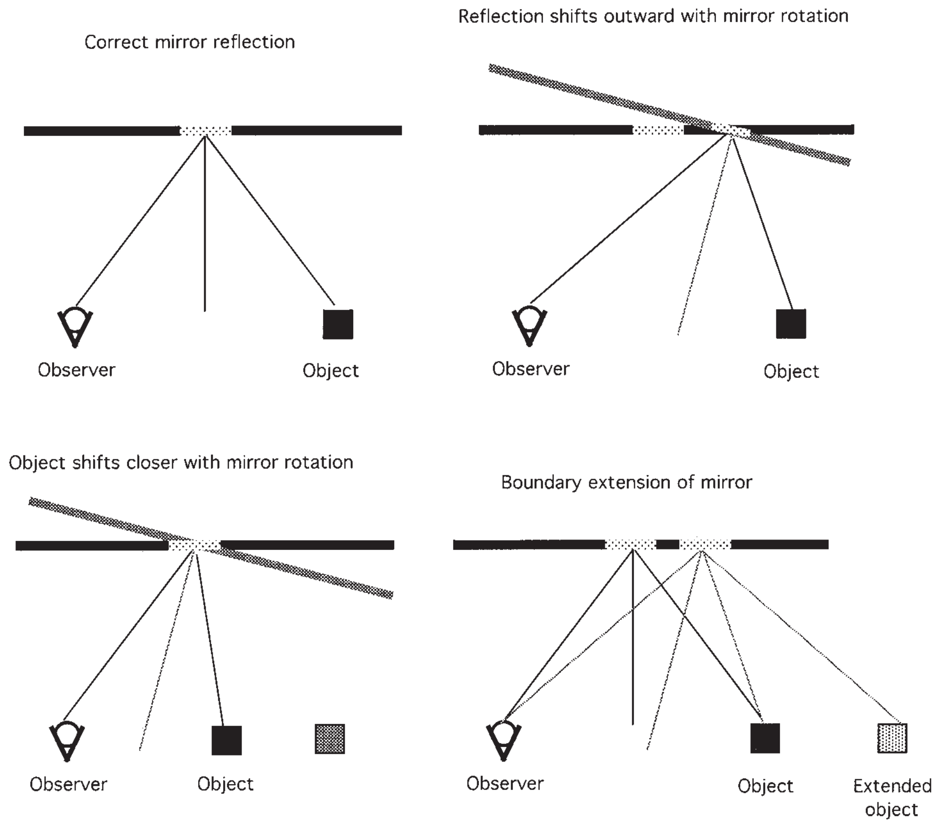


Figure 7. Experiment 3: Average naturalness ratings by eye point and condition. Error bars represent standard errors of the mean.



Correct mirror reflection

Reflection shifts outward with mirror rotation

Object shifts closer with mirror rotation

Boundary extension of mirror

Figure 8. Schematics of the predictions for correct performance, mirror rotation, and boundary extension. Top left: Mirror reflection according to Fermat's law. The thick solid line indicates the mirror in its actual orientation. The shaded area is the correct location of the mirror image of the cube as seen by the observer. Top right: The egocentric mirror rotation hypothesis: When the participant is asked to predict the location of the mirror image based on a visible object, the mirror image is shifted away from the observer toward his or her right. The gray line indicates the mirror rotated around the erroneous location of the mirror image such that Fermat's law is preserved. The mirror is rotated toward the observer. Bottom left: The converse situation. When the participant is asked to position the object while its mirror image is given, the egocentric mirror rotation hypothesis predicts that the object is displaced toward the participant. Again a mirror rotation toward the observer would preserve Fermat's law. Bottom right: Boundary extension hypothesis for the task to produce the mirror image based on a visible object. The world is extended such that the object is taken to be farther away from the observer (here gray object to the right). This explains a mirror image displacement away from the observer to his or her right.

predict that mirror images appear most natural when they are shifted outward. The more oblique the eye points, the stronger this bias should become. Note also that if the task is reversed and the object in the world has to be located on the basis of a mirror reflection, the egocentric mirror rotation hypothesis predicts that the object is placed too far to the inside toward the observer. This is illustrated in the bottom left panel of Figure 8.

