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Naive Optics: Understanding the Geometry of Mirror Reflections

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Paper-and-pencil tasks showed that many university students believed that when laterally approaching a mirror, they would see a reflection in the mirror before it was geometrically possible. Participants failed to adequately factor in the observer's location in the room. However, when asked about the behavior of a ray of light, participants knew about the law of reflection. No differences between psychology and physics students were detected, suggesting that the phenomenon is widespread and refractory to training. The findings were replicated with observers making judgments about image locations in a real room using a pretend mirror. Possible heuristics about mirror reflection that might explain the data are discussed. Naive optics is a promising venue to further knowledge of how observers understand basic laws of physics.

Intuitive or naive physics is an area that has been studied extensively in cognitive psychology (for an overview, see Smith & Casati, 1994). It is not only children that hold incorrect beliefs about physical phenomena; many adults also hold beliefs that are inconsistent with accepted scientific theories of classical mechanics. For instance, erroneous naive beliefs have been found in the cases of falling objects (Caramazza, McCloskey, & Green, 1981; Kaiser, Proffitt, & McCloskey, 1985; McCloskey, Caramazza, & Green, 1980; McCloskey, Washburn, & Felch, 1983), surface orientation of liquids (Hecht & Proffitt, 1995; Robert & Harel, 1996), wheel dynamics (Proffitt, Kaiser, & Whelan, 1990), and projectile motion (Bozzi, 1990; Bozzi & Bressan, 1987; Hecht & Bertamini, 2000; Krist, Fieberg, & Wilkening, 1993).

Naive beliefs about visual perception have also been reported recently. Cottrell and Winer (1994) and Winer, Cottrell, Karefilaki, and Chronister (1996) have claimed that many people believe perception is an extramissive process, contrary to the accepted scientific explanation that light is reflected or emitted from objects and then enters the eyes. Extramission theory posits that something shoots out of the eyes of the beholder toward the fixated object(s). The belief dates back to antiquity and exists in a number of literal and geometric varieties (see, e.g., Hatfield & Epstein, 1979). Similar to most naive theories, the frequency of this belief declines somewhat with age (Cottrell & Winer, 1994), but is still found in a large proportion of adults (see also Winer & Cottrell, 1996; Winer, Cottrell, Karefilaki, & Gregg, 1996; cf. Langley, Ronen, & Eylon, 1997, who found no clear evidence for extramission beliefs in 14- to 15-year-old students).

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This article is concerned with naive beliefs about the reflection of light and optical phenomena, which we refer to as *naive geometrical optics* (henceforth abbreviated to *naive optics*). With few exceptions, naive optics has been overlooked in the psychological literature, and, consequently, this article attempts a first assessment of the naive understanding of the geometry of mirror reflection.

Naive beliefs can be related to scientific beliefs that were present in the history of science before being superseded by more modern theories. In mechanics, much naive physics seems to be Aristotelian (Bozzi, 1990; McCloskey, 1983). In the case of optics, one ancient belief already mentioned that might persist in naive physics today was the principle of extramission. On the other hand, some aspects of geometrical optics have been well understood for centuries. The concept of a ray as the direction of rectilinear propagation was present in Euclid's *Optics*, and Euclid also knew that the angle of incidence and the angle of reflection on a mirror are equal, although he omitted to mention that they must also be coplanar (Ronchi, 1970). Hero of Alexandria (circa 100 A.D.) explained these facts by postulating that light always follows the shortest possible path, coming therefore very close to discovering Fermat's principle, that is, the principle of least time (Hecht & Zajac, 1974).

Flavell, Green, Herrera, and Flavell (1991) have found that the knowledge that it is only possible to see things within a straight line of sight is acquired around the age of 5 years, but the question of what knowledge of geometrical optics is present in adults has not yet been addressed from a psychological perspective (but see Langley et al., 1997, for a summary of educational research into preconceptions about various areas related to light and optics in older teenagers and college students). One obvious reason for this is that, strictly speaking, light rays cannot be observed, so optics is a less obvious research venue than mechanics. Nevertheless, there are many familiar phenomena that are governed by the laws of geometrical optics and could thus have been conducive to the intuitive acquisition of laws of optics. For instance, such knowledge is relevant in situations in which people have to judge if they are hidden from someone else's view. Mirrors constitute a wonderful test case for an analysis of naive understanding of the basic laws of geometric optics.

An oft-cited demonstration of human fascination with mirrors is their use in art. However, even more interesting for our purpose is that sometimes the mirror reflections depicted in paintings are incorrect. Examples include *The Bar at the Folies-Bergères* by Edouard Manet (1832–1883) and *Las Meninas* and the *Rokeby Venus* by Diego Rodríguez de Silva y Velázquez (1599–1660). Inspection of the positions and size of the people in the scene reveals their impossibility, but it requires some attention, suggesting a certain degree of tolerance in people's expectations of how a mirror behaves. For instance, Gregory (1998; all three paintings are reproduced in his book) has pointed out that the face of the lady in the *Rokeby Venus* is much too large. It is even more interesting, given that an observer can see her face from the angle of observation, that the impression that she is actually admiring herself in the mirror cannot possibly be true. It should be noted that we are not suggesting that these painters do not know how reflection works; it could equally be that these impossible but aesthetically pleasing reflections are examples of artistic license.

Naive beliefs often have little internal consistency and (according to Champagne, Klopfer, & Anderson, 1980) are preparadigmatic in the Kuhnian sense. Langley et al. (1997) agreed with this, as they found that students' responses to a range of tasks looking at their conceptions of light varied widely depending on contextual factors, such as whether an observer was present. This suggests that there may be significant variation in the naive conceptions held about what will be visible in a mirror, and these also may differ depending on the specific details of the questions asked. However, we do not think that as in other intuitive physics tasks (e.g., horizontality of liquid surfaces) there are any frames of reference that could be inducing a specific bias. Champagne et al. (1980) have reasoned that formal education in physics ought to lead to a decline in the incidence of naive beliefs, but the evidence for this is somewhat mixed.

Generally, it has been found that education in the relevant area does not improve performance on naive physics tasks (Caramazza et al., 1981; McCloskey et al., 1983; Robert & Harel, 1996). However, Clement (1982) found that students who had completed a mechanics course were slightly better at problems involving force and acceleration than students who had only just enrolled in one, and Kalichman (1986) found that students of the natural sciences and engineering were more accurate on water-level tasks than students of the social sciences and business, although naive beliefs were still noticeable in both studies. It may be that naive beliefs continue to interfere with the correct physics knowledge because the latter is only learned subsequent to the establishment of the naive beliefs and in a specific educational context. A number of studies have found that expertise (defined as repeated experience with the physical phenomenon in question) also does not significantly improve performance in naive physics tasks. For example, Hecht and Bertamini (2000) found that even observers who regularly play ball sports will tolerate a variety of impossible trajectory paths for a projectile; Hecht and Proffitt (1995; but see Vasta, Rosenberg, Knott, & Gaze, 1997) found that bartenders and waitresses were worse than bus drivers and housewives at realizing that the surface of a liquid always stays horizontal; Proffitt et al. (1990) found that cyclists were no better than anyone else at problems involving wheel dynamics.

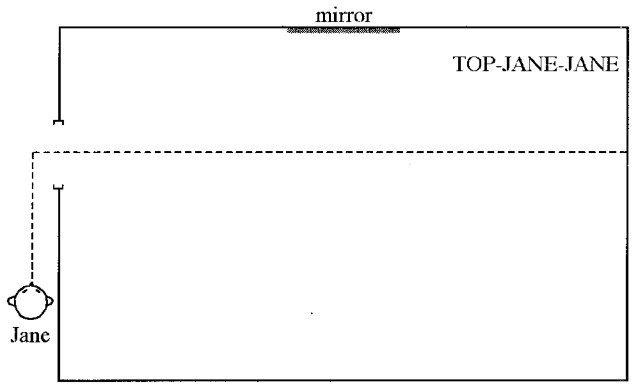
To investigate naive beliefs about geometrical optics, we asked people to predict what would be made visible by a mirror. Anecdotal evidence and pilot data had previously suggested to us that many people make errors in predicting when they would see themselves or another object when they or the object was moving into the visibility region of the mirror. This is despite that most people should have learned at school that for a specular surface, such as a mirror, the angle of incidence is equal to the angle of reflection (Fermat's principle or the law of reflection). Although knowledge of this law does not necessarily lead to the ability to use it to predict mirror images, the consequences of the law of reflection are easily observed in real life experiences with mirrors, and it is hard to go through a full day of activities in the Western world without using or being exposed to at least one mirror or specular surface. Therefore, in a sense, all of our participants were experts. For instance, people should know that as they change position, what is visible to them in a mirror changes systematically. It is unlikely that people are confused by the complex behavior of concave and convex mirrors, because most man-made mirrors and natural reflecting surfaces (such as pools of water) are planar surfaces. We expected errors and variability in individual predictions, which could be attributable to various incorrect implicit models of mirror imagery, including Gregory's idea that people perform an incorrect mental transformation between the object and its mirror image (Gregory, 1998).

