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Naive Optics: Predicting and Perceiving Reflections in Mirrors

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Undergraduate students predicted what would be made visible by a planar mirror. A paper-and-pencil task confirmed previous findings that when approaching a mirror from the side, participants expected to see their reflection in the mirror earlier than they actually would. This early response was found for all mirrors when the observer moved horizontally—even when the mirror was placed on the floor or the ceiling—but not when the observer moved vertically (in a lift). The data support the hypothesis that many people imagine the world in the mirror as rotated around the vertical axis. When participants had to judge manipulated mirror reflections according to their naturalness, a high degree of tolerance was found. In contrast to the prediction task, a rotation around the vertical axis was judged to be less natural than other distortions. The authors conclude that perceptual knowledge and predictive knowledge lead to different patterns of errors.

Naive physics (as defined by Proffitt, 1999; Smith & Casati, 1994) studies the commonsense beliefs that people hold about the way the world works (see also McCloskey, 1983, who calls it "intuitive physics"). Most of the naive physics literature has dealt with beliefs about classical mechanics (e.g., Hecht & Bertamini, 2000; McCloskey, Washburn, & Felch, 1983; Pittenger & Runeson, 1990), but there are some findings that relate to optics. For example, Cottrell and Winer (1994; Winer & Cottrell, 1996; Winer, Cottrell, Karefilaki, & Chronister, 1996) have studied the extramission belief in children and adults (the belief that sight arises from light emitting from the eyes). More recently, Croucher, Bertamini, and Hecht (2002) systematically studied knowledge of what should be reflected in a mirror. Two types of question were used—a paper-and-pencil task involving a diagram of a room and a mirror and a task in which people were asked to position themselves in a room so as to make their image appear in (or disappear from) a mirror. Because the mirror in this second task was covered in brown paper, participants had to rely on their knowledge of mirror reflections.[1] Striking misconceptions about mirror reflections were found when participants were confronted with schematic scenarios. However, participants know about the law of reflection, or more precisely the equality of incident and exiting angles. The current article replicates and extends these findings with schematic scenarios. In addition, we investigated perceptual judgments of scenes containing a mirror and found perceptual knowledge to differ from the explicit knowledge demonstrated in the paper-and-pencil tasks.

Croucher et al. (2002) found that many participants made significant errors when asked to indicate where an observer would be able to see a target in a mirror. For example, the correct answer in Figure 1A was that the cat would have to be level with the near edge of the mirror before the observer could see it. However, participants predicted that the observer would see the cat's reflection when it was still some distance to the side of the mirror. Croucher et al. found that this error extended to predictions regarding when the observer would become visible to herself in a mirror as she walked into a room. The error was present whether the target (i.e., the cat) was imagined to be stationary while the observer moved or vice versa. This type of error was found with undergraduate students, whether they were registered for a psychology or for a physics degree.

This consistent error (henceforth referred to as the *early error*) remained when participants were asked to position themselves so that they could just see their own reflection in a pretend (nonreflective) mirror. In summary, participants tended to believe that they would see themselves in mirrors before they actually would

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[1] Mirrors have been the focus of research and debate in psychology for a long time. Probably the most famous example is the argument over why mirrors invert a person's image left–right but not top–bottom (Gardner, 1967; Gregory, 1997). Another use of mirrors has been in testing whether individuals recognize themselves in the mirror, therefore demonstrating a sense of self-identity. Children show this ability at around 2 years of age, whereas most animals fail the test, with the exception of some of the great apes (Amsterdam, 1971; Gallup, 1977; Povinelli, 2000). However, this article is concerned with a more basic aspect of understanding mirror reflections: namely, what people expect to see in a mirror and when mirror reflections look natural.

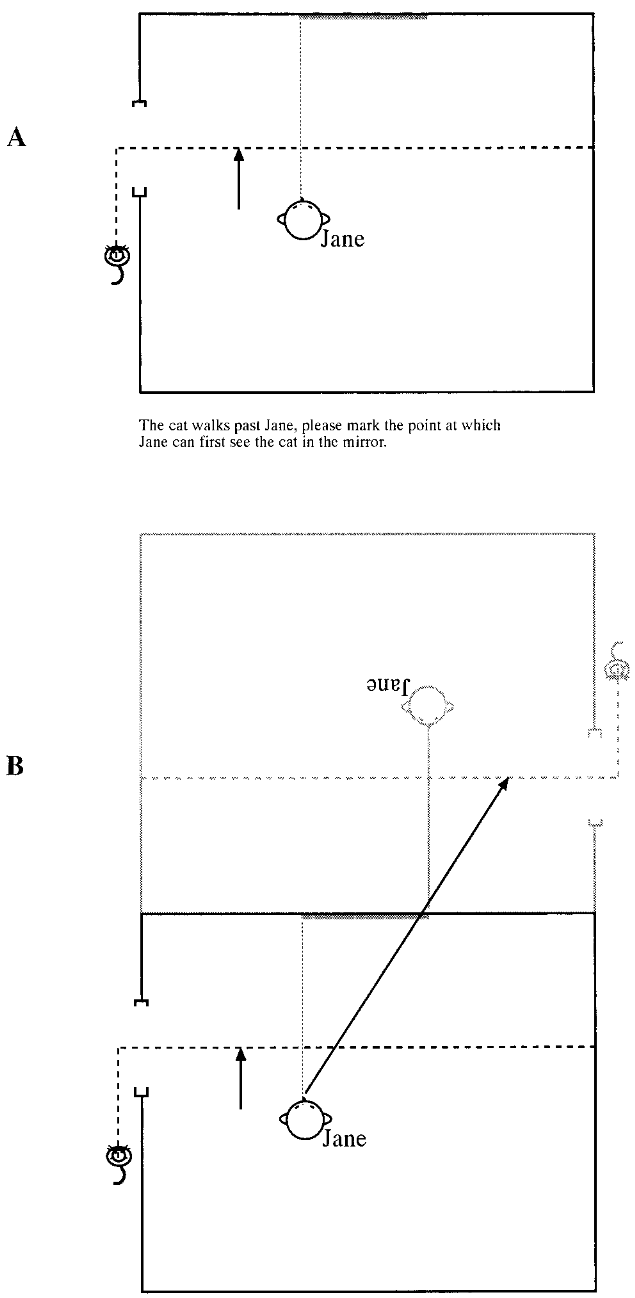


Figure 1. A: A condition from Experiment 2 in Croucher et al. (2002). The arrow represents the mean position chosen by the participants. The thin dotted line represents the correct response for the condition. The instructions at the bottom were printed on the page. From "Naive Optics: Understanding the Geometry of Mirror Reflections," by C. J. Croucher, M. Bertamini, and H. Hecht, 2002, *Journal of Experimental Psychology: Human Perception and Performance, 28,* p. 554. Copyright 2002 by the American Psychological Association. Adapted with permission. B: A diagram showing how the belief that the virtual room is reflected horizontally can explain the mistake in the response. In this example, although the cat is walking from the left in the room, it may be conceived of as walking from the right in the virtual room.

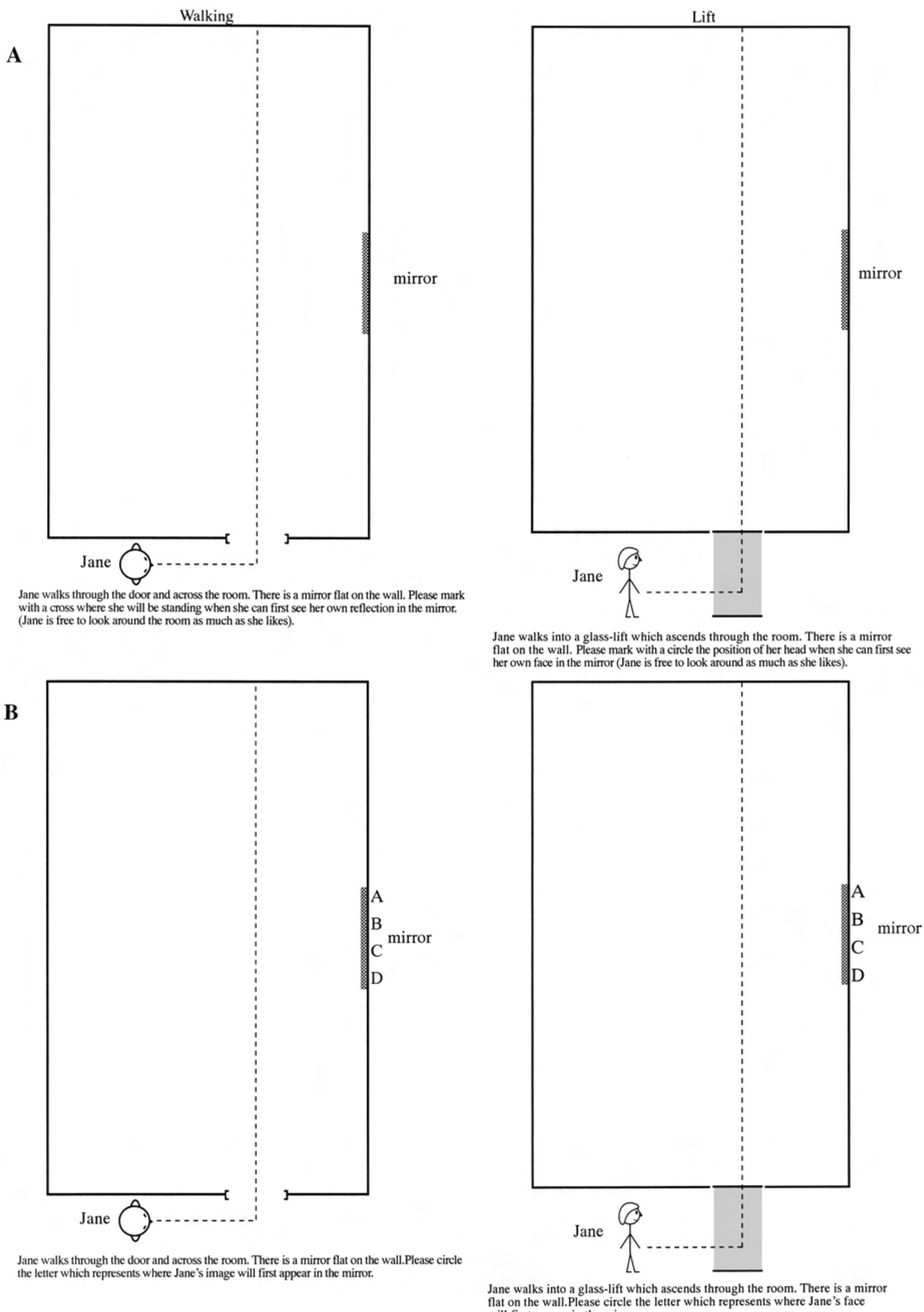
(Croucher et al., 2002). This finding is intriguing, because people have a wealth of experience walking over to mirrors to view their reflections. Four possible hypotheses could explain these findings (Croucher et al., 2002).

1. *Egocentric mirror rotation:* Observers may not take the orientation of the mirror surface into account, or they may misperceive the mirror to be rotated toward being orthogonal to their line of sight. The logic of this hypothesis is that if people perceive a space opening up beyond the frame of a mirror, the surface capturing that visual information in a dynamic, 2-D cross section is an abstraction. In other words, even though the glass surface of a mirror is a concrete material object, it is not represented. Therefore, if people are required to take the surface into account to estimate what is visible in a mirror, they tend to assume a default orientation of the surface orthogonal to the line of sight (or to be biased toward this default).

2. *Capture:* Observers may conceptualize mirrors as pictures that capture images for further inspection so that the location of the observer is irrelevant. This hypothesis was partly supported by the fact that two different locations of observers led to the same pattern of responses. In other words, mirrors may be treated as pictures. Mirrors are in reality different from pictures in a number of ways; they are more similar to apertures in that in a mirror, we see solid objects with appropriate perspective (from any point of observation), shading, binocular parallax, and motion parallax.[2] However, mirrors share with pictures two properties: They have a surface that can be visible (and is often framed) and the objects inside them cannot be touched.

3. *Boundary extension:* When making judgments about the positions of objects in mirrors, observers may overestimate the extent of virtual space compared with what would actually be visible in a mirror. Thus, when asked to remember a scene in the mirror, they may broaden the boundaries and judge a larger part of the world to have been captured by the mirror image than was the case. There is evidence that something similar happens for photographs. Observers remember scenes that they saw in a photograph as extending beyond what was actually presented (Intraub, 1997; Intraub & Bodamer, 1993; Intraub & Richardson, 1989). After seeing a photograph with a busy scene, observers had to rate photographs from a set that included the same amount, more (zoom out), or less (zoom in) of the same scene. Observers tended to pick the extended-boundary photograph as the one seen before (Intraub & Richardson, 1989). Although boundary extension was first described as a memory effect, recent work has shown that it is more appropriately described as a perceptual phenomenon (Gottesman & Intraub, 2002). In particular, it is known that it works for short retention intervals, that it only works when an extended background is present, and that it is not eliminated even when observers are aware of it beforehand. If boundary extension

[2] The fundamental difference between a mirror image and a painting was very clear in Leonardo da Vinci's notes, and it was one reason for his dissatisfaction with his art ("Painters often fall into despair of imitating nature when they see their pictures fail in that relief and vividness which objects have that are seen in a mirror"; as quoted in Ono, Wade, & Lillakas, 2002, p. 85). The issue can even be traced back to Plato's *Republic* (see Gombrich, 1960).