Thus, the mirror rotation hypothesis makes clear predictions: For tasks in which mirror images have to be placed, these images should be expected to be shifted outward from their true location. This was found in Experiment 1. Also the displacement error should become larger with obliqueness of the eye point, but the would-be rotation of the mirror should remain constant. This seems to be the case when one looks at Figure 9. Here the results of Experiment 1 have been plotted in absolute placement errors of the mirror image as well as in corresponding degrees of egocentric mirror rotation. With the exception of a straight-on view (which does not allow for egocentric mirror rotation), the magnitude of the would-be mirror rotation is constant at around 4°. For tasks in which the observer marks a point when he or she first sees himself or herself in the mirror (or last sees himself or herself), the mirror rotation hypothesis predicts that this point should be marked before (or behind) the correct location. This was indeed found in Experiment 2. The mirror rotation hypothesis relates to the observer's line of sight and thus predicts that when the observer moves laterally in front of the mirror, opposite biases should be found depending on whether the observer is positioned to the right or to the left of the mirror's midline. This was indeed the case as shown by the bias's always being toward the outside.

While mirror rotation describes the results of the first two experiments, it is partially inconsistent with Experiment 3. Left- and right-shifted mirror images should have produced a significant difference. This difference may have been absorbed in the interaction between eye point and condition. Outwardly shifted mirror

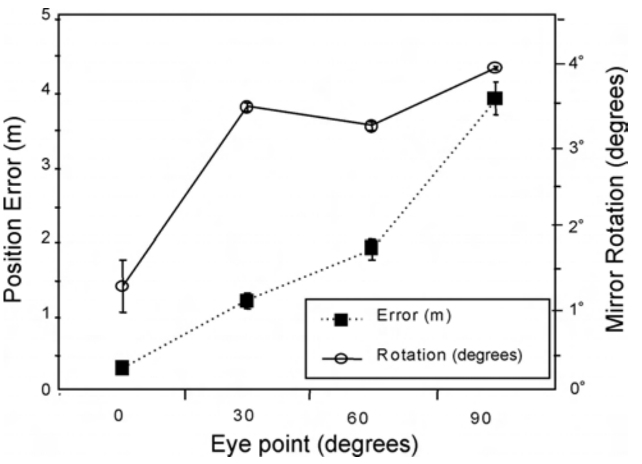


Figure 9. The results of Experiment 1 expressed in terms of mirror rotation: Average position errors (dotted line) were expressed in terms of misperceived mirror rotation (solid line) toward the observer's line of sight and around the vertical center of the mirror image. Note that these would-be mirror rotations are small and variable for head-on views (eye point = 0°) while remaining consistently around 3° to 4° for oblique eye points. Error bars indicate standard errors of the mean.

images looked increasingly natural with more oblique eye points (see Figure 7). However, outward shifts should have looked even more natural than canonical events, which was not the case even for the 60° eye point.

The discrepancies between the naturalness ratings and the positioning tasks used in Experiments 1 and 2 may be due to the ratings' ability to access different perceptual knowledge because of their intuitive nature. Or, the mirror rotation hypothesis could be wrong. Experiments 4 and 5 sought to explore the second possibility further. In Experiment 4, we assessed whether viewing objects in a real mirror would provide the necessary ecological information to make accurate judgments. Experiment 5 tested to what extent observers are able to explicitly produce the appropriate orientation of a mirror when looking at a given mirror image.

Are the results of all three experiments better understood in terms of a stretching or compression of the mirror space? This is akin to the picture perception effect introduced earlier as the boundary extension hypothesis by Intraub and colleagues (e.g., Intraub & Berkowits, 1996; Intraub & Richardson, 1989). Applying this effect to mirror images, the boundary extension hypothesis states that the mirror captures more of the world than it actually does, as if its boundaries were larger than they actually are. In Experiment 3, boundary extended scenes were judged natural, but strangely, boundary contraction fared equally well. The fact that observers failed to differentiate between extension and contraction speaks against the boundary extension hypothesis.

Experiment 4: Locating Objects Viewed Through a Real Mirror

Experiment 3 has revealed perceptual knowledge about mirror reflection beyond what was accessible with computerized placements tasks. Thus, it appeared necessary to replicate the persistent bias to place mirror objects too far to the outside within a maximally ecological setup. We designed a task that allowed full view of an object in an actual mirror. Then, the mirror was covered, the object was taken away, and observers were asked to recreate the object position in the world.

Method

Observers. Twelve students at the Johannes Gutenberg-Universität Mainz volunteered to participate in the study (6 women, 6 men, age range = 18–47 years). They had normal or corrected-to-normal vision.

Apparatus, stimuli, and design. A planar mirror (41 cm wide and 29 cm tall) was mounted in a vertical position. The observer was seated 34 cm in front of the mirror such that his or her line of sight was vertically at the center of the mirror (the chin rest was 109 cm above the ground) and laterally 4 cm to the right of the center. A small aluminum cylinder served as target (2.3 cm high, diameter = 1.5 cm). The target could be positioned at one of eight locations behind and to the side of the observer, as indicated in Figure 10. The object was placed in each position once for each of three mirror conditions. In one mirror condition, the mirror was viewed binocularly with the head supported by the chin rest. In a second mirror condition, the mirror was viewed monocularly with the head being supported by the same chin rest. The slight deviation of the interocular point in the binocular condition from the monocular viewpoint was accounted for when calculating the judged angles. In a third mirror condition, observers were allowed to move their head out of the chin rest once to the left (and back) and once to the right (and back) roughly covering one interocular distance. The room had a white ceiling and a uniformly blue floor. A part of the white wall was also visible.