The experiments reported in this article tested students' knowledge of reflection by two methods. Experiments 1A, 1B, 2, and 3 tested the understanding of the law of reflection by use of various paper-and-pencil tasks. Experiments 4 and 5 used occluded mirrors in a real room.

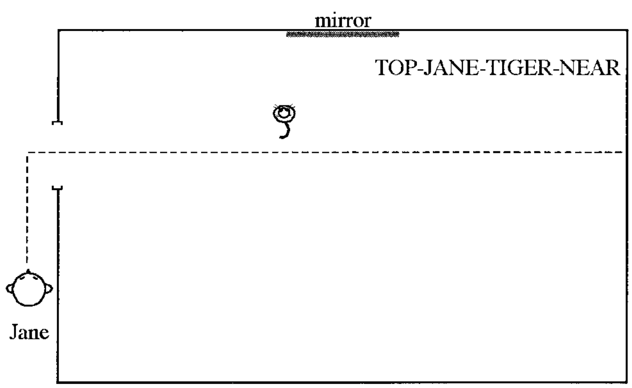
Experiment 1A: What Is Visible in a Mirror?

Because no work has been reported on what people believe about what is visible in a mirror, we designed a range of mirror tasks to be administered between subjects to explore the responses of participants. Instead of an introspection approach, which would be hard to quantify and difficult to analyze, a paper-and-pencil methodology was adopted. To avoid undue complexity and confounding variables, we designed all the conditions so that movement was only in one dimension relative to the mirror (i.e., horizontal or vertical, and parallel to the mirror's surface).

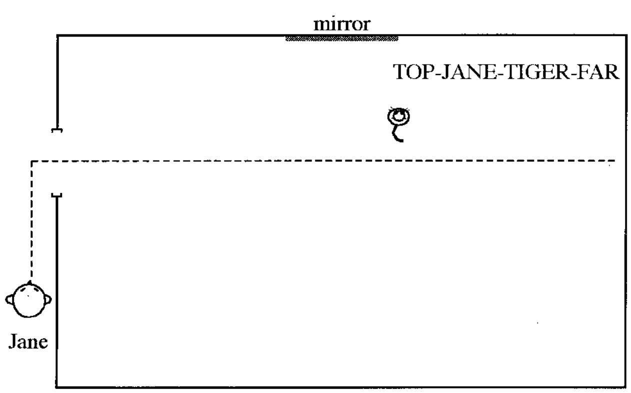
An item in our pilot studies depicted a top view of a room with a mirror on one wall, in which a person was shown standing outside the door and imagined walking across the room parallel to the mirror. We asked where this person would first be able to see herself. Many participants believed that this point came before the person arrived in front of the mirror, which is physically impossible. This task was retained for the current experiment, and six variations on it were added (Figure 1). Two of these were cross-sectional side views in which the person was climbing up or down a rope: This was to see whether naive beliefs differed between conditions in which movement was vertical and horizontal relative to the mirror. The other four new conditions involved another character, a cat. In these conditions, the person was always the observer and the cat was always the target. This allowed us to separate the movement of the observer and the movement of the target, as well as to compare a moving point of observation with a stationary point of observation. We varied whether the person or



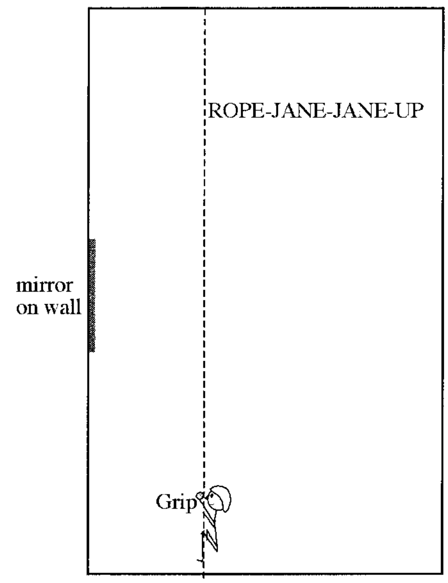
Jane walks through the door and across the room, please mark the point at which she can first see herself in the mirror.



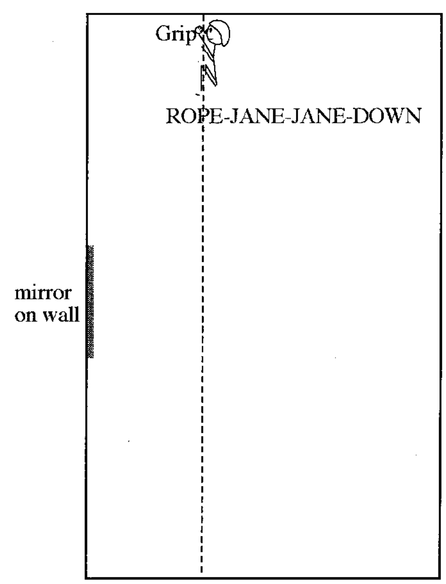
Jane walks through the door and across the room, please mark the point at which she can first see the cat in the mirror.



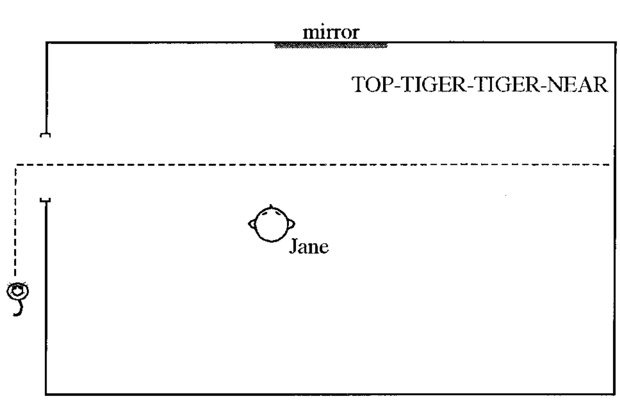
Jane walks through the door and across the room, please mark the point at which she can first see the cat in the mirror.



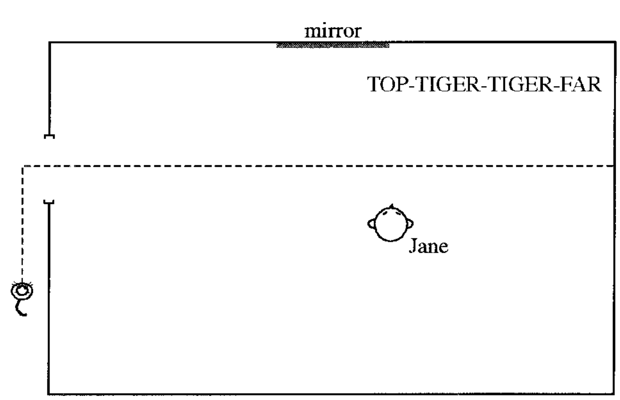
Jane climbs up the rope. Please mark the place her grip will be when she can **first** see her eyes in the mirror.



Jane climbs down the rope. Please mark the place her grip will be when she can **first** see her eyes in the mirror.



The cat walks through the door and across the room, please mark the point at which Jane can first see the cat in the mirror.



The cat walks through the door and across the room, please mark the point at which Jane can first see the cat in the mirror.

the cat walked across the room (while the other stood in line with one edge of the mirror). Another factor was crossed with this: the position of the stationary individual, either at the near or far edge of the mirror. We were interested in seeing whether the relative positions of the observer and of the target were taken into account by participants. On the basis of our pilot results, we expected participants to overestimate what would be seen in a mirror by expressing the belief that the observer would be able to see themselves or the cat before it was physically possible.