A
Walking
mirror
Jane
Jane walks through the door and across the room. There is a mirror flat on the wall. Please mark with a cross where she will be standing when she can first see her own reflection in the mirror. (Jane is free to look around the room as much as she likes).
Lift
mirror
Jane
Jane walks into a glass-lift which ascends through the room. There is a mirror flat on the wall. Please mark with a circle the position of her head when she can first see her own face in the mirror (Jane is free to look around as much as she likes).
B
A
B
C
D
mirror
Jane
Jane walks through the door and across the room. There is a mirror flat on the wall.Please circle the letter which represents where Jane's image will first appear in the mirror.
A
B
C
D
mirror
Jane
Jane walks into a glass-lift which ascends through the room. There is a mirror flat on the wall.Please circle the letter which represents where Jane's face will first appear in the mirror.

is a general effect of scene perception, it is possible that observers generally overestimate the space visible in a mirror and, consequently, when asked to make predictions, they make the early error.

4. *Left–right reversal:* There was one condition in Croucher et al. (2002) in which the early error was not present, and that was a vertical movement by the character up or down a rope with a mirror on the wall. This suggests that there is something special about left–right displacements that does not extend to up–down displacements. People have an understanding that there is some type of left–right reversal in mirrors and may extrapolate from this to expect a reversal of the imagined visual space around a vertical axis, thus misplacing objects in the mirror reflection. This idea is similar to what Gardner (1967) suggested as an explanation for why the image in a mirror is left–right reversed (see also Gardner, 1990; Gregory, 1997).

On the basis of this hypothesis, people would then predict an observer's reflection to appear from the left as the observer approaches from the right, and in turn this might lead to an overestimation of what is visible from the side. Figure 1B shows how this would explain the results of Experiment 2 in Croucher et al. (2002). This fourth hypothesis would explain why the early error was not present for vertical movements.

These four hypotheses need to be tested in more detail, with consideration also given to how they can be compounded in some cases. Responses in most tests run by Croucher et al. (2002) were distributed multimodally, suggesting that subgroups exist in the population with different sets of beliefs. In the present article, we explore in particular the fourth hypothesis in more detail. That is, we predicted that if some people conceived of the virtual world inside a mirror as rotated around a vertical axis, they would misplace the images in the mirror accordingly. Something on the left side of the mirror in the room would be expected to be located on the right side of the mirror because it is on the right side of the virtual world.

This rotation around a vertical axis is an inappropriate way to describe a mirror reflection. For example, if the mirror image of a person is generated by a rotation of 180°, a right-handed person would not become left-handed in a mirror. The change of handedness is a consequence of the reflection, but the actual transformation that matches one object onto its virtual image is more complicated than (and cannot be reduced to) any rigid rotation in 3-D space. One possibility is a rotation outside the third dimension, but people cannot imagine such rotations. The left–right reversal hypothesis proposes that people think of a reflection as a simple 180° rotation around a vertical axis. In Experiments 1 and 2, we tested the idea that the people who made the early error would also indicate that the image of the person moving in the room would appear on the opposite side of the mirror. Such a finding would support the left–right reversal hypothesis.

Some of the current experiments used paper-and-pencil tasks similar to those used by Croucher et al. (2002). All of their experiments involved a mirror in which no reflection could be seen. Participants therefore had to rely on some mental imagery or memory. On the one hand, their errors were surprising in part because memory of what is visible in similar situations should have been sufficient to correctly answer the question. On the other hand, people may not hold mnemonic representations of common events even after thousands of occurrences. People may simply interact with mirrors in a direct way—as, for instance, when one shaves using a mirror—and there is evidence that visual control of action is dissociated from visual recognition of objects (Milner & Goodale, 1995). Our tasks relied on some memory of or abstract knowledge about mirrors and therefore could not be performed by feeding visual information directly into a motor control system.

However, it is also possible that knowledge is acquired about reflections but only at a perceptual level. Participants may have no problem distinguishing between correct and incorrect mirror reflections when the reflections are visible. If so, the error found in some tasks would relate more to incorrect reasoning about mirrors than to total lack of knowledge about how mirrors work. Other tasks used in the naive physics literature have revealed a dissociation between conceptual and perceptual knowledge. For instance, people can perceptually recognize as natural a ball leaving a C-shaped tube along the tangent (a straight line; Kaiser, Proffitt, & Anderson, 1985), even though they tend to predict a curvilinear path in a paper-and-pencil task (McCloskey, Caramazza, & Green, 1980).

Outside of the naive physics literature, there is other evidence about the limits of spatial reasoning. Pani and colleagues (Pani, 1993, 1997; Pani, Jeffres, Shippey, & Schwartz, 1996; Pani, Zhou, & Friend, 1997) have shown clear limitations in people's abilities to reason about spatial transformations. For instance, Pani et al. (1997) showed that people fail in predicting how a simple, familiar geometric shape will look when tilted, even after the shape has been studied in that orientation. There may be *base organizations* that people apply even when such organizations are inadequate for solving the task at hand (Pani, 1997), and this may be similar to the application of the left–right strategy discussed above (see Figure 1B).

To test perceptual performance, in Experiments 3 and 4, we presented correct and incorrect mirror reflections in a set of computer generated images of rooms. Participants judged whether the reflections were accurate. Results showed that perceptual knowledge was limited in that large distortions were accepted as natural. However, perceptual knowledge was accurate in one respect: Left–right reversals looked unnatural, a result that contrasts with the paper-and-pencil results.

Figure 2 (opposite). Stimuli used in the walking and lift conditions of Experiment 1. The instructions were printed at the bottom of the page, and each participant saw either the walking or the lift condition. The figure shows only movement from the bottom to the top, but each participant was tested on both up and down directions. Moreover, each diagram was shown in two items to ask (A) where Jane would be positioned when she would first see her reflection and (B) where in the mirror her image would appear.

Experiment 1: What Is Visible in a Mirror and Where in the Mirror It Will Be

In this experiment, participants were required to mark on a diagram where a character would be positioned when she would first see her reflection in a mirror. We included a replication of the basic question from the Croucher et al. (2002) study and a set of new conditions.

As shown in Figure 2, a room was presented in which the character (Jane) was either walking or moving in a lift. The top-down view of the room was placed vertically on the page so as to match the vertical orientation of the room with the lift. In the experiments conducted by Croucher et al. (2002), the walking conditions presented the character moving horizontally across the page, and the rope conditions presented the character moving vertically across the page. By presenting both conditions at the same orientation on the page, Experiment 1 sought to verify that the results found by Croucher et al. were not an artifact of test design. We expected that responses would tend to be too early in the walking condition but not in the lift condition.

For the vertical motion, the character moved in a glass lift. Moreover, she walked into the lift along an L-shaped path similar to the path in the walking condition. This was done to keep the walking and the lift conditions as directly comparable as possible. Following the question about where Jane would start seeing herself in the mirror, a second question was asked on a separate page, but with an identical room layout. The second question regarded where in the mirror Jane would first see her reflection. By looking at the answers to this question, we sought to test the left–right reversal hypothesis, predicting that people would select a location in the mirror on the opposite side with respect to the location of Jane (i.e., they would imagine Jane's reflection to appear on the right when Jane moved from the left, as in Figure 1B). Since the movement was up or down on the page, we here use the terms *left* and *right* with respect to an observer, such as Jane, standing in front of the wall with a mirror. Finally, and importantly, because the participants answered both questions, we were able to test whether there was a correlation between the answers.

Method

Participants. All participants were students of psychology or combined honors including some psychology. They comprised 57 women and 8 men, a ratio not atypical for a psychology degree. They were tested in a first-year psychology class at the University of Liverpool, Liverpool, United Kingdom. Their average age was 20.24 years ($SD = 0.39$ years).

Materials. Participants were presented with four schematic drawings representing a character called Jane who was said to move either up or down the page along a dashed line past a depicted mirror. Examples of the stimuli are shown in Figure 2.

In two drawings (moving up and moving down with respect to the page), the participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. This question is henceforth referred to as the *Jane task.* In the remaining two drawings, participants were required to indicate where in the mirror Jane would first see her reflection, selecting one of four possible locations, labeled *A, B, C,* and *D* (Figure 2B). This question is henceforth referred to as the *reflection task.* Each Jane task was followed by the corresponding reflection task on a separate page. These constituted two questions about the same problem.

The experiment was administered in two conditions to two independent groups of participants. In one, Jane was said to walk along the dashed line. In the other, Jane was said to move along the same line in a glass lift. In both conditions, Jane's indicated movement was vertical on the page.

Procedure. The test was administered in a classroom at the end of a lecture. An overhead projector was used to display a set of general instructions. The specific instructions were printed at the bottom of the page and can be seen in Figure 2. Participants were instructed to work independently. Unlike in previous experiments (Croucher et al., 2002), it was made clear in the instructions that Jane was free to look in any direction she pleased. This was important because if participants assumed that Jane had to look in the direction orthogonal to the wall at all times, this might produce an underestimation of the early error.

Results and Discussion

The distance was measured between the edge of the mirror closest to Jane and the position at which participants marked Jane to be standing when she could first see her reflection: This distance is henceforth referred to as *Jane distance.* Two distance scores were available for each participant—one for each direction. A two-way analysis of variance (ANOVA), with condition (walking or lift) and direction (moving from top or bottom of page) as factors was conducted on Jane distance. The analysis revealed a significant main effect of condition, $F(1, 63) = 6.70$, $p = .01$, with greater accuracy in the lift condition. The analysis revealed a nonsignificant main effect of direction, $F(1, 63) < 1$, and a nonsignificant Condition $\times$ Direction interaction, $F(1, 63) < 1$. The absence of an effect of direction suggests that participants were not confused about which part of Jane was the target, despite the fact that in the down condition, her feet would have been visible in the mirror before her face.

Since no effect of direction was found, a mean Jane distance was derived for each participant, combining distances across direction. One-sample *t* tests, with test value zero, were conducted on mean Jane distance in each condition separately. The analysis revealed that participants' responses were significantly early in the walking condition, $t(36) = 4.60$, $p < .001$, with the mean response 21.43 mm before mirror edge ($SD = 28.36$ mm). The analysis revealed nonsignificant errors in the lift condition, $t(27) = 0.92$, $p = .37$, with the mean response 4.81 mm before mirror edge ($SD = 24.09$ mm). Responses, including mean responses, are presented superimposed over the drawings in Figure 3. These results are consistent with the findings of Croucher et al. (2002).

The next stage of analysis was conducted on the location in the mirror where participants predicted Jane's reflection would first appear. This is henceforth referred to as *reflection location.* To enable comparisons across direction of motion relative to the page, reflection locations were recoded relative to Jane's motion (on the test sheets, Location A was always at the top). In all cases, we defined the *first* reflection location as the one closest to Jane's starting position, and this was the correct answer. The *fourth* location was at the far edge of the mirror from Jane, and therefore this answer reflected participants' expectations that Jane's reflection would appear at the opposite end of the mirror, perhaps because it was moving in the opposite direction to Jane (see Figure 1B). The percentages of responses in each condition selecting each reflection location are provided in Figure 4A. Participants preferred the extreme positions.