Procedure. The three mirror conditions were administered in separate blocks in different counterbalanced orders for each participant. Within each block, the sequence of object locations was randomized among the eight positions. After a few practice tasks with different positions, the observer was given 5 s to observe the target cylinder via the mirror. Then the mirror was covered, and the object was removed (made invisible to the observer), who was then asked to take a laser pointer and point at the exact location behind him or her where the object in the world had previously stood when

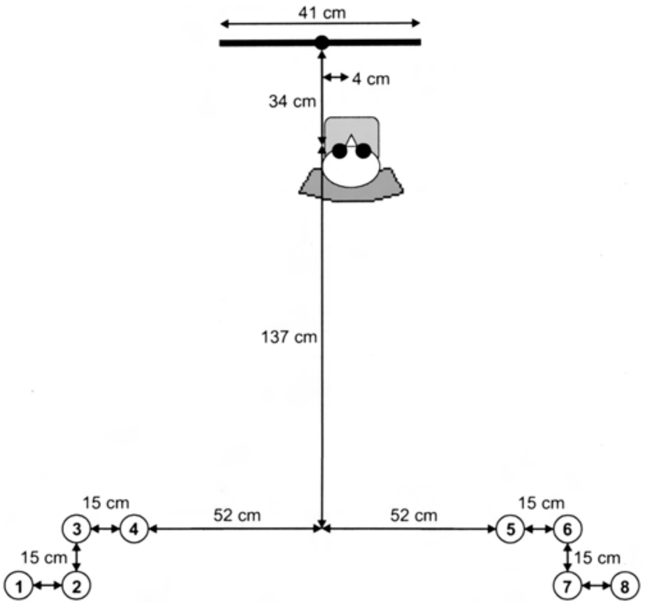


Figure 10. Schematic of the experimental setup used in Experiment 4. Eight target positions had to be reconstructed in the world, one at a time, on the basis of seeing the target object in the mirror.

viewed through the mirror. Observers were asked to avoid picking individual reference objects, such as scratch marks on the floor, but rather to get an overall impression for how the objects were located in the room. No time limit was imposed.

Placement errors in horizontal and vertical direction were computed for each mirror condition and side of presentation (left or right) separately by averaging the values of the four corresponding positions. In addition, the placement errors were computed as angles with respect to the position of the object in the mirror. The angular errors of the four positions on each side of the observer were averaged separately for each mirror condition.

Results

A repeated measures ANOVA with the factors mirror condition (three levels: monocular, stereo, and monocular moving), side (two levels: objects on the left or the right side behind the observer), and error direction (two levels: placements could deviate horizontally away from the observer or toward the observer, *x*; or vertically toward the mirror or away from it, *y*) was conducted on the placement errors. No significant main or interaction effects could be found, although the vertical placement errors seemed to be slightly lower in the stereo condition, $F(2, 22) = 2.94$, $p = .074$ (see Figure 11). However, the average of the placement errors in the horizontal ($M = 6.52$, $SD = 8.42$), $t(11) = 2.69$, $p = .021$, and the vertical direction ($M = 7.22$, $SD = 7.68$), $t(11) = 3.26$, $p = .008$, respectively, differed significantly from 0, thus indicating a systematic tendency to place the object too far to the outside and too close to the mirror.

The lateral placement errors can be expressed as angular errors as seen from the observer. The average of the angular errors across the factors mirror condition and side ranged from −1.12° to 5.74°, where positive values indicate angles away from the observer and vice versa ($M = 2.60°$, $SD = 2.36$). They differed significantly from 0, $t(11) = 3.81$, $p = .003$.