Method

Participants. All participants (153 women and 31 men; this ratio is not atypical for a psychology degree) 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 19.5 years.

Materials. Participants were presented with schematic drawings and asked to indicate either where a person called Jane would first see herself in the depicted mirror or where she would first see a cat called Tiger. We gave names to the characters in the drawing to make the task less abstract and more engaging. Only one character was moving in each condition, and, to ensure that everyone understood the tasks and the positions in the room, we provided the path along which the moving individual traveled as a line (with a 2-mm dash to aid measurement). Movement was always in only one dimension and parallel to the mirror. The seven tasks, as presented, are shown in Figure 1. Only one task was given to each participant, so there were seven groups altogether.

For ease of reference, we labeled the scenarios using strings, such that the first part of the string indicated the task type (Top or Rope), the second part indicated the individual who moved (Jane or Tiger), and the third part indicated the target individual (Jane or Tiger). Finally, a fourth part was added when there was a stationary character, to indicate the lateral alignment of that character with the mirror (Near = the character was aligned with the near edge of mirror; Far = the character was aligned with the far edge of mirror). The two Rope tasks were identical apart from whether Jane climbed up or down, so the fourth component was Up or Down for these two items. Thus, Top-Jane-Tiger-Far was a task using a bird's eye view in which Jane walked parallel to the mirror, and we asked when she could first see Tiger, who was standing in line with the far edge of the mirror. Note that the stationary individual stood in a different position in Top-Tiger-Tiger and Top-Jane-Tiger to avoid any possible suggestions of occlusion (this meant that the stationary individual was not in the exact same place across the conditions, and the correct answers differed accordingly).

Procedure. The test material was administered to the class in a break during the lecture. An overhead projector was used to display a set of general instructions, including a request that people did not confer and that they read the questions carefully before answering. The questions for each condition were as shown in Figure 1. We gave each participant the original item and a left–right reversed version of it (not shown in Figure 1), to balance any possible left–right response bias (order was counterbalanced).

Results and Discussion

A mixed analysis of variance (ANOVA) showed there were no differences between left and right reversed versions of the items, $F(1, 180) = 0.01$, $p = .956$; this did not interact with condition, $F(6, 180) = 0.46$, $p = .836$, and therefore the data were collapsed over the two measurements. For each participant, the two responses were averaged in the following analysis. The mean lateral distances from the near edge of the mirror are shown in Table 1 (which allows for useful comparisons between the Near items and Far items). The mean errors are also shown (these are the same as the mean distances from the edge for all but the Far items). A negative error shows that on average, participants indicated the observer could see the target before it would be visible, and, correspondingly, a positive error indicates judged visibility lagging actual visibility.

The data from Experiment 1A are displayed in Figure 2 in a format similar to the stem and leaf representations invented by Tukey (1977). The mean response for each participant is shown to the nearest 4 mm for the sake of clarity, but the statistical analysis was based on data with a 1-mm resolution, measured with a ruler on the response sheet. Each open circle in Figure 2 represents 1 participant, and stacked open circles mean that more than 1 participant made their response at that point. Each dumbbell shape represents the mean response for each condition to the nearest millimeter. The one-sample *t*-test values and significance levels are also included in Figure 2. These tests show whether the means differ from zero, when zero is the near edge of the mirror. Values of *t* are shown for the mean error when the correct answer differs from the edge of the mirror.

Looking at the means, there were four main findings. First, an overestimation effect (things were judged to be visible too early) was pervasive but limited to top views (see one-sample *t*-test values in Figure 2). For both Rope-Jane-Jane-Up and Rope-Jane-Jane-Down, the mean was close to zero and the variability was low. The other conditions showed much greater variability (see the discussion on individual differences below), which suggests that they were significantly more difficult than the Rope items. One-sample *t* tests confirmed that the means of all but the Rope-Jane-Jane-Up and Rope-Jane-Jane-Down groups were significantly displaced from the near edge of the mirror (see Figure 2 for *t* values).

Second, the fact that people were much better on the Rope items suggests that people might think more effectively, or differently, about movement relative to the mirror in the vertical as opposed to the horizontal. To test for a viewpoint effect, we pooled the Rope results and compared them with Top-Jane-Jane (this case was similar to the Rope conditions as it was the only one in which there was only one character involved). This confirmed that people were significantly worse on Top-Jane-Jane even though Top-Jane-Jane was not any more complex, $t(27.04) = -2.27$, $p = .031$ (after adjustment for unequal variances). However, the participants in the Rope condition were presented with a side view that might have made the fact of Jane looking straight ahead more salient than in the other conditions. It is important to note that because no systematic error was present for the Rope conditions, the possibil-

Figure 1 (opposite). The seven items used in Experiment 1A. Each participant was given only one item, but in two versions, which were identical except for a left–right reversal of the layout to balance response biases. The names of the items are superimposed on the items in the figure, but did not appear on the sheet given to the participants. The names list the viewpoint (Top or Rope), the character moving (Jane or Tiger), the target (Jane or Tiger), and the position of the stationary character (opposite the Near or Far edge of the mirror). In the Rope condition, the fourth component indicates whether Jane is climbing up or down the rope.

Table 1
Experiment 1A: Mean Lateral Distances From the Near Edge of the Mirror, Standard Errors of the Means, and Mean Errors for Each Condition

Group	*N*	Mean distance (mm)	*SEM*	Mean error (mm)
Top-Jane-Jane	25	−14	6.56	−14
Rope-Jane-Jane-Up	28	0	1.19	0
Rope-Jane-Jane-Down	27	3	3.10	3
Top-Jane-Tiger-Near	27	−34	8.29	−34
Top-Jane-Tiger-Far	26	−60	6.38	19
Top-Tiger-Tiger-Near	26	−16	6.38	−16
Top-Tiger-Tiger-Far	27	−31	7.86	2

Note. Values are rounded to the nearest millimeter.

ity is ruled out that in the top view items, people were just randomly placing responses or making production errors. If participants assumed that the correct answer must be in between the edge of the room and the edge of the mirror (for example), because of some implicit demand characteristic of the task, they would have done so in the Rope items as well.

Third, if only one person was present (see Panel 1 of Figure 2) observers made significant errors. However, when another character entered the equation (Tiger), larger systematic errors occurred, suggesting an effect of the number of characters. For Top-Jane-Tiger-Near, Top-Jane-Tiger-Far, Top-Tiger-Tiger-Near, and Top-Tiger-Tiger-Far, the mean response fell a significant distance away from the mirror's edge. This is interesting because for the Near items, the correct answer was in line with the mirror's edge (see Panels 2 and 4 in Figure 2). In fact, the position of the stationary individual made no noticeable difference to the shape of the overall distribution, which suggests that many people were not taking the positions of the observer and target properly into account. The means are somewhat earlier for the Far items than for the Near items, but this is only significant for the Top-Jane-Tiger pair, $t(51) = 2.45$, $p = .027$. We suggest, therefore, that although for the Far items the responses were closer to the correct answer, the similarity with the responses to the corresponding Near items may mean that the position of the stationary character was not properly factored. By comparing Top-Jane-Tiger and Top-Tiger-Tiger, we are also comparing the case in which the point of observation was stationary with the case in which it was moving, possibly creating an imagined optic flow not only in the room, but also in the projection of the room on the mirror. This factor did not seem to lead to different responses, so there is no clear evidence concerning whether the imagined optic flow helped our participants in answering correctly.

Additionally, there appear to be individual differences related to different strategies, as the responses (excluding the Rope tasks) do not fit a normal distribution. Across all the conditions, 30%–60% of the observers responded correctly. The answers given by a noticeable minority (less than 10%) of observers suggest that they treated the mirror as capturing everything that is not directly occluded from view. In other words, for a group of participants, the reflected object became visible the moment the mirror itself came into view (see, in particular, Top-Jane-Tiger-Near and Top-Tiger-Tiger-Far). There were also a small minority who responded too late (less than 10%, except in Top-Tiger-Tiger-Far; see below), who had perhaps misunderstood the task in some way. Alternatively, it is possible that some individuals may have the idea that nothing can be seen in a mirror unless that object is in front of it. Even when the observation point was changed (as in Top-Tiger-Tiger-Far), 25% of participants placed their responses at the edge of the mirror, the position that would have been correct for any of the other items. However, it is also possible that the participants did not pay attention to the task; in addition, there was no pronounced cluster at the mirror edge in Top-Jane-Tiger-Far. Thus, some observers seem to construe the problems differently than required by the law of reflection.