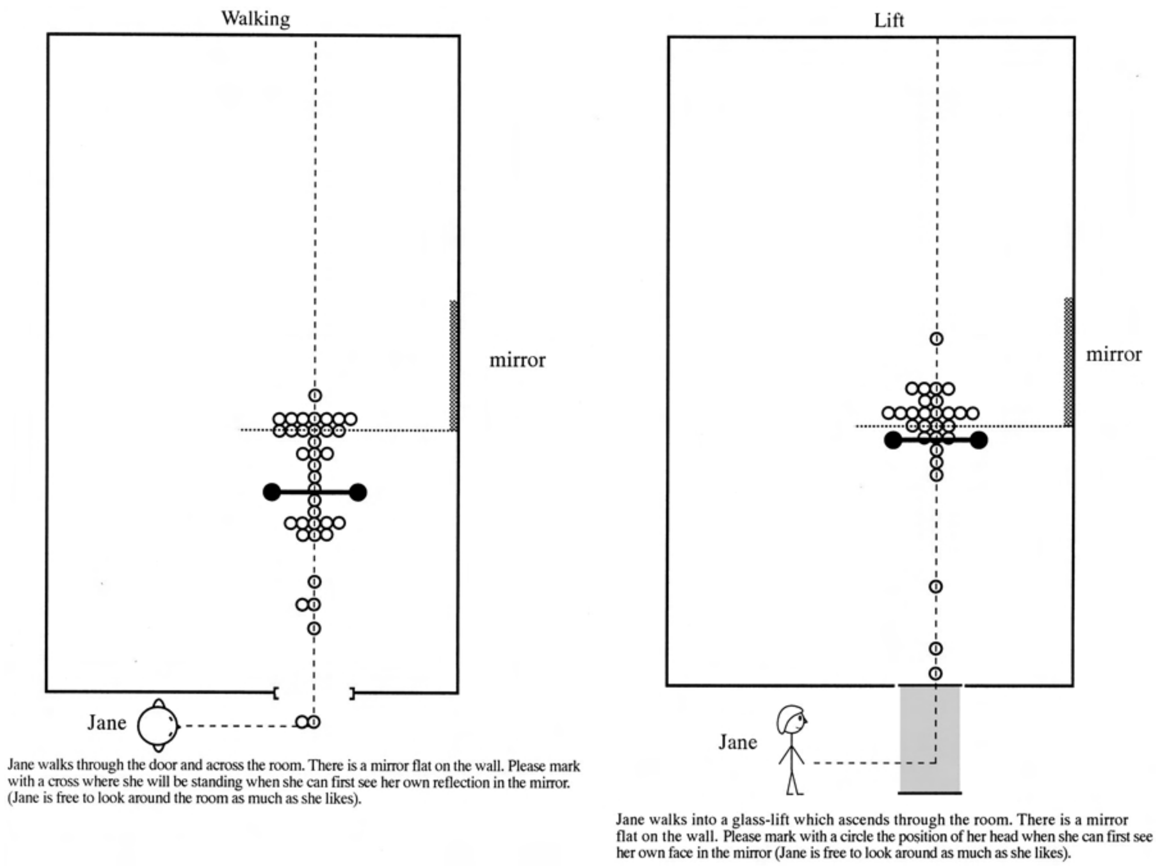


Figure 3. Data for the walking and lift conditions of Experiment 1, averaged across direction for each participant. Although only the up direction is shown, responses were combined across direction of motion, and each circle represents the average of two values for one individual. Responses are rounded to 4-mm intervals for plotting purposes, whereas in the statistical analysis they had a 1-mm precision. The correct responses are represented by thin dotted lines, and the mean responses are marked with dumbbells.

For the purpose of further analysis, the four reflection locations were combined into two general positions—the first and second locations were then referred to as *near* reflections, and the third and fourth locations were referred to as *far* reflections. A series of chi-square analyses was conducted on the selection of near or far reflection locations, in each condition (walking and lift) and direction separately. The analyses revealed nonsignificant effects of reflection location in all combinations of condition and direction ($N = 37$ for walking; $N = 28$ for lift), $0.03 < \chi^2(1) < 2.31$, all ps $> .05$. In each condition and direction, participants predicted Jane's reflection to appear on the near or far side of the mirror equally, even though the near side was the correct response.

In the next stage of analysis, we investigated the relationship between Jane distance and reflection location. This analysis was conducted within the walking condition only, in which the early error was a significant effect. In each position, responses were split according to corresponding Jane distance. The *early* group consisted of all responses predicting that Jane would see her reflection when she was standing at least one dash (2 mm) from the mirror's edge. The remaining responses constituted the *correct* group. The percentage of each group of responses that selected each reflection location is provided in Figure 4B. The reflection locations were then combined into near and far reflections, as above. Chi-square analyses were conducted on the selection of near or far reflection locations by the early and correct groups in each direction separately. The analyses revealed significant Group $\times$ Reflection Position interactions for the top-down direction, $\chi^2(1, N = 37) = 5.87$, $p = .02$, and for the bottom-up direction, $\chi^2(1, N = 37) = 7.10$, $p = .01$. For both directions, participants who made the early error demonstrated a preference for far reflection locations, and the correct group demonstrated preference for near reflection locations.

In summary, Experiment 1 replicated the findings of Croucher et al. (2002): Some participants expected a character to see her reflection in a mirror before she reached the near edge of the mirror, but only when the character moved horizontally with respect to the mirror and not vertically (in the lift condition). Using one dash (2 mm) as a criterion, 62% of the responses were early in the walking condition, compared with only 29% in the lift condition. (There are slight discrepancies between these percentages and those represented in Figure 3 because Figure 3 presents values averaged across direction.) In addition, participants who made the

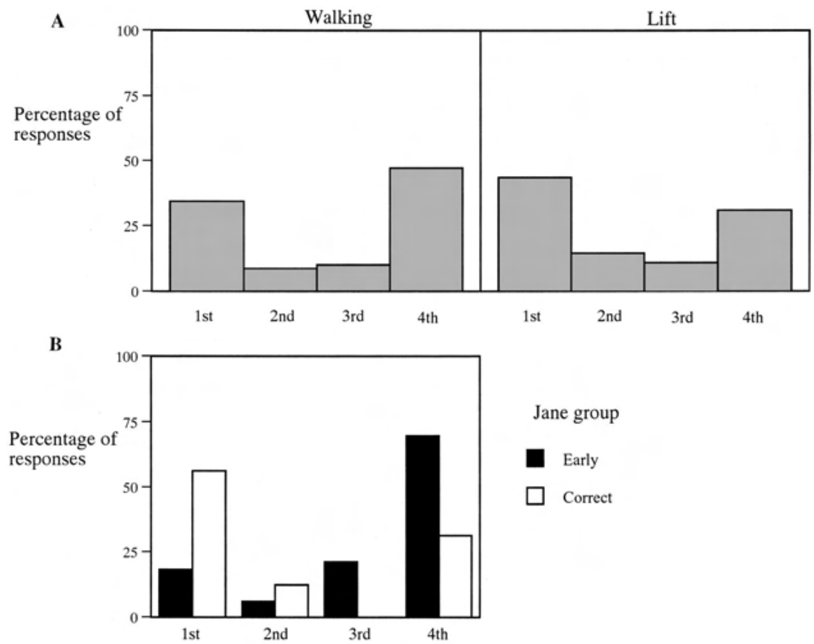


Figure 4. Data from Experiment 1: percentages of responses predicting that Jane's reflection would appear at each position, in each condition, averaged across directions. In each case, the first reflection position was nearest to Jane and was the correct answer. A: Percentages of responses in each condition. B: Percentages of responses divided into two Jane groups on the basis of corresponding performance in the first task (early vs. correct responses). This analysis was performed only for the walking condition because the early error was not significant in the lift condition.

early error in the horizontal condition tended to expect the character's reflection to appear on the opposite side of the mirror. This finding provides support for the left–right reversal hypothesis.

Experiment 2: Mirrors on Floors and Ceilings

This experiment used the same methodology as Experiment 1 to explore the extent to which participants' knowledge about reflections extended to mirrors placed on floors and ceilings. One surprising finding with respect to the early error was that it did not extend to mirrors on walls when Jane was moving vertically in a glass lift (Experiment 1). If the early error depends on large familiarity with moving horizontally in front of a mirror on a wall, then it should not generalize to floors and ceilings. By placing the mirror on the floor or the ceiling, we created a less familiar layout.

Although it may seem paradoxical that the most familiar condition is the one which produced the early errors, there are some examples in the literature in which familiarity leads to taking the wrong approach to a problem. For example, Hecht and Proffitt (1995) found that performance on the Piagetian water-level task decreased with expertise. Handling liquid-filled containers on a daily basis appeared to make bartenders and waitresses lose the knowledge that water remains invariably horizontal with respect to the environment. This was the price for greater accuracy with respect to the local reference system (i.e., the glass) needed to keep the liquid inside the container. Actions in front of mirrors could similarly distract from the law of reflection in favor of physically incorrect but practically reliable conceptions (but see also Vasta, Rosenberg, Knott, & Gaze, 1997). However, if the critical variable that leads to the early error is horizontal displacement (from left to right instead of from up to down), then we should find a similar early error when the mirror is located on the floor or ceiling.

Method

Participants. All participants (57 women, 9 men, and 1 whose gender was not indicated) were students of psychology or combined honors including some psychology. They were tested in a first-year cognitive psychology class at the University of Liverpool. Their average age was 20.37 years (SD = 4.58 years). Participants were sampled from the same population as in Experiment 1, with no overlap.

Materials. The materials were similar to those used in Experiment 1, in which Jane was either moving horizontally (walking along the line) or vertically in space (traveling in a lift). However, Jane was now always moving horizontally in space, walking along the line, while the mirror was also horizontal, either on the floor or on the ceiling. As in Experiment 1, participants were required to indicate where Jane would be positioned on the line when she would first see her reflection and to indicate where in the mirror (from a choice of four locations) she would first see her reflection. Again, participants answered each type of question twice—once in each direction. Participants answered all four questions in either the floor or ceiling condition. Examples of the stimuli are shown in Figure 5.

Procedure. The test was administered in a classroom at the end of a lecture. An overhead projector was used to display a set of general instructions. The specific instructions were printed at the bottom of the page and are presented in Figure 5. It was made clear in the instructions that Jane was free to look in any direction she wanted.

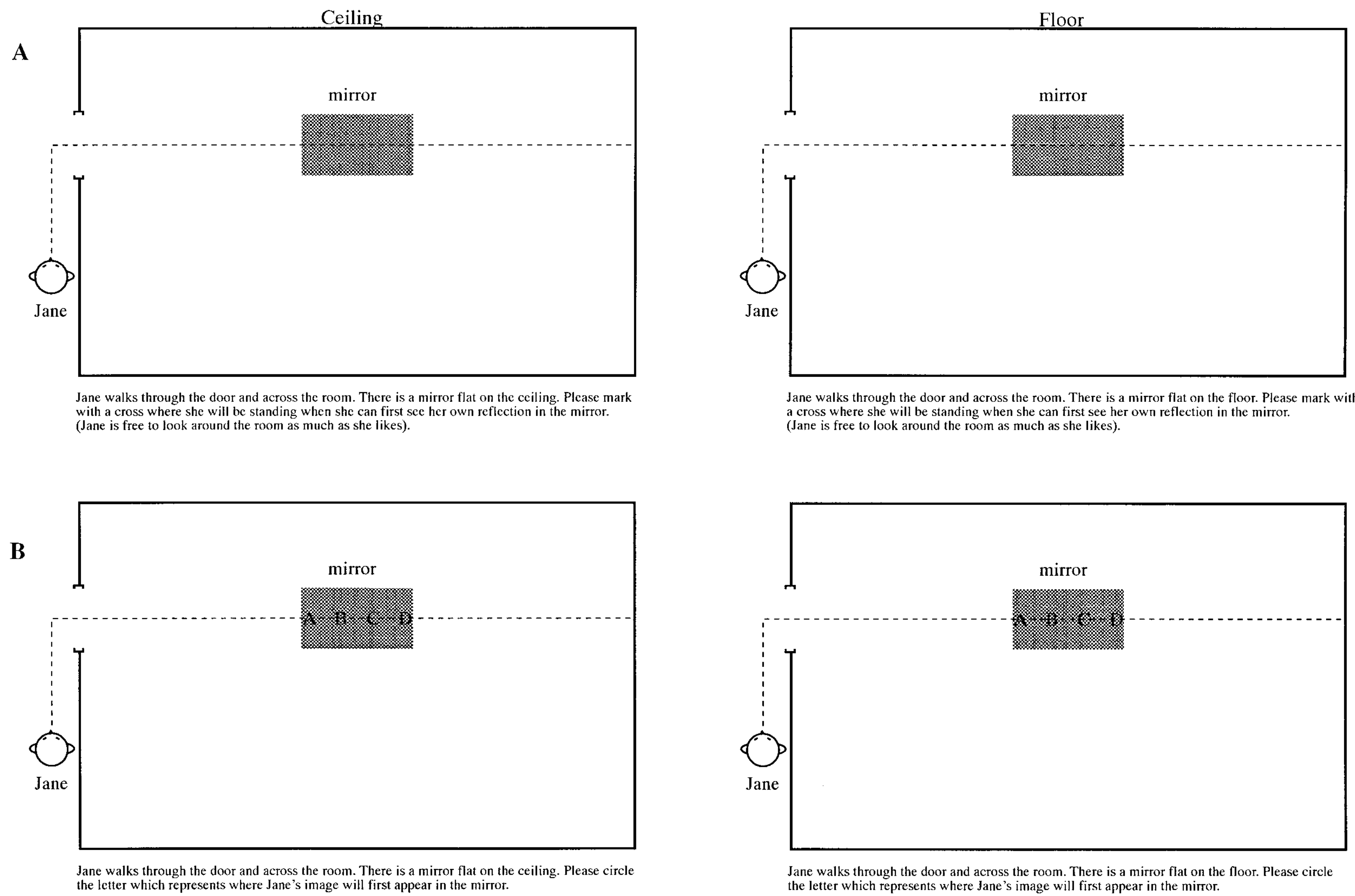


Figure 5. Stimuli used in the ceiling and floor conditions of Experiment 2. The instructions were printed at the bottom of the page, and each participant saw either the ceiling or the floor condition. The figure shows only movement from left to right, but each participant was tested on both directions. Moreover, each diagram was shown in two items to ask (A) where Jane would be positioned when she would first see her reflection and (B) where in the mirror her image would appear.

Results and Discussion

The first analysis was conducted on the distance from the near edge of the mirror at which participants predicted Jane would first see her reflection (Jane distance). A two-way ANOVA, with mirror position (floor or ceiling) and direction (walking from left or right) as factors, was conducted on Jane distance. The analysis revealed nonsignificant main effects of mirror position, $F(1, 65) < 1$; and direction, $F(1, 65) = 3.23$, $p = .08$; and a nonsignificant Direction × Mirror Position interaction, $F(1, 65) < 1$.