Discussion

Observers were somewhat more accurate than in the previous experiments. The magnitude of the error was slightly less than that obtained with the computer graphics displays. However, once more, we found a clear outward bias. In addition, unlike computer generated images, a 3D localization was possible. Objects were placed too far to the outside and too close to the observer. Such underestimation of distance from the observer was not found by Higashiyama and Shimono (2004). However, their task was rather different: Observers had to match the distance between themselves and the mirror image with the distance between themselves and another object in the world. Their task was self-referenced, whereas ours was world referenced. The above placement errors are partially compatible with the boundary extension hypothesis, but the boundary extension hypothesis makes no predictions about the *y* displacement from the observer. This displacement can be explained by the egocentric mirror rotation hypothesis with two qualifications. First, in past experiments the axis of the would-be mirror rotation did not matter. Here, it makes a difference whether

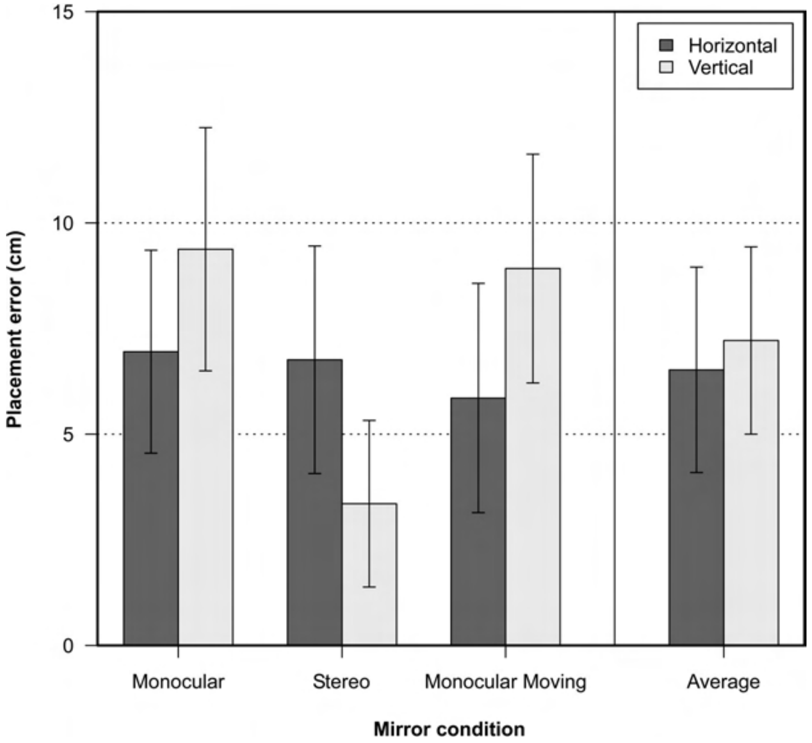


Figure 11. Experiment 4: Average horizontal and vertical placement errors as a function of mirror condition. Positive values in the horizontal direction indicate placement errors away from the observer; positive vertical errors indicate a displacement toward the mirror (and the observer). Error bars indicate standard errors of the mean.

the axis is assumed to be the center of the mirror or the center of the object's image in the mirror. In the former case, objects on the observer's left should be displaced outward whereas objects to the observer's right should be displaced inward. This was clearly not the case. In the latter case, the objects should always be displaced to the outside, which was in fact found. Thus, mirror rotation must mean a mistaken rotation of the mirror around the mirror object.

Second, one would have to assume a two-stage process in which a perceptual phase is followed by a reconstruction phase. During the perceptual phase, the surface of the mirror is being misperceived as rotated too far toward the observer's line of sight (the standard mirror rotation hypothesis). This rotation does not enter awareness and thus causes the mirror image to move to the outside (and closer toward the mirror) as seen (with awareness) by the observer. This is consistent with findings in tasks in which the observer has to locate the mirror image (e.g., Experiment 1). During the second stage, the reconstruction phase, the observer reconstructs the world object on the basis of the remembered and outwardly displaced mirror image. On the basis of this image, the world is constructed as likewise displaced outward (and too close to the mirror). Note that with a fixed planar mirror, images that are farther outside have to correspond to objects that are located farther to the outside.

We grant that this two-stage refinement of the mirror rotation hypothesis is done ex post and obviously requires further testing. In addition, no observer spontaneously reported the mirror to have been oblique or rotated when asked after the experiment. Thus, we devised a final experiment to directly measure judged mirror rotation.

Experiment 5: Adjusting the Rotation of the Mirror

If the mirror rotation hypothesis is true, then a consistent error should be found when observers have to orient the mirror to match a given mirror image. This was tested with an adjustable mirror. A displacement of the mirror image to the outside when one is asked to locate a would-be mirror image is consistent with an egocentric mirror rotation toward the observer. Conversely, when the mirror has to be adjusted on the basis of a given mirror image, we would expect a bias to rotate the mirror too far away from the observer's line of sight and toward the real-world object. This could be thought of as a compensation or a subtraction of the egocentric mirror rotation bias that becomes necessary when the task is changed from positioning the mirror image to rotating the mirror (without affecting the mirror image).

Method

Observers. Ten students at the Johannes Gutenberg-Universität Mainz volunteered to participate in the study (4 women, 6 men, age range = 22–29 years). They had normal or corrected-to-normal vision.