We suspect that there may be a number of possible reasons for the responses of the largest erroneous group, the 14%–50% who placed their responses too early, but not as soon as the mirror was visible. A possible explanation for this overestimation effect is that some people conceive of an extended visibility zone of a mirror independent of observer position, although their everyday experience contradicts this conception. This fixed visibility zone hypothesis would predict that there would be no difference between Near and Far conditions: a proposition that is not inconsistent with our data, although it was between subjects. However, this hypothesis cannot be applied to the Rope items, so this extension is apparently lateral but not vertical. We investigated this hypothesis further in Experiment 5. Another explanation may be that people think mirrors always reflect at an angle when the observer is looking at another object, possibly because of experience of being able to view objects in a mirror that are not directly in one's line of sight. Different proportions of response types were given depending on the task, which suggests the possibility of a number of task-specific heuristics being used. This would be consistent with the idea that many people do not have a fully scientific conception of mirror reflection (i.e., they do not use a single general method to predict what will be visible in a mirror, although they need only to apply the law of reflection to answer correctly for all cases).

No consistent differences between men and women were found, but note that the sample was over 80% female. No age or program-of-studies analysis was possible in this experiment, because virtually everyone was between 18 and 21 and all were psychology students.

Experiment 1B (Control): Do People Know How Simple Reflection Works?

This experiment was performed to find out what proportion of people possessed the knowledge that on a mirror, the angle of incidence is equal to the angle of reflectance, and also to test people's ability to reproduce an angle presented to them. We then compared the results to the size of the errors in Experiment 1A.

Method

Participants. The participants were 23 first-year psychology undergraduates at the University of Liverpool. This sample of students came from the same population as those of Experiment 1A, but without overlap. There were 3 men and 20 women. The mean age was 18.6 years.

Materials. Participants were given items asking them either to reproduce an angle (Line condition) or to draw how a ray of light would be reflected from a mirror (Mirror condition). Participants were given two items each, one with a 60° angle of incidence and one with a 30° angle of incidence. The Mirror item was presumed to elicit perceptually internalized or declarative knowledge about how light is reflected from mirrors, and the Line item was to establish baseline accuracy for drawing angles that could be taken into account when analyzing the errors in Experiment 1A. The items are shown in Figure 3, along with the mean responses. The dimensions of the mirror and border were the same as those in Experiment 1A.

Procedure. The test material was handed to the students as they entered their lecture hall. Each received an instruction sheet and two items, as described in the materials section. The sheets were collected at the end of the lecture.

Results and Discussion

The mean responses are shown superimposed on the items in Figure 3. For the Line tasks, the mean error was 0.13° ($SE = 1.11$), and for the Mirror tasks, the mean error was 0.14° ($SE = 1.09$). One-sample t tests confirmed that none of the errors differed significantly from zero: for the Mirror items, $t(10) = 0.08$, $p = .940$, and for the Line items, $t(11) = 0.16$, $p = .873$. Moreover, there was no significant difference between responses to the Line and to the Mirror items.

There was a clear ceiling effect in all four conditions. The Mirror results suggest that our student population possessed the knowledge that the angles of reflectance and incidence are equal when light is reflected from a mirror. Many of the participants in Experiment 1A were not applying this knowledge. Furthermore, the Line items showed that production errors were extremely low. The errors for the top view conditions in Experiment 1A were much larger than would be expected from the errors in Experiment 1B. Thus, the results of Experiment 1B provided further support for the hypothesis that some people hold an incorrect naive understanding of how mirrors work, in parallel with the correct knowledge about angles of reflection. This is consistent with Langley, Ronen, and Eylon (1997), who found that people were more accurate on their optics tasks when there was no observer present (23% of their students achieved accuracy in the no-observer condition as opposed to 0% in the observer condition). They suggest that perhaps the inclusion of an observer confounds people's responses because it places the emphasis on vision rather than optics, and there might be naive conceptions that are related to vision but not to optics. It is unclear, however, how the inclusion of an observer could affect people's responses in our tasks, which simply asked them about visibility rather than the details of how a mirror image is actually formed.

Experiment 2: Mirrors and Windows Compared

Experiment 2 was designed to see whether people responded in the same way to tasks using windows and mirrors. We designed tasks in which Jane would see the same scene through a window as in a mirror, and we looked at the differences. The rationale for this was the theory that people think of mirrors as apertures or windows to a reversed copy of the world (Gregory, 1998; Loveland, 1986). However, if the only misconception present was that mirrors were conceptualized as windows, nobody would have predicted that the observer would see the target before they would in Experiment 1A. We expected that participants would not overestimate visibility through a window, but would still do so for a mirror.

Method

Participants. The participants were from two third-year lectures in psychology at the University of Liverpool. All were psychology students or combined honors students. There were 16 men and 55 women. Their mean age was 23 years.

Materials. The items used were based on those used in Experiment 1A, but the dimensions were changed slightly to allow for the cat to be pictured walking outside the room in the window items. The main factor of Experiment 2 was whether a mirror or a window was present; in either case, Jane would see the same image of the cat in the mirror or through the window, respectively (see Figure 4). There were also Near and Far variants as in Experiment 1A.

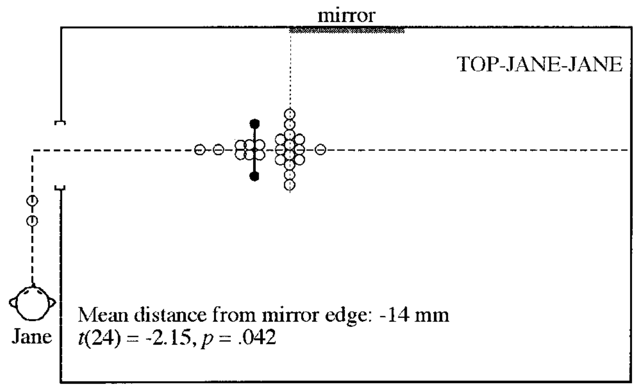
Results and Discussion

Responses were analyzed using the same steps as in Experiment 1A. Individual data and mean responses are plotted superimposed on the original items in Figure 4. The mean distances from the edge of the mirror or window and mean errors are shown in Table 2. Participants were much more accurate in the Window task than in the Mirror task. For the Mirror items, the overestimation effect was replicated, but for the Window items, responses were significantly different from zero in the positive direction, $t(37) = 7.72$, $p < .001$. Responses to the two situations were therefore qualitatively different. Mirror-Tiger-Tiger-Near replicated Experiment 1A—many people predicted that the person would see Tiger in the mirror before this was optically possible. People never predicted that Jane could see the cat before she actually would when it walked past a window outside. In fact, on average, they were too late, albeit with a smaller bias. Thus, in this case, for which it would have been a useful strategy to think of the mirror as analogous to a window, many people were using some other (less successful) strategy.

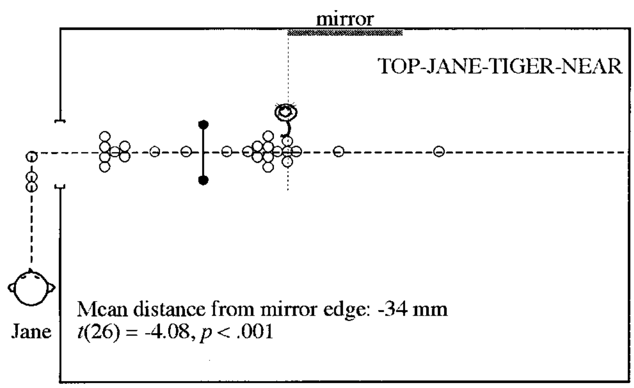
Once again, the mean responses for the Mirror items were in almost exactly the same place in the room regardless of where the observer stood. There was no significant difference in mean response distance from the mirror edge between the Far and Near mirror items, $t(33) = -0.12$, $p = .909$. It is interesting that the pattern of responses was so similar between tasks that had different correct answers, and this pattern is qualitatively similar to those obtained in the Top-Tiger-Tiger conditions of Experiment 1A.