A mean Jane distance was derived for each participant, combining distances across direction. One-sample *t* tests were conducted on mean Jane distances. The analyses revealed that responses were significantly early when the mirror was on the floor, $t(31) = 2.91$, $p = .01$, with mean distance 12.75 mm before the mirror's near edge ($SD = 28.82$). Responses were also significantly early when the mirror was on the ceiling, $t(34) = 3.18$, $p < .001$, with mean distance 20.71 mm before the mirror ($SD = 38.51$ mm). Responses, including mean response, are presented superimposed over the drawings in Figure 6. Because no difference was found between direction, the responses were combined across direction of motion. To investigate whether performance differed between the floor and ceiling conditions, an independent samples *t* test, with condition as the factor, was conducted on mean Jane distance, revealing nonsignificant effect of condition, $t(65) = 1.00$, $p = .32$.

Performance was also measured by the percentage of responses that were early, using the same criterion of Experiment 1 (i.e., at least 2 mm early, corresponding to one dash from the mirror's edge). For the floor and ceiling conditions, the values were 47% and 46%, respectively. (These values differ slightly from the values represented in Figure 6, for which values were averaged across direction for each participant.) This compares to 62% in the walking condition of Experiment 1 and 29% in the lift condition.

The next stage of analysis was conducted on the location in the mirror where participants predicted Jane's reflection would first appear (reflection location). Reflection locations were recoded relative to Jane's motion: In all cases, the first reflection location was closest to Jane's starting position and was the correct answer. Percentages of the responses in for each respective reflection location are presented in Figure 7A, which demonstrates a clear preference for the extreme positions. The four reflection locations were combined into two general positions—the first and second locations were referred to as near reflections, and the third and fourth locations were referred to as far reflections. Chi-square analyses were conducted on the selection of near or far reflection locations, in each condition and direction separately. The analyses revealed significant effects of reflection location when the mirror was on the floor, when Jane was moving left, $\chi^2(1, N = 37) = 5.12$, $p = .02$, and when Jane was moving right, $\chi^2(1, N = 37) = 6.82$, $p = .01$, with a greater preference for near reflections. The analyses revealed nonsignificant effects of reflection location when the mirror was on the ceiling, in each direction, both $\chi^2(1, N = 35) = 1.40$, $p = .24$.

In the next stage of analysis, we investigated the relationship between Jane distance and reflection location. This analysis was conducted on both the floor and ceiling data, because the early error was a significant effect in both conditions. In each direction,

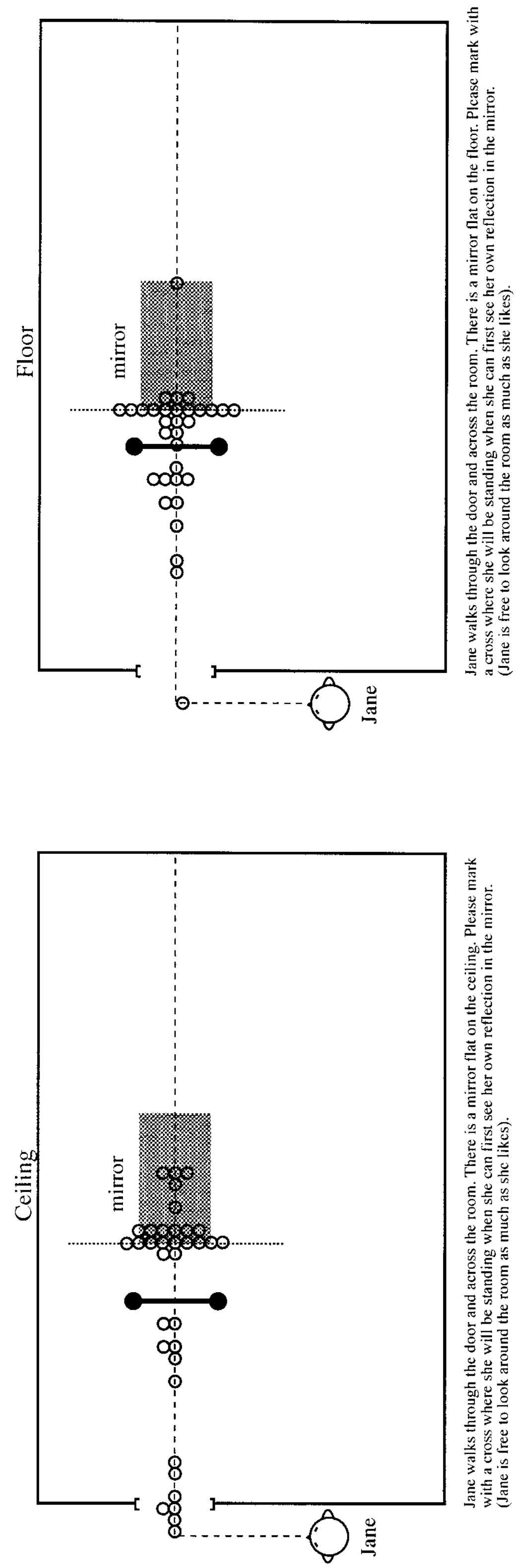


Figure 6. Data for the ceiling and floor conditions of Experiment 2, averaged across direction for each participant. Responses (open circles) are rounded to 4-mm intervals. The correct responses are represented by thin dotted lines, and the mean responses are marked with dumbbells.

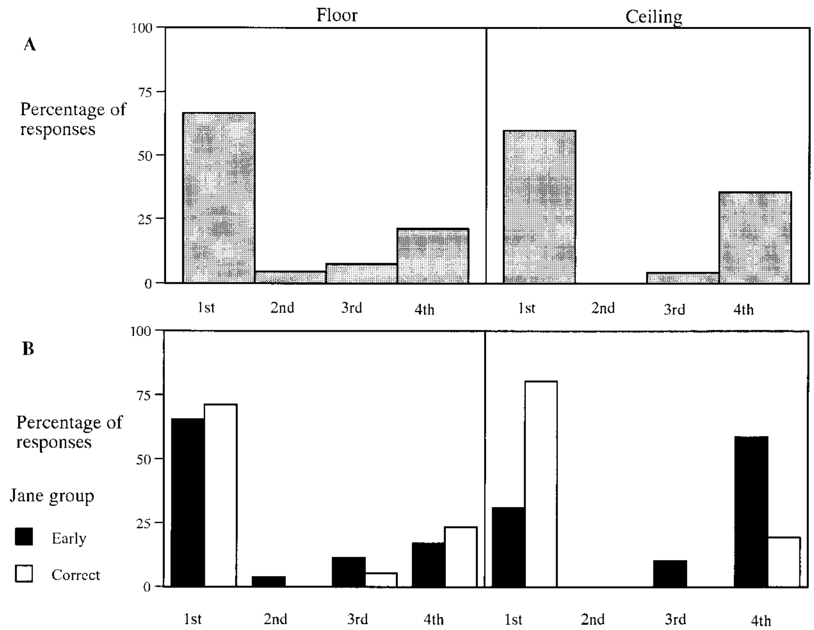


Figure 7. Data from Experiment 2: percentages of responses predicting that Jane's reflection would appear at each position, in each condition, averaged across directions. In each case, the first reflection position was nearest to Jane and was the correct answer. A: Percentages of responses in each condition. B: Percentages of responses divided into two Jane groups on the basis of corresponding performance in each condition (early vs. correct responses).

responses were split according to corresponding Jane distance. The *early* group consisted of all responses predicting that Jane would see her reflection when she was standing 2 mm or more from the mirror's edge. The remaining responses formed the *correct* group. The percentage of responses within each group in each condition selecting each reflection location is presented in Figure 7B. The reflection locations were then combined into near and far reflections, as above. Chi-square analyses were conducted on the selection of near or far reflection locations by the early and correct groups, in each condition and direction separately. The analyses revealed nonsignificant Group × Reflection Location interactions when the mirror was positioned on the floor, when Jane moved left, $\chi^2(1, N = 32) = .41$, $p = .52$, and when Jane moved right, $\chi^2(1, N = 32) = .08$, $p = .78$. The analyses revealed significant Group × Reflection Location interactions when the mirror was placed on the ceiling, when Jane moved left, $\chi^2(1, N = 35) = 7.78$, $p = .01$, and when Jane moved right, $\chi^2(1, N = 35) = 9.60$, $p <$ .001. The early group demonstrated preference for far reflections, and the correct group demonstrated preference for near reflections.

Experiment 2 demonstrated that some people expected a character to be able to see her reflection when she was still some distance from the side of the mirror, both when the mirror was on the floor and when it was on the ceiling. This corroborated the findings of Experiment 1 and of Croucher et al. (2002), in which the mirror was on a wall and was approached horizontally. However, the early error was not as clear as in Experiment 1, especially for the floor condition, in which the mean distance was only 12.75 mm (as opposed to 21.43 mm in the walking condition of Experiment 1). The findings also suggest that this error may have resulted from the mistaken belief that reflections move in the opposite direction of the viewer, but only when the mirror was on the ceiling. For the floor condition, although there was evidence of an early error, participants showed a preference for the near reflections. It may be that mirrors located at people's feet are a special case with respect to the question of where reflections are located. This idea is discussed in more detail in the final Discussion section.

Experiment 3: Perceiving Correct and Incorrect Reflections

The methodology in Experiments 3 and 4 was different from that used in the previous experiments. We created computer models of four different rooms with different furniture. On the wall opposite the observer was a mirror with a reflection of the room. The critical aspect of these new stimuli was that an actual reflection was present in front of our participants, and therefore there was no need to imagine or guess locations of the mirror image. We were interested in presenting actual mirror reflections for two main reasons. First, it may be possible that paper-and-pencil tasks force participants to develop reasoning strategies that may go wrong or that are imprecise (e.g., Pani, 1997; Bryant & Tversky, 1999). At the same time, participants may have learned how an actual mirror behaves and might recognize correct and incorrect reflections without effort. Second, by creating systematically incorrect reflections and assessing their subjective naturalness, we hoped to resolve more finely the perceptual understanding of naive observers. In theory, it is possible that the most natural reflection is different from an actual mirror reflection, just as the motion of a pendulum is judged to be most natural when it differs from its canonical motion (Bozzi, 1990; Pittenger & Runeson, 1990).

Method

Participants. Seventy-two adults (49 women, 23 men) at the University of Liverpool participated in Experiment 3. Their mean age was 23.21 years ($SD = 6.11$ years).

Materials. Four rooms (office, kitchen, living room, and bedroom) were computer generated using the graphics packages MAXON CINEMA 4D 5.2 (MAXON GmbH, Friedrichsdorf, Germany) and Adobe Photoshop 6.0-1. Each was manipulated to create six reflection types (correct, tilted, left–right reversed, left–right flipped, compressed image, and expanded image). Twenty-four distinct images resulted. The reflection types are described in more detail below. In each image, the same mirror (140 cm × 140 cm) was placed on the facing wall. A character (170 cm tall) was positioned level with the edge of the mirror, at a distance of 450 cm from the mirror, orthogonal to the mirror–wall. The scene was simulated to be viewed from the position of the character's head, at an angle of 15° along the horizontal so that the mirror was centered in the image. This situation is comparable to viewing at arm's length a photograph taken with a normal 50-mm lens.

The four rooms were a kitchen, a living room, an office, and a bedroom. They were of different sizes and shapes, but the size of the mirror and the position of the virtual observer were fixed. The 3-D models of the furniture and the objects were created in-house or chosen from noncopyrighted databases. Plans showing the layout of the four rooms to scale are presented in Figure 8. Note that lighting was always from multiple sources (at least three) so that the directions of the shadows were relatively uninformative.