Apparatus, stimuli, and design. A scene with a bottle standing on a blue irregularly patterned floor and against the background of a white wall was created. The scene was photographed through a planar mirror using different mirror rotations. A rotation angle of 0° was assigned to the point where the bottle appeared in the middle of the mirror. Other photos were taken at mirror rotations −6°, −4°, −2° (counterclockwise), 2°, 4°, and 6° (clockwise) with respect to the 0° position. The camera was positioned at the interocular point of an observer as designated by a chin rest to be 120 cm above the ground. The resulting pictures were cropped and copied onto a set of transparencies.

The center of the adjustable mirror (vertical rotation axis) was located 59 cm to the right and 105 cm in front of the camera. The size of the mirror was 41 × 29 cm, its center was 76 cm above the ground. The mirror could be rotated 26° clockwise or counterclockwise away from the 0° position. Between the eye point and the mirror, with its center aligned, was a glass plate that could support a clear transparency on which the respective mirror images were printed. The glass plate was perpendicular to the line of sight and 97 cm in front of the observer. As a means of facilitating seeing the image on the transparency as being located in the mirror plane (the mirror was now covered with white paper), the bottom edge of the glass plate was occluded by a board attached to the chin rest. The object (bottle) that was depicted on all transparencies was also physically present in its proper location on the floor, 125 cm to the observer's right and 62 cm behind him or her.

Procedure. In each trial, the observers were asked to close their eyes; the experimenter placed a transparency in front of the mirror and rotated the mirror to a random starting position of −12°, 0°, or 12°. After opening their eyes, the observers were asked to spread their attention and to attempt to see the image on the surface of the mirror. They then judged the mirror's proper orientation as to be compatible with the mirror image and the object that was visible to their right. Observers were allowed to inspect the stimulus as long as they liked and to ask the experimenter to change the mirror's orientation until the mirror image appeared to be in the proper location.

All transparencies were presented twice to each observer in different random orders. In sum, every observer was asked to adjust the mirror rotation in 14 trials. The values were then averaged across repetitions.

Results

Observers were able to produce the accurate mirror rotation. A repeated measures ANOVA with the factor correct mirror rotation (seven levels) was conducted on the mean mirror rotation produced by the observers. A significant main effect of the correct mirror rotation on the produced values was obtained, $F(6, 54) = 7.96$, $p < .001$. As can be seen in Figure 12, the produced mirror rotation closely corresponded to the correct rotation. The average estimation error (i.e., the difference between the produced and the correct mirror rotation) across all trials showed a trend in the hypothesized direction ($M = -1.59$, $SD = 6.24$) but did not differ significantly from 0, $t(9) = 0.80$, $p = .442$.

Discussion

Observers were remarkably accurate in determining the orientation of the mirror to match object and mirror image. A tendency in the hypothesized direction (mirror orientations outwardly away from the observer's line of sight) was far from reaching significance. This lends some credibility to the two-stage mirror rotation hypothesis but by no means proves it. The two-stage process of first misperceiving the mirror to be rotated too far toward the observer, which then becomes basis for the reconstruction of the object's position in the world, awaits further testing.

General Discussion

In Experiment 1, observers had to place an object's mirror image into a blank mirror. The ability to do so in a static visual scene showed performance much superior to cognitive productions as elicited by paper-and-pencil tasks. However, a clear bias to locate the mirror image too far to the outside (outward bias), away