Experiment 3: Does Training Improve Performance?

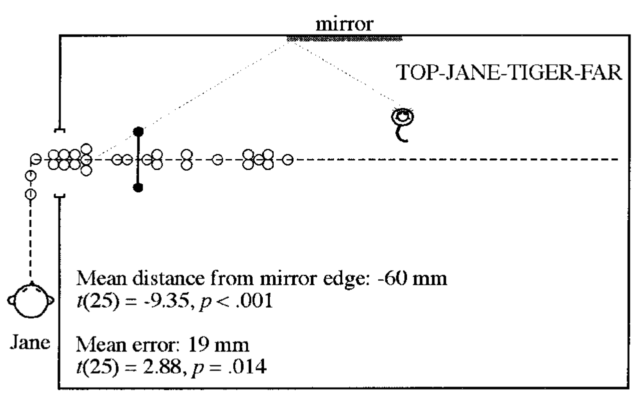
The comparison of Experiments 1A and 2 with Experiment 1B suggests that knowledge of the law of reflection does not always lead to a correct answer when people are asked about what is visible in a mirror. All of the psychology students in Experiment 1B clearly knew the law of reflection, but those in Experiments 1A and 2 did not apply it. This is consistent with findings in the naive physics literature that past training in physics has little effect on responses (Caramazza et al., 1981; Champagne et al., 1980; Clement, 1982; McCloskey et al., 1983; Proffitt et al., 1990). To test for such immunity to experience, we decided to replicate Experiment 1A in the context of a first-year physics class at the University of Liverpool. The populations were comparable in age and culture but not in gender ratio.



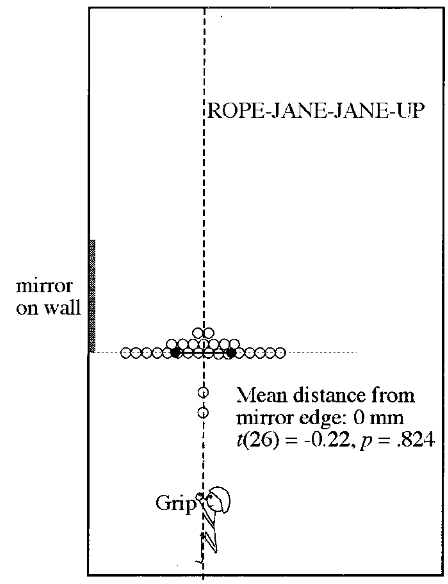
Jane walks through the door and across the room, please mark the point at which she can first see herself in the mirror.



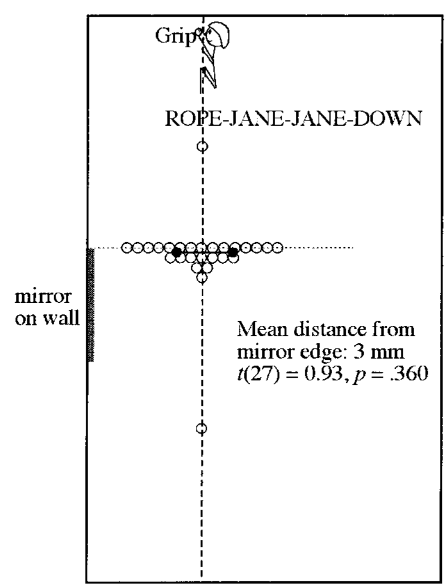
Jane walks through the door and across the room, please mark the point at which she can first see the cat in the mirror.



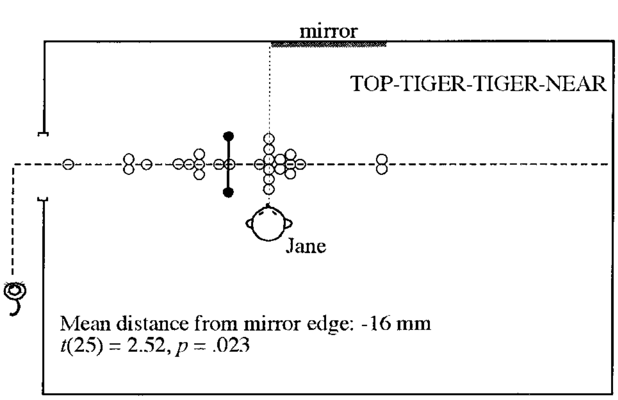
Jane walks through the door and across the room, please mark the point at which she can first see the cat in the mirror.



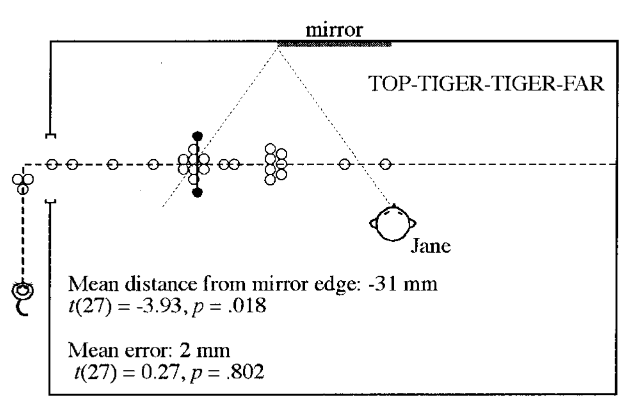
Jane climbs up the rope. Please mark the place her grip will be when she can **first** see her eyes in the mirror.



Jane climbs down the rope. Please mark the place her grip will be when she can **first** see her eyes in the mirror.



The cat walks through the door and across the room, please mark the point at which Jane can first see the cat in the mirror.



The cat walks through the door and across the room, please mark the point at which Jane can first see the cat in the mirror.