The mirror was given the reflective properties of a planar specular surface, and CINEMA 4D rendered the image accordingly. The manipulated reflections were created by altering the position and size of the mirror or viewpoint as necessary in a modified scene. The rendered images were then copied into Photoshop, in which the manipulated reflection was pasted

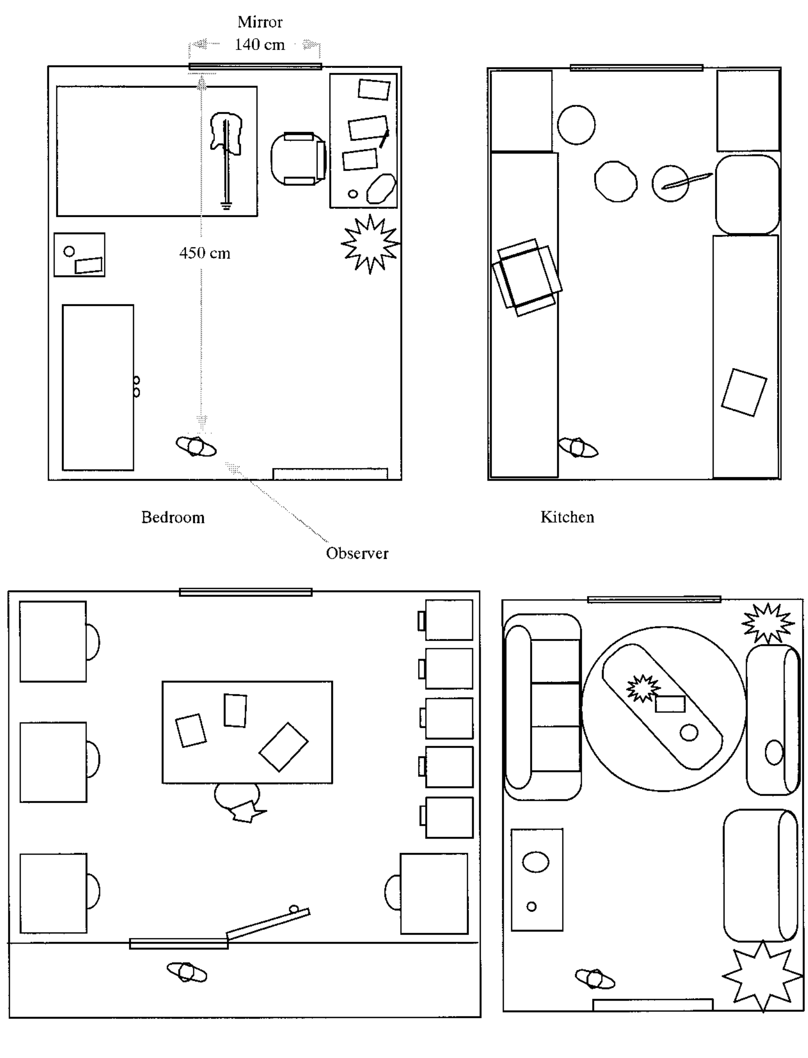


Figure 8. Stimuli used in Experiments 3 and 4. Top-down plans for each of the four rooms. The distance from the observer to the mirror was fixed at 450 cm, and the mirror was always 140 cm on each side.

onto the unmanipulated image of the room. The six reflection types were created in the following ways:

1. *Correct reflection:* This image was produced by CINEMA 4D following the rules of geometrical optics. This image was therefore very similar to what would be seen in a physical mirror. However, it is important to note that there are limits to what can be achieved with ray-tracing algorithms. Shadows in particular were sharp because the rendering did not use radiosity. Nevertheless, for the purposes of the study, the important aspect was that the geometry of what was visible in the mirror was correct.

2. *Tilted:* The mirror surface was tilted 10° around its midvertical axis toward the point of view. This made the virtual surface almost orthogonal to the line of sight of the observer. The reflection was then cropped to fit the shape of the mirror frame (which was not tilted). Unlike in the other manipulations, the orientation of the surface in which the reflection takes place was incompatible with the visible frame of the mirror, if a rectangular mirror is assumed. The ensuing distortions were similar to those occurring when a photograph or a movie screen is viewed from an oblique angle. Although this is potentially a cause of distortion, perceived shape has been shown to be remarkably robust, especially for rectangular shapes (Cutting, 1987; Kerzel & Hecht, 1997; Kubovy, 1986; Yang & Kubovy, 1999).[3]

3. *Left–right reversed:* The mirror image was produced by reflecting the contents of the entire room, including the character, through a vertical plane that ran perpendicular to the mirror and intercepted the mirror at its center (this moved every object to the opposite side of the room). The viewing position remained unchanged. Therefore, unlike the other manipulations, this operation separated the viewpoint from the character because the character moved to the other side of the room. In this sense, it was like looking at someone else in the mirror. It is important to note that this manipulation is equivalent to the behavior of a mirror that shows a virtual room in which everything has been rotated by 180° around a vertical axis.

4. *Left–right flipped:* The correct reflection in the mirror was reflected around its midvertical axis and pasted back onto the mirror. In common with the left–right reversed manipulation, objects on the right side of the room appeared on the left in the mirror. However, because the viewing position was not central to the mirror, the perspective information inside the virtual room was not equivalent to that for a room rotated by 180°.

5. *Compressed image:* The dimensions of the mirror were increased by 20% (i.e., from 140 cm × 140 cm to 168 cm × 168 cm), therefore increasing the area by 44%. The rendered reflection was then scaled down to fit the original mirror frame. The reflection therefore included more of the room than would have been visible in a real mirror. Please note that although more of the room could have been visible if the mirror, instead of being larger, had been farther away, these two manipulations are not equivalent.

6. *Expanded image:* The dimensions of the mirror were reduced by 20% (i.e., from 140 cm × 140 cm to 112 cm × 112 cm), therefore decreasing the area by 36%. The rendered reflection was then scaled up to fit the original mirror frame. The reflection therefore included less of the room than would have been visible in a real mirror. One of the basic aspects of a mirror is that an object at a given distance in front of the surface of the mirror will appear to be located at the same distance inside the mirror. Because the size of the reflection was altered, this property was destroyed by both the compressed and expanded manipulations.

All six types of reflection for one of the rooms (the office) are presented in Figure 9. Clearly, these were six qualitatively different conditions, and care is taken in the interpretation of the differences. Nevertheless, it is important to note that they were generated following the set of hypotheses discussed in the introduction. The tilted condition was intended to present observers with a mirror whose surface was roughly orthogonal to their line of sight. The two reflected conditions presented the observers with mirrors in which objects on the left side appeared on the right in the virtual room. The compressed and expanded conditions increased and decreased the amount of space and items visible in the mirror. Moreover, the boundary extension hypothesis predicts an asymmetry between these two manipulations—that is, only the compressed image should look natural.

Procedure. The pictures were produced in color on A4 paper and presented to participants in a folder. Participants viewed only one type of reflection in all four rooms. They were told that these were rooms created on a computer, and their judgment on the quality of the images was sought. No special mention of the mirror was made, and participants responded in their own time, rating, on a scale of 0 to 10, how correct the image as a whole appeared to them (10 indicating most accurate). After they had rated all four images, participants were asked whether there was anything about the images that they did not like. Responses were noted at time of testing. Each type of reflection was viewed by a different group of twelve participants.

Results and Discussion

First, participants' ratings of each type of reflection were analyzed across room. Figure 10A presents mean ratings of each reflection in each room. A two-way ANOVA, with room and reflection as variables, was conducted on participants' ratings. The analysis revealed a significant main effect of reflection, $F(5, 66) = 2.72$, $p = .03$, and a nonsignificant main effect of room, $F(3, 198) = 2.11$, $p = .10$. The analysis also revealed a significant Room × Reflection interaction, $F(15, 198) = 1.97$, $p = .02$, which accounted for 13.0% of the variance (η^2). A series of pairwise comparisons were conducted to further investigate the effect of reflection. Left–right reversed and left–right flipped images were given significantly lower naturalness ratings than correct and compressed images (all ps $< .05$). Correct and compressed images were rated equivalently. Figure 10A suggests that the interaction between room and reflection was due to the particularly low ratings of the left–right flipped image in the bedroom. Inspection of this image suggested that the arrangement of the chair and bed in this room made the inconsistency of relative object positions between room and reflection particularly salient (see Figure 9).

The next stage of analysis investigated how many participants claimed that there was something wrong with the images. Of particular interest was how often participants claimed that there was something wrong with the image compared with how often they identified in what manner the mirror reflection was wrong. Participants were divided into the following four categories: (a) those who stated that nothing was wrong with the images, (b) those who stated that there was something wrong with the image but not with the reflection (e.g., the colors were not natural), (c) those who stated that something was wrong with the reflection but did not identify the manipulation (e.g., the lights didn't look right in the

[3] Our images of rooms with mirrors could be compared to images of rooms with photographs on a wall. After manipulation, our mirror images were inconsistent with the room layout in a manner similar to how a scene in a photograph is not an extension of the room. It is known that under these conditions, distortions may be perceived in the picture (Pirenne, 1970). This is especially true for the tilted manipulation because of the change in orientation. The (absence of) distortions that might be expected when entertaining a particular mistaken hypothesis about mirror reflections might be an interesting side issue. However, we believe it was not a noticeable effect in our experiments. Perceived shape has been shown to be remarkably robust, especially for rectangular shapes (Cutting, 1987; Kerzel & Hecht, 1997; Kubovy, 1986; Yang & Kubovy, 1999).

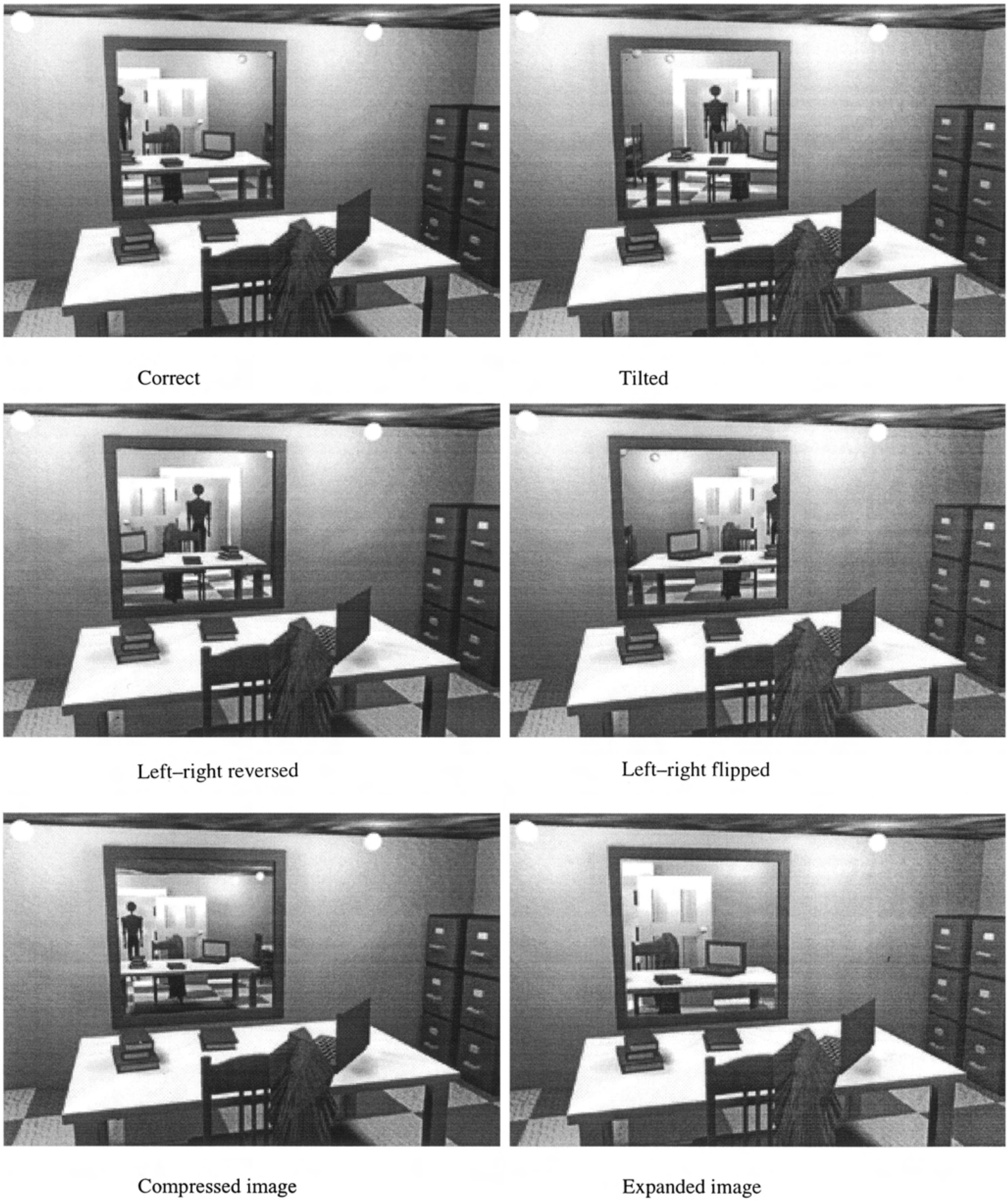
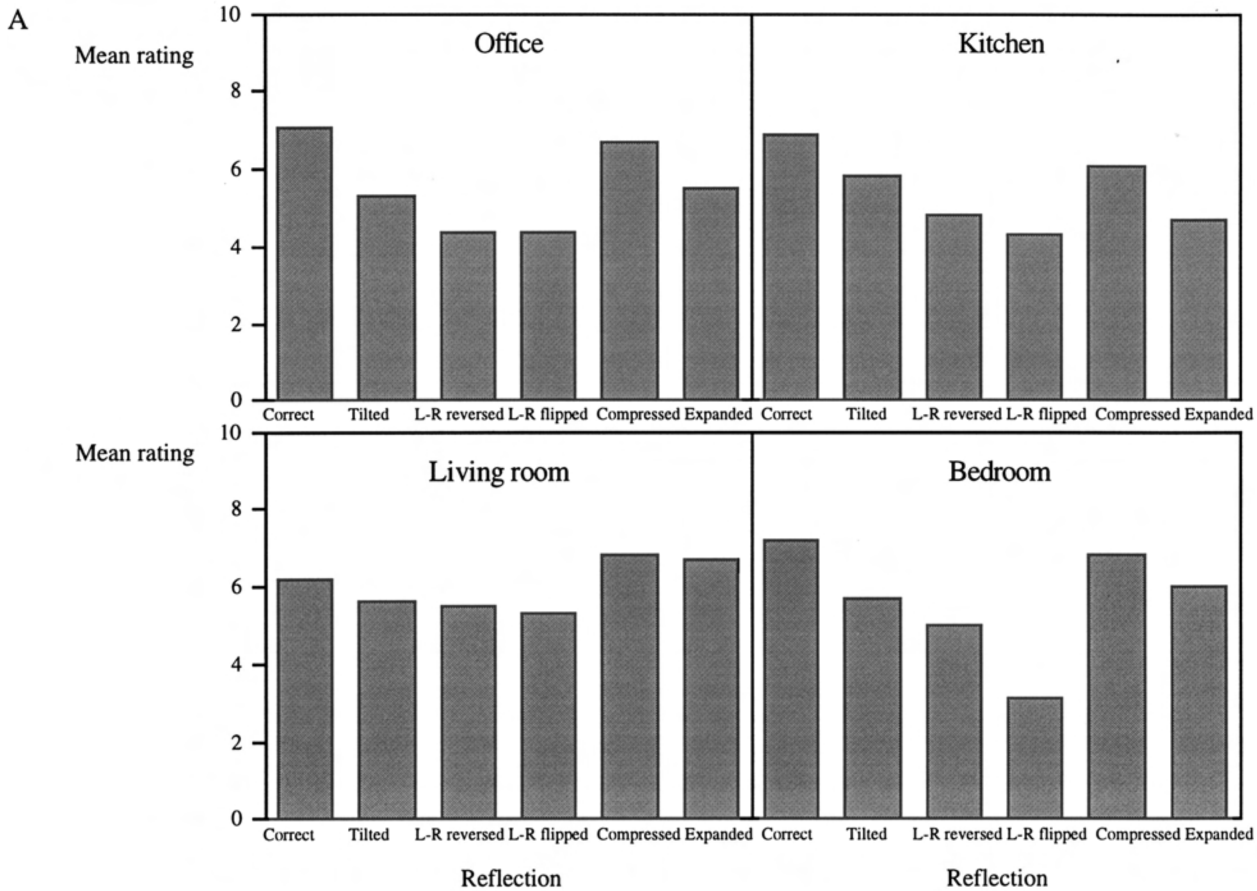