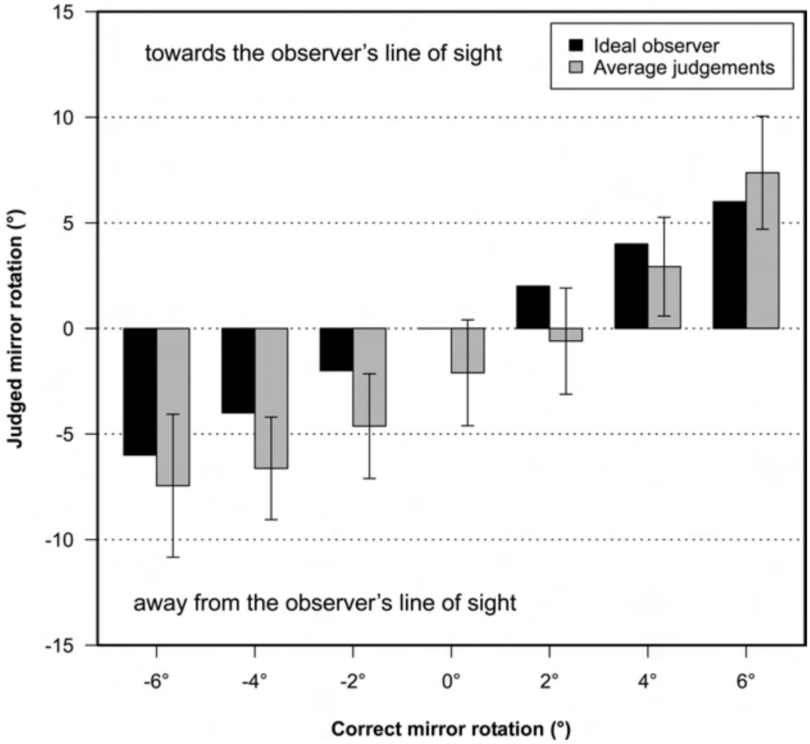


Figure 12. Experiment 5: Mean adjusted mirror rotation as a function of the correct values represented by the different transparencies. Error bars indicate standard errors of the mean.

from the observer, remained present. This bias grew with the obliqueness of the view. In Experiment 2, motion was introduced. The motion information could be exploited equally well; it failed to significantly further reduce the outward bias both for observer-related (Experiment 2A) and object-referenced mirror images (Experiment 2B). Experiment 3 attempted to tap into implicit knowledge about mirror reflection by soliciting naturalness judgments of dynamic scenes that contained impossible reflections. Observers were tolerant of compressions and expansions of the entire mirror space; they also judged shifts to the outside to be rather natural. In other words, their implicit knowledge is consistent with their explicit ability to locate the mirror image and to indicate their position in space where a mirror image should surface. In other words, the outward bias is consistent for all graphic presentations. Experiments 4 and 5 introduced real mirrors to rule out the possibility that the outward bias is an artifact of picture viewing. This could indeed be ruled out. The outward bias persisted with real mirrors, albeit with reduced magnitude. In addition, a bias to perceive mirror objects as too close to the observer was found.

Qualitative Effects of Visualization but Only Quantitative Effects of Added Realism

Conceptual errors when judging where a mirror image should appear to an observer are not, or are only partially, replicated in visual contexts. Perceptual knowledge was superior to conceptual knowledge assessed in paper-and-pencil tasks of analogous situations (Bertamini, Spooner, & Hecht, 2003; Croucher et al., 2002). The presence of a visual rendition of the room and the mirror facilitated performance dramatically in comparison to conceptual judgments on the basis of schematic drawings. Pointing; placing of mirror images; and, to a lesser degree, naturalness ratings yielded consistent results. Dynamic translation of the observers' viewpoint added little advantage over mere visualization. There was no evidence for left–right reversals or large mislocalization of mirror images on the order of 30° or 40°. Rather, errors were consistent and comparatively small. The consistent mislocalization of mirror images corresponded to angular errors of about 4°. The mirror image was consistently placed too far to the outside. The use of a real mirror in combination with a real-world positioning task produced a qualitatively identical outward bias of smaller magnitude as did two-dimensional (2D) visualizations. Real mirrors also revealed that the outward bias is supplemented by a bias to locate mirror objects closer to the observer than they are.

Was the visualization advantage mediated by the provision of a defined eye point? Yes, the superiority of graphic presentation was particularly strong for head-on views of the mirror. The more oblique the observer position with respect to the mirror surface, the stronger the outward bias.

Raising the viewpoint, on the other hand, or moving it closer to the mirror had no significant effects. Only the angle of the line of sight with respect to the mirror influenced accuracy in stationary scenes. Thus, the main function of visualization seems to lie in defining the lateral observer position. This interpretation is in keeping with studies that show orthogonal views to be much easier to judge than oblique views (see, e.g., Kerzel & Hecht, 1997; Siddiqi, Kimia, Tannenbaum, & Zucker, 2001).

The Superiority of Vertical Scenes

Vertical arrangements of otherwise identical scenes were judged more accurately than horizontal arrangements. This effect was found in paper-and-pencil tasks as well as in visual animation. This consistent effect may have the same root as our greater facility with vertical symmetry. That is, left–right mappings are more salient to the eye than other types of symmetry (e.g., Wagemans, 1995). The greater confusability of left–right as opposed to up-down for symmetrical objects or reflections has even been found in pigeons (Todrin & Blough, 1983).

It is curious that errors are smaller for highly unusual orientations, such as when climbing down a rope or standing the image on edge. This suggests that our familiarity with mirrors we encounter when moving on horizontal terrain exacerbates egocentric mirror rotation. However, this difference was particularly clear when no visualization was available, so that perceptual knowledge could not be assessed. Consequently, the relative difficulty with the left–right axis as opposed to the up-down axis may be related to similar findings where people had to conceptualize or reason from a map about spatial locations (e.g., Bryant & Tversky, 1999; Bryant & Wright, 1999; Rodrigo & de Vega, 1995).