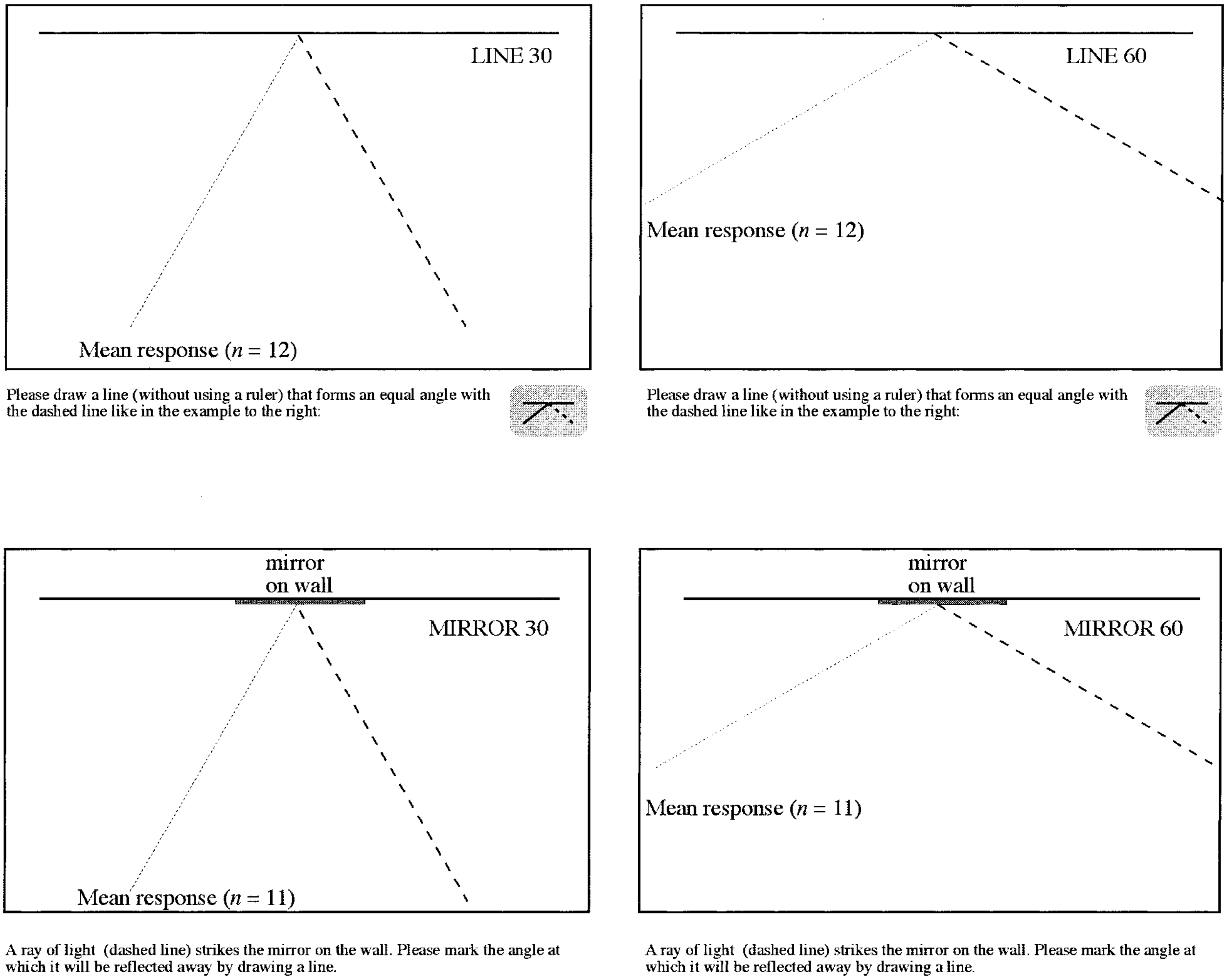


Figure 3. Mean responses of participants in Experiment 1B, superimposed on the items administered. The mean error for all four conditions was less than 1°. Whether a Mirror or a Line condition was used was a between-subjects factor, and each person was given a 30° item and a 60° item.

Method

Participants. The participants were first-year students enrolled in a physics class at the University of Liverpool. There were 55 men, 15 women, and 5 more participants who did not report their gender. The mean age was 19.9 years.

Materials and procedure. Four paper-and-pencil tasks were taken from Experiment 1A. The tasks used were Top-Jane-Jane, Rope-Jane-Jane-Down, Top-Tiger-Tiger-Near, and Top-Tiger-Tiger-Far (see Figure 5). Some items were left out to ensure reasonable group sizes. Only one Rope task was used, because it made no difference in Experiment 1A whether the person traveled up or down. Top-Jane-Tiger-Near and Top-Jane-Tiger-Far were dropped, because they were so similar to Top-Tiger-Tiger-Near and Top-Tiger-Tiger-Far. Everything else in the procedure was identical to Experiment 1A.

Results and Discussion

This study replicated the findings of Experiment 1A. The responses, mean responses, and *t* values for each condition are shown in Figure 5. Once again, visibility was overestimated on Top-Jane-Jane and Top-Tiger-Tiger-Near, whereas those in the Rope-Jane-Jane-Down condition were accurate. As in Experiment

Figure 2 (opposite). Results of Experiment 1A, by condition, superimposed on the tasks. Each open circle represents the mean response of 1 participant, and each dumbbell represents the mean for each condition. The individual responses are shown to the nearest 4 mm in all figures for the sake of clarity, but were measured to the nearest millimeter for statistical analysis. The thin dotted line represents the correct response for that condition. One-sample *t*-test values and probabilities are also shown for mean lateral distance from the mirror's edge and for mean errors when these two statistics differed.

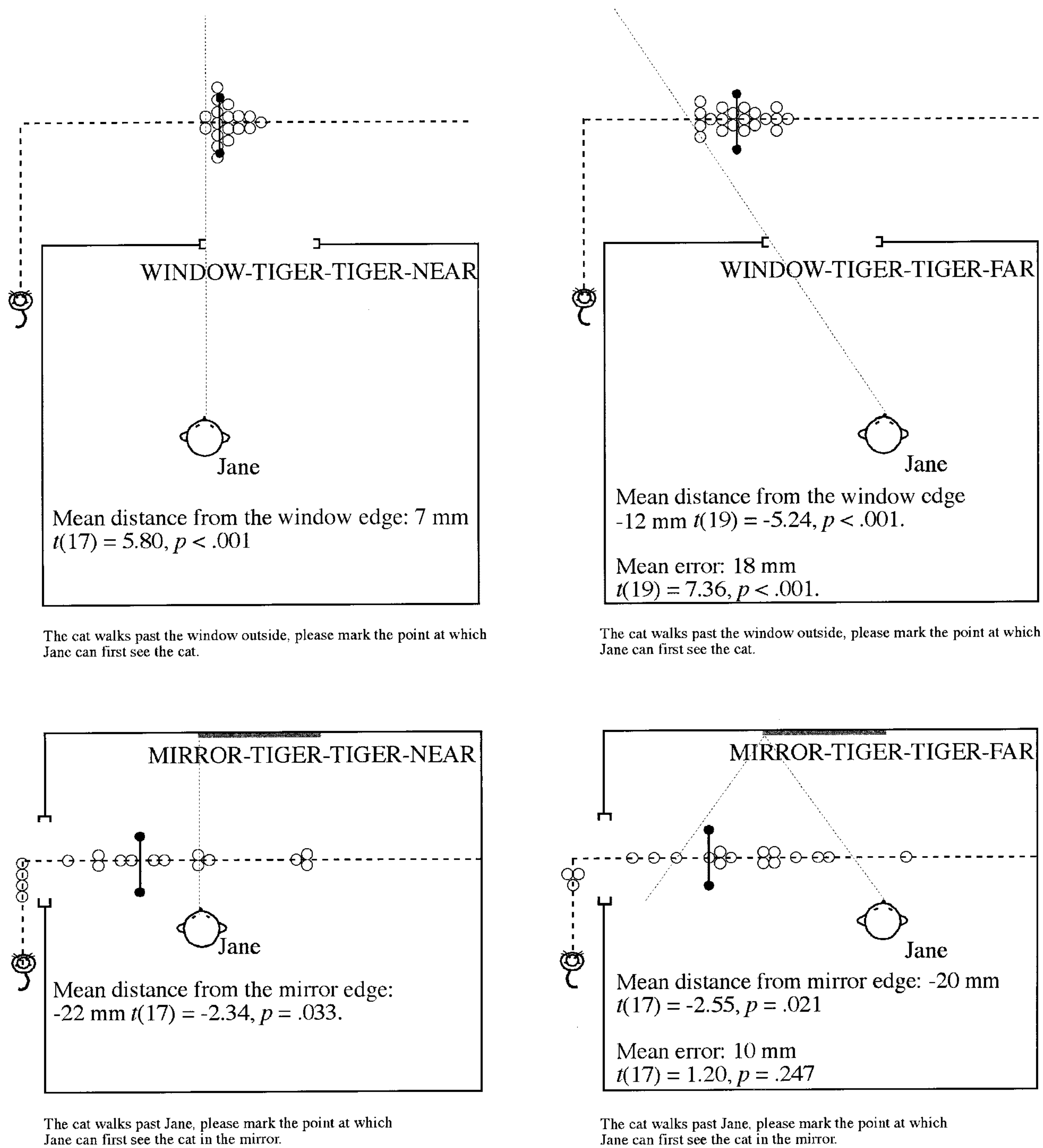


Figure 4. Results of Experiment 2, superimposed on reproductions of the items used. As in Figure 2, each open circle represents the mean response of a single participant to the nearest 4 mm, each dumbbell represents the mean for that condition, and each thin dotted line represents the correct response. One-sample t-test values and probabilities for each mean lateral distance from the mirror edge and mean errors (if different) are shown.

1A, Top-Tiger-Tiger-Near and Top-Tiger-Tiger-Far did not differ from each other, $t(36) = -1.29$, $p = .203$.