Figure 9. Stimuli used in Experiment 3. All six types of mirror reflection are shown for one of the four rooms (office). (A color version of this figure is available in the online version of this article, which is part of the PsycARTICLES database.)



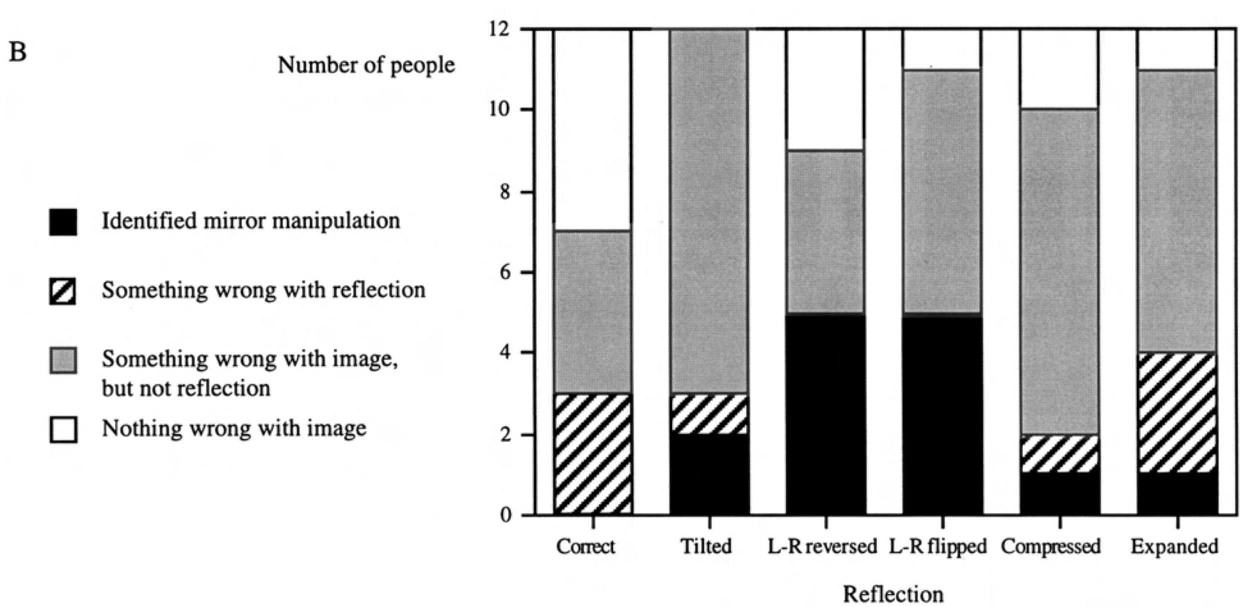


Figure 10. Data from Experiment 3. A: Mean naturalness ratings given to each image, on a 0 (least accurate) to 10 (most accurate) scale, separately for each of the four rooms. B: Numbers of participants making each type of comment about each type of reflection. L-R = left–right.

mirror), and (d) those who identified the manipulation (e.g., the reflection was the wrong way round). The number of participants falling into each category is presented in Figure 10B.

Cross-tabulation analyses were conducted on the frequency data, with the four response categories above and the six reflection types. Wilks's Lambda was used to indicate the asymmetrical predictive relationships between the two variables. The analyses revealed that reflection type did not predict response (Λ = .06, p = .64), indicating that the proportions of each type of response were similar within each reflection. The analyses revealed that response predicted reflection type (Λ = .17, p = .04), indicating that the pattern of reflections did differ within response category: The first three response categories contained similar proportions of participants across reflection types, but the group of participants who identified the reflection manipulation included more people who had seen the left–right reversed and left–right flipped reflections than people who had seen the other types of reflection.

In summary, participants rated the left–right manipulated images lower than the other images. Participants were also more likely to notice the manipulation in the left–right images than in the other images. This finding suggests that, although participants' perceptual knowledge about reflections was weak enough to accept reflections that were wrong in some ways, their knowledge was sufficient to recognize the error in images in which the mirror reflection had been in some way reversed about its midvertical axis.

The most striking aspect of the results is the high level of tolerance for distortions in mirror reflections. Figure 10B shows the number of participants who claimed that something was wrong in the mirror (31% in total). This can be compared with the 53% who picked other aspects of the image for criticism. Because participants were specifically asked what was not right in the computer-generated images, some guessing or artistic criticism of the objects was to be expected. Moreover, three participants did not like the correct reflection. One participant in this group interestingly volunteered the suggestion that perhaps the image in the mirror should have been left–right reversed. Presumably, this person would have found the reversed image more natural. (This individual was not categorized as having identified the mirror manipulation, because this response was incorrect.)

Given this high tolerance, participants in Experiment 4 were explicitly directed to consider the reflection reproduced in the images. Moreover, the type of reflection was changed to be a within-subject variable.

Experiment 4

The same models of four rooms from Experiment 3 were used in Experiment 4. The main difference was that participants were now specifically asked to judge whether the mirror reflection was correct. In Experiment 3, a high degree of tolerance was found for any reflection that was not left–right reversed. Experiment 4 was conducted to ascertain whether this tolerance would still be present when participants' attention was directed to the mirror reflections.

There were three versions of Experiment 4. In Experiment 4A, the images from Experiment 3 were used. The images were printed on paper, the order of presentation was randomized, and testing was carried out individually. In Experiments 4B and 4C, the images were presented by means of a projector in a classroom; therefore, only one randomization of the order was possible, but this provided an efficient way to administer the test to a large sample. Experiment 4B used the same images as Experiment 4A. In Experiment 4C, the angle from which the room was viewed was changed. The observer in the model was placed in the same location, at the same distance as before, but was now looking directly to his or her front. The resulting images might have made the viewer's position relative to the mirror clearer. These images also had a more natural feel because the mirror reflection was not centered in the image.

Method

Participants. Undergraduates (23 female, 17 male) at the University of Liverpool participated in Experiment 4A. Their mean age was 21.02 years (SD = 2.93 years). Experiment 4B tested a sample of school students (39 female, 13 male; mean age = 17.91 years, SD = 0.96 years) and their parents (19 female, 13 male; mean age = 48.65 years, SD = 4.45 years) during a university open day. Experiment 4C tested a similar sample of school students (38 female, 14 male; mean age = 18.27 years, SD = 0.93 years) and their parents (19 female, 12 male; mean age = 48.44 years, SD = 4.24 years).

Materials. Experiments 4A and 4B used the same 24 images used in Experiment 3, with six reflections (correct, tilted, left–right reversed, left–right flipped, compressed image, and expanded image) in each of four rooms (office, kitchen, living room, and bedroom). In Experiment 4A, the images were presented on paper in an A4 binder. In Experiment 4B, the images were presented in a lecture theatre using a projector. In Experiment 4C, the images were constructed in the same manner except that the angle of view was orthogonal to the mirror. They were also presented in a lecture theatre using a projector. Examples of the orthogonal images used in Experiment 4C are provided in Figure 11. In Experiments 4B and 4C, participants were also administered a paper-and-pencil test, identical to the Jane task used in Experiment 1.

Procedure. Participants were instructed that the experimenter was interested in what people know about mirror reflections and that they would be shown a series of images containing mirrors. Participants were required to make two responses for each image—to judge the reflection to be correct or incorrect and to provide a rating from 0 to 10 of their confidence in their answer. In Experiment 4A, responses were noted by the experimenter. In Experiments 4B and 4C, participants marked their own responses on answer sheets and also solved the Jane task, requiring them to mark where on a line Jane would be standing when she would first see her reflection. The Jane task was presented after the 24 room images, displayed on the projector, and printed on the reverse of the answer sheets. Instructions were given as in Experiments 1 and 2.

Results: Experiment 4A (Presented on Paper)

Figure 12A summarizes the likelihood of items of each reflection and each room being identified as a correct reflection (i.e., participant responded *yes*). Correct, tilted, compressed-image, and expanded-image reflections were all identified as correct more often than were left–right reversed and left–right flipped reflections. All items were responded to with similar confidence (the range for different reflections was between 7.2 and 8.5 on a 10-point scale).

Responses and confidence were combined to give a score, henceforth referred to as *acceptance.* Confidence was weighted by response—positive if participant responded *yes* and negative if