The Egocentric Mirror Rotation Hypothesis

Bertamini, Spooner, and Hecht (2003) proposed four partially conflicting hypotheses, each of which is compatible with some salient conceptual error about mirror reflection. First, the capture hypothesis posits that everything directly in front of the mirror will be reflected in it, regardless of the observer's standpoint. Although the capture hypothesis fits some conceptual data, it is clearly falsified for the perceptual tasks used here. Second, the left–right-reversal hypothesis states that observers expect objects to exchange their positions in the mirror scene as if somehow reflected or turned around a vertical axis. The current experiments do not support such left–right reversal. Third, boundary extension is the hypothesis that planar mirrors contain more scenery than they actually can, as if the scene were compressed into a smaller space in the mirror. Boundary extension is often compatible with the outward displacement errors that we found in all graphic and real-world tasks. However, Experiment 3 directly presented boundary extended and boundary reduced mirror scenes and found that both look equally natural. Moreover, boundary extension cannot explain the bias to perceive mirror objects closer to the observer. Finally, fourth, the egocentric mirror rotation hypothesis as formulated by Bertamini, Spooner, and Hecht (2003) also cannot explain all results. The hypothesis states that observers misjudge the mirror to be rotated toward their line of sight, which typically causes the mirror image to migrate outward. However, observers perceive the orientation of the mirror correctly and are even capable of producing the correct mirror inclination in a real-world scene as Experiment 5 has shown.

We suggest a modified version of the mirror rotation hypothesis, which is able to accommodate all results. It assumes a two-stage process. The first stage is an implicit perceptual "judgment": The surface of the mirror is mistaken to be rotated toward the observer's line of sight. This rotation becomes more pronounced when the context is less realistic and graphic (standard mirror rotation hypothesis). The second stage reconstructs the mirror image based on this erroneous mirror orientation, causing the mirror image to move to the outside. For a 3D scene, it also causes the mirrored position to move closer toward the mirror as seen by the observer. The explicit experience of the mirror orientation is unrelated to this process. Although the two-stage mirror rotation hypothesis may appear less parsimonious, it offers three distinct advantages above and beyond its ability to explain more of the data. First, it is ecological in the sense that experiential information about the mirror's rotation is certainly irrelevant to gauge actions based on objects seen in mirrors. Second, it is the only candidate that can explain both the 2D and the 3D positioning errors that observers have produced. Finally, the peculiar hybrid nature of mirror images that falls somewhere between 2D pictures and 3D scenes renders it plausible that they may be susceptible to the so-called picture rotation effect, that is, objects or people in paintings appear to maintain their orientation with respect to the observer regardless of their station point. For instance, the eyes of a portrait appear to follow the observer (Halloran, 1993; von Kues, 1453/1967). In other words, pictures appear as if they were rotated to be perpendicular to the observer's line of sight. Mirrors suffer from the same normalization, albeit to a lesser degree. And just as observers realize that the painting is not physically rotated, they realize the mirror is not physically rotated. We attempt to capture these two layers (would-be rotation of the scene vs. physical nonrotation of the canvas or mirror) with the two-stage mirror rotation hypothesis. Mirrors and pictures are the only cases where a surface is visually specified while at the same time and in the same location a (3D) scene is also specified. This duality (e.g., Kennedy & Ostry, 1976; Pirenne, 1970) is easily noticeable in pictures because the rendered surface world is so different from the contextual world of the observer. Mirrors, on the other hand, duplicate a part of this contextual world. This may be the reason why the errors obtained with real mirrors are considerably smaller than the picture rotation effect (e.g., Goldstein, 1991). Obviously, this is speculative, and the two-stage mirror rotation hypothesis requires further direct testing.

References

Bertamini, M., Latto, R., & Spooner, A. (2003). The Venus effect: People's understanding of mirror reflections in paintings. *Perception, 32,* 593–599.

Bertamini, M., Spooner, A., & Hecht, H. (2003). Naive optics: Predicting and perceiving reflections in mirrors. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 982–1002.

Bryant, D. J., & Tversky, B. (1999). Mental representations of perspective and spatial relations from diagrams and models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25,* 137–156.

Bryant, D. J., & Wright, W. G. (1999). How body asymmetries determine accessibility in spatial frameworks. *The Quarterly Journal of Experimental Psychology, 52A,* 487–508.

Corballis, M. C. (2000). Much ado about mirrors. *Psychonomic Bulletin and Review, 7,* 163–169.

Croucher, C. J., Bertamini, M., & Hecht, H. (2002). Naive optics: Understanding the geometry of mirror reflections. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 546–562.

Gardner, M. (1990). *The new ambidextrous universe: Symmetry and asymmetry from mirror reflections to superstrings.* New York: Freeman.