It has often been found that women are worse at naive physics tasks (Hecht & Proffitt, 1995; Kalichman, 1988; McAfee & Proffitt, 1991; Robert & Harel, 1996), although some studies have failed to find this (e.g., Hecht & Bertamini, 2000), and many others do not discuss gender differences. The physics class we tested was predominantly male, so gender differences were not testable within the sample. But when the results from the psychologists and physicists were pooled (totaling 81 men and 100 women), no

Table 2
Experiment 2: Mean Lateral Distances From the Mirror or Window Edge, Standard Errors of the Means, and Mean Errors for the Four Conditions

Group	*N*	Mean distance (mm)	*SEM*	Mean error (mm)
Window-Tiger-Tiger-Near	18	7	1.18	7
Window-Tiger-Tiger-Far	20	−12	2.38	18
Mirror-Tiger-Tiger-Near	17	−22	9.32	−22
Mirror-Tiger-Tiger-Far	18	−20	7.99	10

Note. Values are rounded to the nearest millimeter.

gender differences were found in the responses, $t(180) = 0.02$, $p = .988$. Also, no significant differences were found when the results from the physics students were compared by condition with the results from the psychology students. For Top-Jane-Jane, $t(28.83) = 1.61$, $p = .119$, after adjustment for unequal variances; for Rope-Jane-Jane-Down, $t(43) = 0.81$, $p = .425$; for Top-Tiger-Tiger-Near, $t(45) = 0.24$, $p = .812$; for Top-Tiger-Tiger-Far, $t(45) = 0.47$, $p = .640$. Robert and Harel (1996) have suggested that men (and science students) might be better at intuitive physics tasks, because spatial reasoning ability is linked to gender and might influence the course people take. However, we found that neither men nor students of physics were superior in correctly predicting what is visible in a mirror.

One noticeable difference in response between psychology and physics students was evident from looking at their actual response sheets. Twenty-seven percent of the physics students drew rays or lines between the observer's eyes, the mirror, and the target, compared with only 6% of psychologists. This finding could be attributed to training in physics and/or a context effect (because they were tested in a physics lecture). However, 12% of all physics students (vs. 3% of all psychologists) drew rays and got the answer wrong (error larger than ±15 mm, a conservative criterion considering this is 15% of the total distance between the door and the mirror in the top view conditions). Surprisingly, the overestimation effect seems robust to the use of ray diagrams in finding the correct answer.

Experiment 4: Moving the Self in Front of a Mirror

Having ascertained that observers exhibit biases when confronted with paper-and-pencil tasks about mirror reflections, we decided to test people in a real-life setting. We believed that the overestimation of what is visible in a mirror is a general phenomenon that is not dependent on the use of a paper-and-pencil task and should be found when using other kinds of tasks. However, in the past, it has been found that different methodologies yield somewhat different results. Proffitt and Gilden (1989) observed that in many studies, performance improved when observing a computer or real-life representation of events compared with paper-and-pencil tasks. Therefore, it is always important to compare paper-and-pencil tasks with tests that require action in a real environment. For example, McCloskey et al. (1983) found on a paper-and-pencil task that 51% of their participants incorrectly said that an object would fall straight down if dropped by a person walking (the correct answer, disregarding air resistance, is that it falls forward in a parabolic arc). However, participants did better when they had to hit a target on the floor by dropping an object (only 33% reported trying to drop it when it was directly above the target). In Experiment 4, we used a room as similar as possible to the one pictured in Experiment 1A and asked people where they would start to see themselves in a mirror when walking laterally toward it or away from it. Direction of approach was balanced and sagittal distance was kept constant, consistent with previous experiments.

Method

Participants. Students from the Psychology Department at the University of Liverpool (24 men and 24 women) participated in Experiment 4. Their average age was 20.4 years.

Materials and procedure. A computer lab in the Psychology Department of the University of Liverpool was used for this experiment. The room was 440 cm × 574 cm in size, with no windows and no reflective surfaces in which participants would be able to see themselves. A white board was covered in brown paper so participants could imagine it to be a mirror but could not see any reflection during the experiment. The white board was 120 cm wide × 87 cm high, and was vertically centered at approximately eye height. A straight line of masking tape was stuck to the carpet, 120 cm from the mirror surface and parallel to it. At the start position, participants were asked to stand with the tips of their toes behind the masking tape, with their feet together and a masking tape marker in between their feet. There were two conditions: In the Away condition, the marker was in line with the center of the mirror, and participants were asked to step sideways until they thought they would no longer be able to see their eyes in the mirror. In the Toward condition, the marker was at the side of the room, at a lateral distance of 186 cm from the mirror edge, and participants were asked to move sideways toward the mirror until they could first see their eyes in the mirror. Once the participant had stopped, the experimenter placed a marker between their feet (with their feet together) and measured the distance from the start marker.

Results and Discussion

The responses for each participant, means for each condition, and one-sample *t*-test values for lateral distances from the near edge of the mirror are shown superimposed on scale drawings of the experimental room in Figure 6. The mean distance from the mirror's edge for the Away condition was −73 cm ($SE = 17.16$); for the Toward condition, it was −70 cm ($SE = 11.82$). The distributions are similar for the two conditions and are comparable with those of our previous experiments (see Figures 2 and 5).

For the Away condition, any participant whose error was below −186 cm was coded as moving to only −186 cm. This was because in the Toward condition, the start marker was positioned 186 cm from the edge of the mirror, so this was the maximum error possible. This meant that 2 participants in the Away condition who stated that there was not enough space in the room to move to a position where they could not see themselves were coded for statistical purposes as responding at −186 cm.

For both the conditions, the mean responses were significantly different from zero (the edge of the mirror), as measured by one-sample *t* tests: Toward condition, $t(23) = -4.25$, $p < .001$; Away condition, $t(23) = -5.89$, $p < .001$. When the results are visually compared in Figure 6, it is obvious that the mean errors fell in almost exactly the same position in the room for each condition, and the overestimation effect is present in both. A *t* test