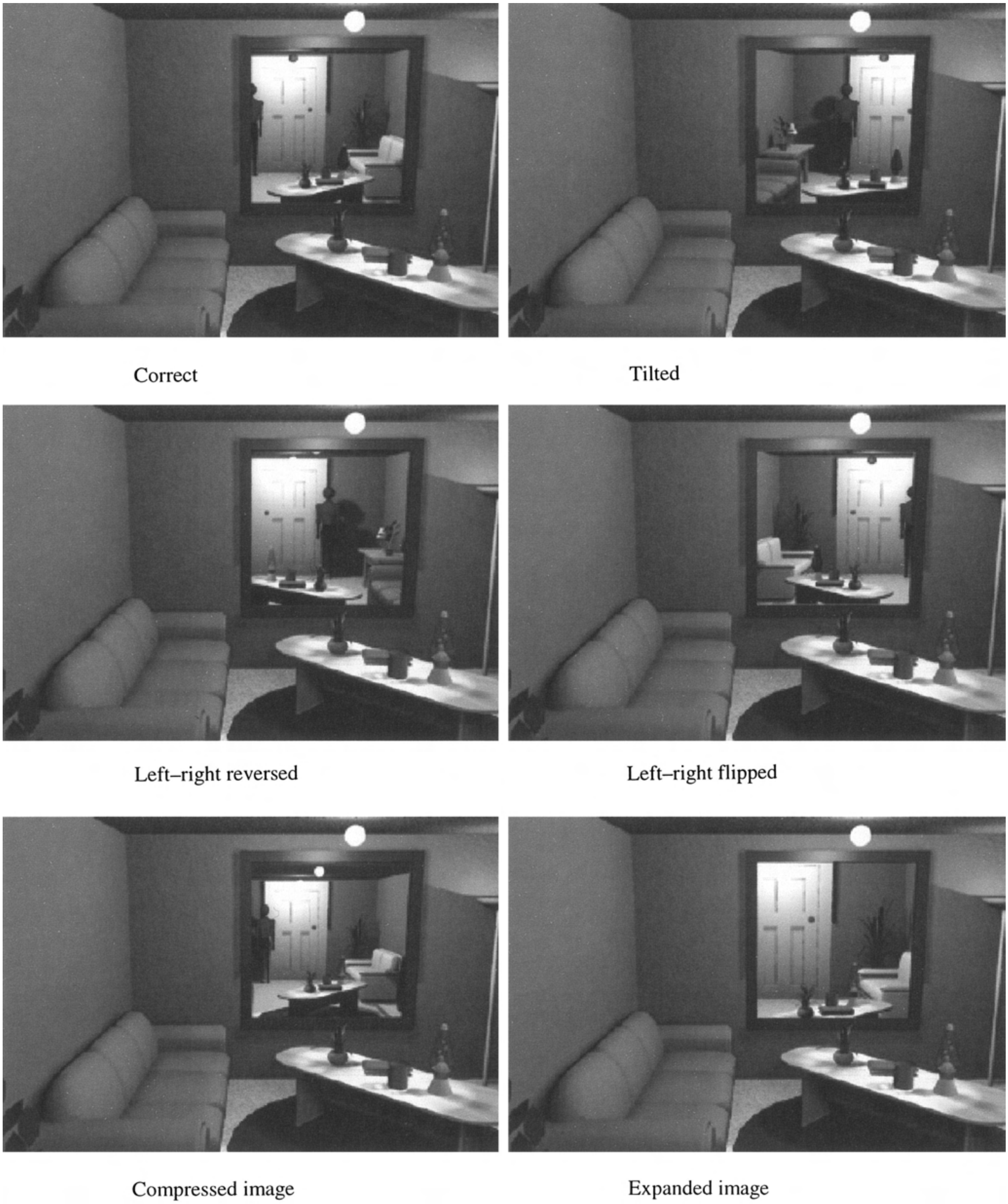
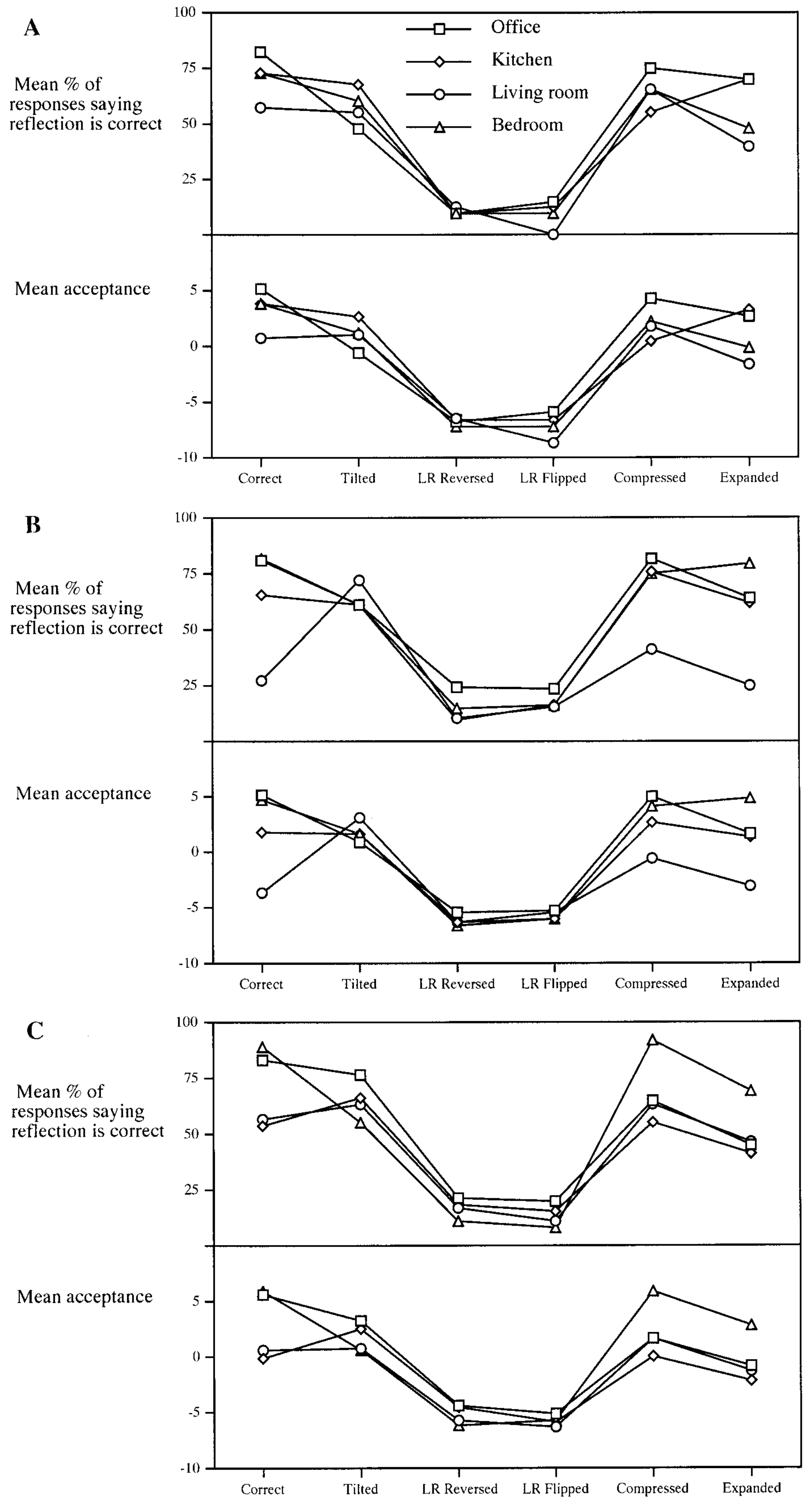


Figure 11. Stimuli used in Experiment 4C. All six types of mirror reflection are shown for one of the four rooms (living room). (A color version of this figure is available in the online version of this article, which is part of the PsycARTICLES database.)


A
B
C
Mean % of responses saying reflection is correct
Mean acceptance
Office
Kitchen
Living room
Bedroom
100
75
50
25
5
0
-5
-10
Correct
Tilted
LR Reversed
LR Flipped
Compressed
Expanded
Reflection

participant responded *no.* For example, when a participant responded *yes* to an item, and rated his or her confidence 10, his or her acceptance score for that item was 10. In contrast, when a participant responded *no* with a confidence rating of 10, his or her acceptance score for that item was -10. When participants were responding at chance, they should have been giving very low confidence scores; both *yes* and *no* responses with confidence 0 would yield acceptance scores 0. Even if participants responded at chance with high levels of confidence but with no correlation between response and confidence, the average score would be close to 0.

The acceptance scores therefore ranged from -10, reflecting confident rejection of items, to 10, reflecting confident acceptance of items as correct reflections, with random guessing reflected by acceptance scores around 0. The lower panel of Figure 12A summarizes acceptance of each reflection and each room.

A two-way ANOVA, with room and reflection as variables, was conducted on acceptance scores for each item. The analysis revealed a significant main effect of room, $F(3, 117) = 5.39$, $p < .001$; a significant main effect of reflection, $F(5, 195) = 54.77$, $p < .001$; and a significant Room $\times$ Reflection interaction, $F(15, 585) = 2.18$, $p = .01$, which accounted for only 5.2% of the variance (η^2).

A series of post hoc Tukey comparisons was conducted on acceptance scores to examine the significant effects revealed by the ANOVA. Comparisons between each room revealed that living room images were accepted less than office and kitchen images (all *p*s $< .05$). Comparisons of each type of reflection revealed that left–right reversed and left–right flipped reflections were accepted less than were all other types of reflection (all *p*s $< .05$). Comparisons of each reflection within each room revealed that, in all rooms, left–right reversed and left–right flipped reflections were accepted less than were all other reflections and that, within the office images, the tilted reflection was accepted less than the correct and compressed image reflections were (all *p*s $< .05$).

Results: Experiment 4B (Presented on Projector)

Figure 12B summarizes participants' likelihood of identifying items as correct reflections and reveals that, in general, correct, tilted, compressed-image, and expanded-image reflections were identified as correct more often than were left–right reversed and left–right flipped reflections. Participants responded with similar confidence to all items (the range for different reflections was between 5.9 and 7.4 on a 10-point scale).

As in Experiment 4A, a measure of acceptance was computed. The lower panel of Figure 12B summarizes acceptance of each reflection type. A three-way ANOVA, with room, reflection, and age group as variables, was conducted on acceptance. The analysis revealed significant main effects of room, $F(3, 204) = 23.18$, $p < .001$, and reflection, $F(5, 340) = 92.12$, $p < .001$, and a significant Room $\times$ Reflection interaction, $F(15, 1020) = 10.16$, $p < .001$, which accounted for 13.0% of the variance (η^2). The main effect of age was not significant, $F(1, 68) < 1$, and there were no other interactions.

To investigate the significant main effects and interactions revealed by the ANOVA, a series of post hoc Tukey comparisons was conducted on acceptance. Comparisons of rooms revealed that living room items were accepted less than were those of all other rooms and that kitchen items were accepted less than were office and bedroom items (all *p*s $< .05$). Comparisons of each reflection demonstrated that left–right reversed and left–right flipped images were accepted less than all other types of reflection and that expanded images were accepted less than compressed images (all *p*s $< .05$).

To investigate the relationship between performance on the two tasks, we divided participants into two groups according to their response to the Jane task. The *early* group consisted of participants whose response was 2 mm or more before the mirror's edge ($n = 39$). All other participants constituted the *correct* group ($n = 31$). A three-way ANOVA, with room, reflection, and group as variables, was conducted on acceptance. The analysis revealed a nonsignificant main effect of group, $F(1, 68) < 1$, and nonsignificant Group $\times$ Room, $F(3, 204) < 1$, and Group $\times$ Room $\times$ Reflection, $F(15, 1020) < 1$, interactions. The analysis revealed a significant Group $\times$ Reflection interaction, $F(5, 340) = 3.84$, $p < .001$. This interaction accounted for only 5.7% of the variance (η^2). The acceptance scores for left–right reversed and left–right flipped images were lower for the correct group than for the early group, but the acceptance scores for compressed and expanded images were higher for the correct group than for the early group. These trends were not significant. Post hoc Tukey comparisons conducted on acceptance of reflections within each group separately revealed that both the early and correct groups accepted left–right reversed and left–right flipped reflections less than they did all other reflections (all *p*s $< .05$). The Tukey comparisons revealed no further significant differences.

Results: Experiment 4C (Orthogonal Views, Presented on Projector)

Figure 12C summarizes responses and shows that participants were less likely to identify left–right reversed and left–right flipped reflections as correct than they were other types of reflections. They responded to all other items with similar confidence (the range for different reflections was between 6.5 and 7.7 on a 10-point scale).

The lower panel of Figure 12C summarizes acceptance of items within room and reflection type (as described in Experiment 4A). A three-way ANOVA, with room, reflection, and age group as variables, was conducted on acceptance of items. The analysis revealed significant main effects of room, $F(3, 168) = 13.37$, $p <$

Figure 12 (opposite). Data from Experiment 4: mean likelihood (percentage of responses) of reflections being identified as correct and mean acceptance—responses weighted by confidence on a 0 (least) to 10 (most) scale—for Experiments 4A (A), 4B (B), and 4C (C). The latter measure combines correct responses with confidence rating in a measure of how acceptable the image was to the observer. LR = left–right.

.001, and reflection, $F(5, 280) = 55.12$, $p < .001$. The analysis also revealed a significant Room × Reflection interaction, $F(15, 840) = 5.99$, $p < .001$ (accounting for 9.7% of the variance); a significant Reflection × Age Group interaction, $F(5, 280) = 3.96$, $p < .001$ (accounting for 6.6% of the variance); and a significant Room × Age Group interaction, $F(3, 168) = 4.26$, $p = .01$ (accounting for 7.1% of the variance). The ANOVA showed no significant main effect of age and a nonsignificant Room × Reflection × Age Group interaction (both Fs < 1).

A series of post hoc Tukey comparisons was conducted on acceptance to investigate the significant main effects and interactions revealed by the ANOVA. Comparisons of each room revealed that office and bedroom images were accepted more than were kitchen and living room images (all ps $< .05$). Comparisons of each type of reflection revealed that left–right reversed and left–right flipped images were accepted less than were all other reflections and that expanded reflections were accepted less than were correct, tilted, and compressed reflections (all ps $< .05$). Comparisons conducted on acceptance of reflection types by each age group revealed that the younger participants exhibited lower acceptance of left–right reversed and left–right flipped reflections than did other participants. Older participants exhibited lower acceptance of left–right reversed and left–right flipped reflections than they did of correct, tilted, and compressed image reflections, with expanded image reflections being accepted less than correct and tilted reflections (all ps $< .05$).

To investigate the relationship between performance on the two tasks, we divided participants into two groups according to their response to the Jane task. The *early* group consisted of participants whose response was 2 mm or more before the mirror's edge ($n = 40$). All other participants constituted the *correct* group ($n = 19$). A three-way ANOVA, with room, reflection, and group (early or correct) as variables, was conducted on acceptance. The ANOVA revealed a nonsignificant main effect of group, $F(1, 57) < 1$, and nonsignificant Room × Group, $F(3, 171) < 1$; Reflection × Group, $F(5, 285) = 1.70$, $p = .14$; and Reflection × Room × Group, $F(15, 855) < 1$, interactions.

General Discussion

We found that participants made large errors in what they believed would be visible in a planar mirror (Experiments 1 and 2). They expected a person to see herself earlier than was actually the case, but only when they imagined the person moving on a horizontal plane (walking across a room). This finding is consistent with earlier work (Croucher et al., 2002). However, when presented with reproductions of correct and incorrect mirror reflections, participants demonstrated a high level of tolerance for distortions (Experiments 3 and 4). In line with the results of other work in naive physics, performance on the explicit prediction tasks and the perceptual tasks was not equivalent. We entertained four hypotheses in the introduction, which we here evaluate in turn.