Goldstein, E. B. (1991). Perceived orientation, spatial layout and the geometry of pictures. In S. R. Ellis, M. K. Kaiser, & A. C. Grunwald

(Eds.), *Pictorial communication in virtual and real environments* (pp. 480–485). London: Taylor & Francis.

Gregory, R. L. (1998). *Mirrors in mind.* London: Penguin.

Haig, N. D. (1993). Reflections on inversion and reversion. *Perception, 22,* 863–868.

Halloran, T. O. (1993). The frame turns also: Factors in differential rotation in pictures. *Perception & Psychophysics, 54,* 496–508.

Higashiyama, A., & Shimono, K. (2004). Mirror vision: Perceived size and perceived distance of virtual images. *Perception & Psychophysics, 66,* 679–691.

Hofstadter, D. R., & Dennett, D. C. (1981). *The mind's I: Fantasies and reflections on self and soul.* New York: Basic Books.

Intraub, H., & Berkowits, D. (1996). Beyond the edges of a picture. *American Journal of Psychology, 109,* 581–598.

Intraub, H., & Richardson, M. (1989). Wide-angle memories of close-up scenes. *Journal of Experimental Psychology: Learning Memory, and Cognition, 15,* 179–187.

Ittelson, W. H., Mowafy, L., & Magid, D. (1991). The perception of mirror-reflected objects. *Perception, 20,* 567–584.

Jones, L., Bertamini, M., & Spooner, A. (2004). *The eyes have it: Naive beliefs about reflections.* Manuscript submitted for publication.

Kaiser, M. K., Proffitt, D. R., Whelan, S., & Hecht, H. (1992). Influence of animation on dynamical judgments. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 669–689.

Kennedy, J. M., & Ostry, D. J. (1976). Approaches to picture perception: Perceptual experience and ecological optics. *Canadian Journal of Psychology, 30,* 90–98.

Kerzel, D., & Hecht, H. (1997). Grenzen der perzeptuellen Robustheit bei perspektivischer Verzerrung [The limits of perceptual robustness in perspective distortion]. *Zeitschrift für Experimentelle Psychologie, 44,* 394–430.

Loveland, K. A. (1986). Discovering the affordances of a reflective surface. *Developmental Review, 6,* 1–24.

Lumsden, E. A. (1983). Perception of radial distance as a function of magnification and truncation of depicted spatial layout. *Perception & Psychophysics, 33,* 177–182.

Morris, R. C. (1993). Mirror image reversal: Is what we see what we present? *Perception, 22,* 869–876.

Pani, J. R., Jeffres, J. A., Shippey, G. T., & Schwartz, K. J. (1996). Imagining projective transformations: Aligned orientations in spatial organization. *Cognitive Psychology, 31,* 125–167.

Pirenne, M. H. (1970). *Optics, painting, and photography.* Cambridge, England: Cambridge University Press.

Proffitt, D. R. (1999). Naive physics. In R. A. Wilson & F. C. Keil (Eds.), *The MIT encyclopedia of the cognitive sciences* (pp. 577–579). Cambridge, MA: MIT Press.

Rimbot, B. (1976). A mirror for reflection. *Annales Medico Psychologiques, 2,* 371–407.

Rodrigo, M. J., & de Vega, M. (1995). The use of direction terms in Spanish: A study on referential semantics. *Scientific Contributions to General Psychology, 13,* 49–64.

Siddiqi, K., Kimia, B. B., Tannenbaum, A., & Zucker, S. W. (2001). On the psychophysics of the shape triangle. *Vision Research, 41,* 1153–1178.

Smith, B., & Casati, R. (1994). Naive physics. *Philosophical Psychology, 7,* 227–247.

Todrin, D. C., & Blough, D. S. (1983). The discrimination of mirror-image forms by pigeons. *Perception & Psychophysics, 34,* 397–402.

von Kues, N. (1967). De visione dei [About God's vision]. In N. von Kues, *Philosophische Schriften* (pp. 93–219). Vienna, Austria: Herder. (Original work published 1453)

Wagemans, J. (1995). Detection of visual symmetries. *Spatial Vision, 9,* 9–32.

Winer, G. A., Cottrell, J. E., Karefilaki, K. D., & Chronister, M. (1996). Conditions affecting beliefs about visual perception among children and adults. *Journal of Experimental Child Psychology, 61,* 93–115.

Winer, G. A., Cottrell, J. E., Karefilaki, K. D., & Gregg, V. R. (1996). Images, words, and questions: Variables that influence beliefs about vision in children and adults. *Journal of Experimental Child Psychology, 63,* 499–525.

Received January 24, 2003
Revision received November 9, 2004
Accepted March 29, 2005 ■