1. *Egocentric mirror rotation:* Do people respond as if the mirror is tilted toward the observer? This was the case for paper-and-pencil tests in the horizontal plane but not in the vertical plane, in which the observer was climbing down a rope (Croucher et al., 2002) or moving in a lift. In Experiments 3 and 4, those mirror reflections that simulated a 10° tilt were perceived as equally natural compared with the canonical cases. Prima facie, the fact that tilted mirrors looked natural seems to support the hypothesis. But the inability to distinguish slightly tilted mirrors from canonical cases might indicate that observers are insensitive to rotation. Thus, the mirror rotation hypothesis finds no direct support. However, larger tilt angles should be investigated to further explore this hypothesis.

2. *Capture:* People consider whether the character can see the mirror. Capture constitutes a nondistinction between a mirror (image) and a picture. If one can see a picture, then one can see whatever is reproduced in the picture. Therefore, if one can see the mirror, then one can see oneself in the mirror. If this is so, participants should have based their responses on when they thought that the observer could see the mirror itself. In this case, they should have predicted that Jane would see her reflection as soon as she could see the mirror (i.e., at the beginning of the dashed line). This was clearly not the case for the majority of participants.

3. *Boundary extension:* People falsely assume that mirrors give larger reflection areas than they actually do (see Intraub, 1997). In other words, people believe that the mirror makes available an extended visual world. Experiments 1 and 2 are partially compatible with boundary extension because of the early error (an overestimation of what is visible). However, boundary extension should apply both vertically and horizontally, but we do not find the overestimation in the lift condition. In Experiments 3 and 4, observers tended to judge compressed mirror images to be just as natural as the canonical mirror image. This is consistent with the hypothesis, although the difference between compressed and expanded images was only significant in one of the analyses, and in general the effect was symmetrical.

4a. *Conceptual left–right reversal:* The virtual world is like a 180° rotation around a vertical axis so that a character standing at the left of a mirror would see his or her reflection on the right. Of the four hypotheses, the first three are symmetrical: They predict equivalent performance across direction of motion. Only the left–right reversal hypothesis predicts that the early error should be related to horizontal motion but not to vertical motion. Experiments 1 and 2 nicely conform with the left–right reversal hypothesis: When the character moved horizontally in a room, participants tended to make the early error. This was the case even when the mirror was placed on the ceiling or the floor, albeit with smaller effect sizes. When the character moved vertically, up or down in a lift, the early error was absent.

In addition, the early error was related to predicted location of the character's reflection. In two conditions—horizontal motion with mirror on wall and horizontal motion with mirror on ceiling—participants who made the early error also tended to predict that the character's reflection would appear on the opposite side of the mirror from the character. This finding provides further support for the left–right reversal hypothesis as it is depicted in Figure 1B. The relationship was not found when the character moved horizontally with the mirror on the floor. This could have resulted for one of two reasons. First, the early error was weaker in the floor condition. Second, there was a type of salience of the reflection location in this condition that was absent in the other conditions: When the character reached the mirror, her feet would actually meet the reflection of her feet. This is a familiar scenario (e.g., when one steps into a puddle or looks down into a lake), and as such, the absence of a significant correlation in the floor condition does not speak against the left–right hypothesis. In short, the pencil-and-paper experiments suggested that people's explicit knowledge about reflections is erroneous in a consistent manner. In particular, some people may expect that the transition from actual world to reflected world is a 180° rotation around a vertical axis. This belief may originate from (erroneous) explicit knowledge of reflections, and it can result in an expectation that a character will see his or her reflection while standing to one side of the mirror.

Other evidence suggests that the difference between up–down and left–right is general to spatial reasoning. When people are asked to describe space, they tend to use up–down descriptions more than they do front–back terms, and they use left–right references least of all (Rodrigo & de Vega, 1995). In addition, when people hear a narrative describing a character in a scene, they tend to encode spatial information relative to the character's body (e.g., Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990). When they are then asked to make decisions about the location of objects in the scene, they respond fastest when the location can be described with respect to the head–feet axis, next fastest with respect to the front–back axis, and slowest with respect to the left–right axis. This preference continues when the character has moved in space (Bryant & Wright, 1999), demonstrating that locations were indeed encoded relative to the body, not space. It has been suggested that the asymmetry of the head–feet axis makes it more salient than the left–right axis (e.g., Bryant & Tversky, 1999; Bryant & Wright, 1999). If so, perhaps our own findings demonstrate that the greater salience of up–down locations than left–right locations extends to reflections. This would be consistent with findings that (self-)rotations are imagined with greater facility in the ground plane than they are in other planes (see, e.g., Carpenter & Proffitt, 2001; Pani, 1993; Parsons, 1987).

4b. *Perceptual left–right reversal:* The left–right reversal hypothesis applied to perceptual judgment entails that observers should judge images that do reverse left and right to be as natural, or almost as natural, as correct renditions. This was clearly not the case. Viewing actual cases of left–right reversal allowed observers to easily identify this manipulation as unnatural.

In summary, Experiments 3 and 4 were conducted to compare predictions about mirror reflections with what can be called *perceptual knowledge.* Different manipulations were introduced to test various possible distortions in how mirror reflections are perceived or remembered. The tilted condition tested whether mirror surfaces rotated toward the orientation orthogonal to the line of sight looked most natural. The left–right reversed and left–right flipped conditions tested whether mirror reflections were expected (and remembered) to reverse locations of objects from left to right. The compressed-image condition, especially when compared with the expanded-image condition, tested whether a phenomenon similar to boundary extension (Intraub, Gottesman, Willey, & Zuk, 1996) may take place for mirror images. Although these two experiments may need to be replicated and expanded upon, the results so far can be summarized in two main findings: (a) Perceptual judgments about mirror images are highly tolerant of distortions. This phenomenon is consistent with what is known about tolerance of distortions in projected images seen from arbitrary points of observation (what Kubovy, 1986, called the *robustness of perspective*). (b) Within this pattern of high tolerance, participants were least tolerant to manipulations in which the locations were left–right reversed. In contrast to the left–right reversal for which we found evidence in the paper-and-pencil tasks, participants identified left–right reversed reflections as incorrect more than they did any other type of manipulated reflection in the perceptual tasks. In other words, there seems to be a dissociation between perceptual and conceptual knowledge about mirror reflections.

In this article, we have compared conceptual and perceptual knowledge by generating images of mirror reflections. For practical reasons, we used images of familiar environments. The rooms we chose contained plenty of straight edges (i.e., corners and furniture) to ensure that enough information about the mirror location and orientation was present in the images. Nonetheless, the images were "photographs" of virtual rooms with mirrors, many of which contained manipulated mirror reflections. Judgments about the naturalness of the mirror reflections could thus have differed from what observers might experience in real rooms. Thus, perceptual knowledge may not have been explored to the fullest. In another set of more recent experiments, we have extended these findings to more sophisticated animations (Hecht, Bertamini, & Spooner, 2003). Some of the experiments even included real-time interactions between the observer and the image in the mirror. Results have confirmed our previous findings that observers make early errors. In another line of inquiry, we have analyzed reproductions of mirrors in paintings, revealing observers' tolerance of incorrect mirror reflections (Bertamini, Latto, & Spooner, 2003).

We conclude that although people's misconceptions about mirror reflections can be explained by the left–right reversal hypothesis, observers are reasonably good at recognizing such reversals as wrong when presented with an accordingly manipulated image. Perceptual judgments are better explained by the boundary extension hypothesis or, simpler yet, by mere tolerance for quantitative distortions. The pattern of results suggests a dissociation of conceptual and perceptual knowledge. Similar dissociations have been found in other areas of naive physics, for example, the behavior of falling objects (McCloskey et al., 1983; Shanon, 1976) and wheels (Proffitt, Kaiser, & Whelan, 1990). Although perceptual knowledge displayed surprisingly large errors, we found it sufficient to reject the left–right reversals that observers may hold in the more conceptual tasks. Finally, even though our work originated from and sits within the literature on naive physics, our findings are probably related to a larger body of evidence on the limits in spatial representation and reasoning (e.g., Bryant & Tversky, 1999; Pani, 1997; Simons, 2000).

References

Amsterdam, B. (1971). Mirror self-image reactions before age two. *Developmental Psychobiology, 5,* 297–305.

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

Bozzi, P. (1990). *Fisica ingenua* [Naive physics]. Milan: Garzanti.

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., Tversky, B., & Franklin, N. (1992). Internal and external spatial frameworks for representing described scenes. *Journal of Memory and Language, 31,* 74–98.

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

Carpenter, M., & Proffitt, D. R. (2001). Comparing viewer and array mental rotations in different planes. *Memory & Cognition, 29,* 441–448.

Cottrell, J. E., & Winer, G. A. (1994). Development in the understanding of perception: The decline of extramission perception beliefs. *Developmental Psychology, 30,* 218–228.

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.

Cutting, J. E. (1987). Rigidity in cinema seen from the front row, side aisle. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 323–334.

Frankin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General, 119,* 63–76.

Gallup, G. G., Jr. (1977). Self-recognition in primates. *American Psychologist, 32,* 329–338.

Gardner, M. (1967). *The ambidextrous universe.* New York: Basic Books.

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

Gombrich, E. H. (1960). *Art and illusion.* Oxford, England: Phaidon Press.

Gottesman, C. V., & Intraub, H. (2002). Surface construal and the mental representation of scenes. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 589–599.

Gregory, R. L. (1997). *Mirrors in mind.* London: Penguin.

Hecht, H., & Bertamini, M. (2000). Understanding projectile acceleration. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 730–746.

Hecht, H., Bertamini, M., & Spooner, A. (2003). *Naïve optics: Understanding dynamic mirror reflections.* Manuscript submitted for publication.

Hecht, H., & Proffitt, D. R. (1995). The price of expertise: Effects of experience on the water-level task. *Psychological Science, 6,* 90–95.

Intraub, H. (1997). The representation of visual scenes. *Trends in Cognitive Sciences, 1,* 217–222.

Intraub, H., & Bodamer, J. L. (1993). Boundary extension: Fundamental aspect of pictorial representation or encoding artifact? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 1387–1397.

Intraub, H., Gottesman, C. V., Willey, E. V., & Zuk, I. J. (1996). Boundary extension for briefly glimpsed photographs: Do common perceptual processes result in unexpected memory distortions? *Journal of Memory and Language, 35,* 118–134.

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

Kaiser, M. K., Proffitt, D. R., & Anderson, K. (1985). Judgments of natural and anomalous trajectories in the presence and absence of motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 11,* 795–803.

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.

Kubovy, M. (1986). *The psychology of perspective and Renaissance art.* Cambridge, England: Cambridge University Press.

McCloskey, M. (1983). Intuitive physics. *Scientific American, 245,* 114–119.

McCloskey, M., Caramazza, A., & Green, B. (1980, December 5). Curvilinear motion in the absence of external forces: Naïve beliefs about the motion of objects. *Science, 210,* 1139–1141.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 636–649.

Milner, A., & Goodale, M. (1995). *The visual brain in action.* London: Oxford University Press.

Ono, H., Wade, N., & Lillakas, L. (2002). The pursuit of Leonardo's constraint. *Perception, 31,* 83–102.

Pani, J. R. (1993). Limits on comprehension of rotational motion: Mental imagery of rotations with oblique components. *Perception, 22,* 785–808.

Pani, J. R. (1997). Descriptions of orientation in physical reasoning. *Current Directions in Psychological Science, 6,* 121–126.

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.

Pani, J. R., Zhou, H., & Friend, S. M. (1997). Perceiving and imagining Plato's solids: The generalised cylinder in spatial organization of 3D structures. *Visual Cognition, 4,* 225–264.

Parsons, L. M. (1987). Imagined spatial transformation of one's body. *Journal of Experimental Psychology: General, 116,* 172–191.

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

Pittenger, J. B., & Runeson, S. (1990, December). Paolo Bozzi's studies of event perception: A historical note. *International Society for Ecological Psychology (ISEP) Newsletter, 4*(3), 10–12.

Povinelli, D. J. (2000). *Folk physics for apes.* Oxford, England: Oxford 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.

Proffitt, D. R., Kaiser, M. K., & Whelan, S. M. (1990). Understanding wheel dynamics. *Cognitive Psychology, 22,* 342–373.

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.

Shanon, B. (1976). Aristotelianism, Newtonianism and the physics of the layman. *Perception, 5,* 241–243.

Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition, 7,* 1–15.

Smith, B., & Casati, R. (1994). Naïve physics: An essay in ontology. *Philosophical Psychology, 7,* 225–244.

Vasta, R., Rosenberg, D., Knott, J. A., & Gaze, C. E. (1997). Experience and the water-level task revisited: Does expertise exact a price? *Psychological Science, 8,* 336–339.

Winer, G. A., & Cottrell, J. E. (1996). Effects of drawing on directional representations of the process of vision. *Journal of Educational Psychology, 88,* 704–714.

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.

Yang, T. L., & Kubovy, M. (1999). Weakening the robustness of perspective: Evidence for a modified theory of compensation in picture perception. *Perception & Psychophysics, 61,* 456–467.

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