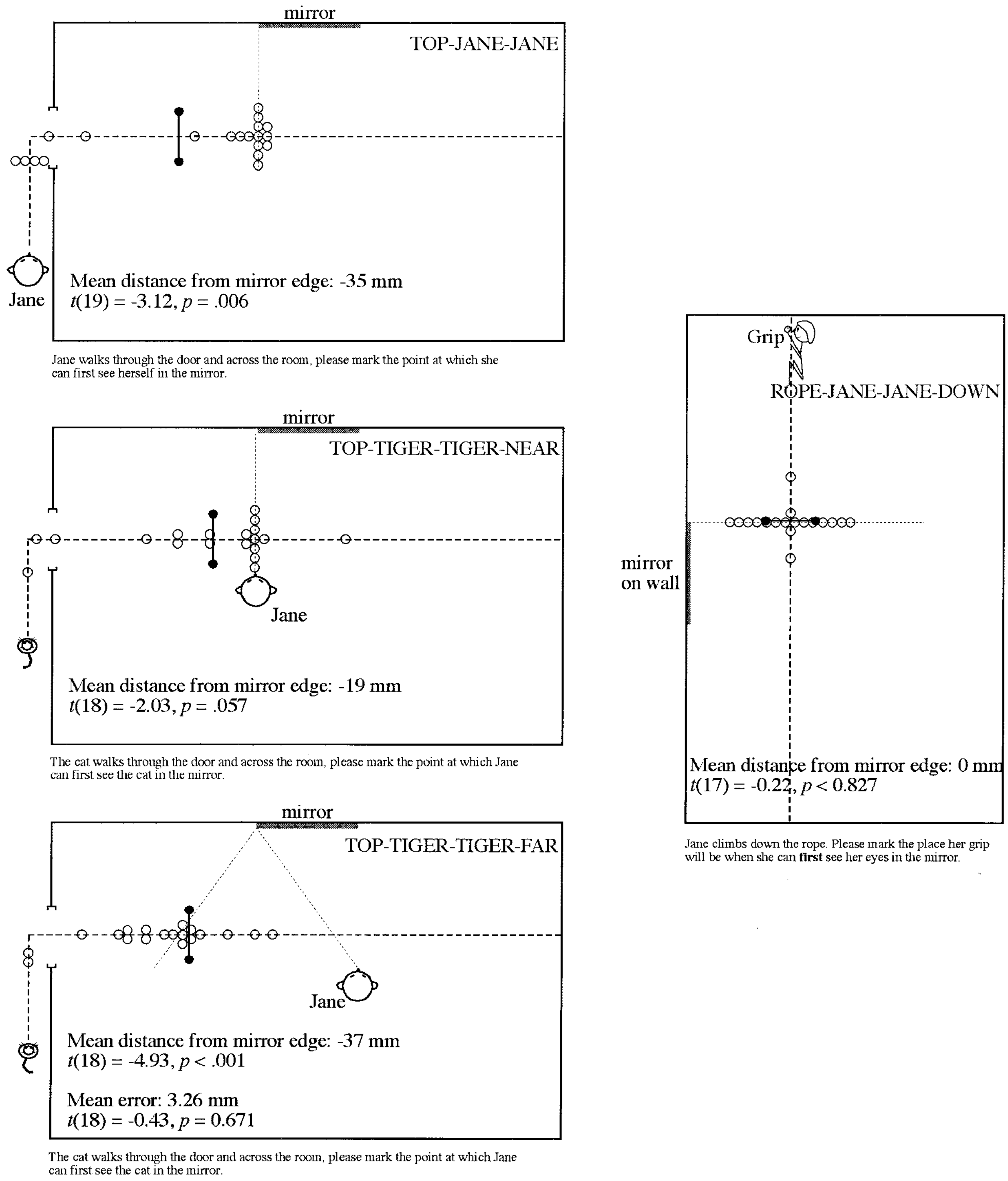


Figure 5. Results of Experiment 3, superimposed on the items used. The open circles represent participants' responses, the dumbbells are the mean responses for each condition, and the thin dotted lines are the correct answers. The participants in Experiment 3 were physics students, yet their responses were no more accurate than those of the psychology students. In addition, they were mostly men and the psychologists were mostly women, and a comparison between the two samples showed no gender differences.

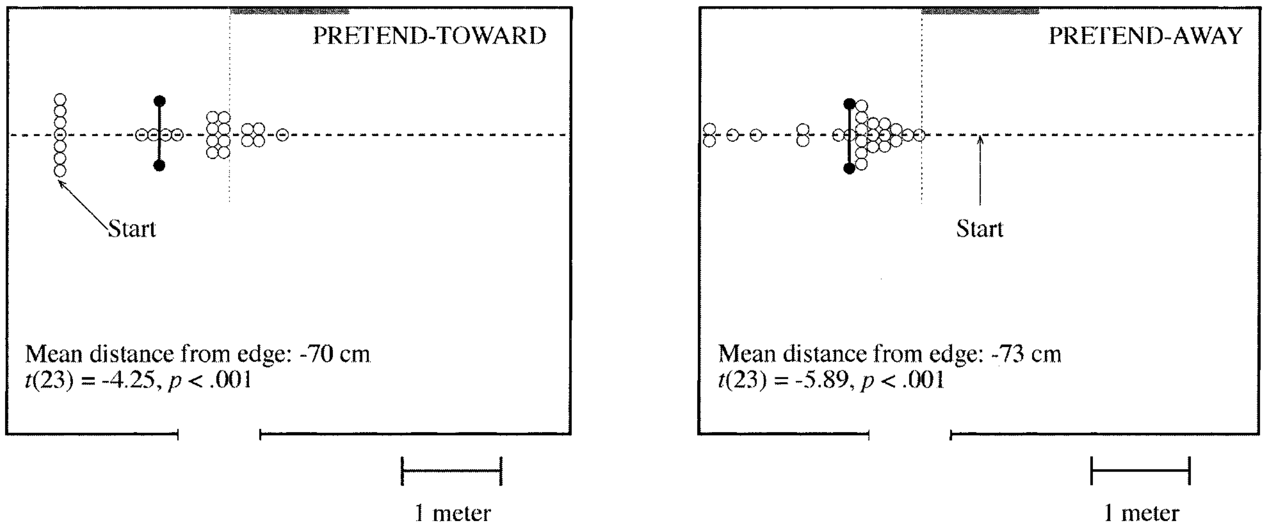


Figure 6. Results of Experiment 4, superimposed on a scale drawing of the room used. In this experiment, participants were asked to physically move either into or out of the visibility zone of a pretend mirror (a white board covered in brown paper). The width of a person's feet when together was measured to be approximately 20–25 cm, so the responses (open circles) are shown to the nearest 30 cm (as before, the responses were analyzed as exact responses). The thin dotted lines are the correct answers and the means are the dumbbells, and it can be seen that over half of all participants clearly got the answer wrong. Each condition is shown separately, but there was no significant difference between them.

for independent samples confirmed that there was no difference between the two conditions, $t(40.94) = -0.15$, $p = .879$.

We thought it was important to try to compare Experiment 4 with the paper-and-pencil studies to see whether there were any differences. We rescaled the responses of Top-Jane-Jane in Experiment 1A to be comparable with those of Experiment 4 by assuming that the rooms were the same width. (This made the room in Top-Jane-Jane 574 cm × 365 cm, which was judged to be a reasonable size for a room, and the mirror 113 cm wide, virtually the same size as the 120-cm one in the real room. The doorway of the real room was 84 cm wide, and the doorway in the paper-and-pencil items was 51 cm wide when scaled up, which is quite narrow, but again not entirely unrealistic.) The Experiment 4 data were compared with the data from the Top-Jane-Jane condition in Experiment 1A, as this was the condition without the cat and was therefore most similar. Any Top-Jane-Jane responses beyond −186 cm after being transformed were coded as −186 cm, because this was the largest error possible in the Toward condition of Experiment 4. The adjusted mean response for Top-Jane-Jane in Experiment 1A was −27 cm, whereas in Experiment 4, the mean response was −71 cm. The difference between these two means was significant, $t(60.37) = -2.95$, $p = .004$ (after adjustment for unequal variances), which shows that people performed much worse on the real-life version. This is contrary to previous findings that have suggested that people's actions are better calibrated to physical reality than their perceptions or predictions (Krist et al., 1993; McCloskey et al., 1983). However, our test did not rely on procedural skills but, on the other hand, required imagination. Counterintuitively, the optic flow induced by the observers' motion relative to the mirror and the room did not help our participants in answering correctly when they had to imagine what they would see in the mirror.

There were no differences between men and women on our paper-and-pencil tasks, but gender differences were tested again here, because the task was different and we had the opportunity to sample an equal number of men and women. In Experiment 4, the mean response for women across both conditions was −82 cm ($SE = 15.99$), and for men, it was −61 cm ($SE = 12.98$). The average error for men was lower, but no significant gender differences were detected, $t(46) = -1.04$, $p = .300$.

A few participants in this experiment asked whether they were allowed to look to the side or whether they had to keep looking straight ahead while moving parallel to the mirror. This suggests that they thought that if they could look directly at the mirror they could see themselves in it from any angle. In reality, they could not see themselves until they were in front of the mirror, irrespective of direction of gaze. Those who asked were told they could look wherever they wanted, but if other participants had made the silent assumption that they must always look straight ahead, we may have an underestimation of the effect in the data. This is similar to the idea of active looking rather than direction of light propagation being important in naive conceptions of optics in which an observer is involved (see Langley et al., 1997). Presumably, a similar effect could have occurred in the paper-and-pencil tasks as well, and could have been even more pronounced in them because there was less opportunity to ask for clarification of the task from the experimenter.

Experiment 5: Effects of Mirror Size

A small sample of participants in Experiment 4 who responded incorrectly were asked if they could explain their answer. A few reported that a mirror allows for a certain fixed amount of the environment to be visible, extending to the left and right of the physical position of the mirror. Because this was also suggested by some of our paper-and-pencil data, we tested for an effect of mirror size on the judgment of reflection. If some observers hold the mistaken view that mirrors capture a piece of the world from a fixed visibility zone, rather than reflecting it, they might believe that larger mirrors capture proportionally more of the world. Although a within-subjects study could show whether individuals take mirror size into account when working out the size of the visibility zone, the results might be problematic because the act of altering the mirror width during the experiment would reveal what was being tested. Therefore, we adopted a between-subjects design and performed an experiment similar to Experiment 4, but with mirror size as a factor. We also interviewed all participants about their responses in an open-ended manner, to try and ascertain some of the strategies that may have been in use by our sample.

Method

Participants. Participants were students in the psychology department at the University of Liverpool. There were 23 men and 25 women, and the mean age was 21.7 years. None had participated in Experiment 4.

Materials and procedure. The experimental materials were the same as in Experiment 4, except that mirror width was varied (75 cm, 50 cm, or 25 cm; see Figure 7). We changed only the horizontal dimension of the mirror and kept its original height (87 cm). The 48 participants were divided evenly across the three mirror width conditions. White paper was attached to the covered white board, and each participant was instructed that only the white part (in the center) was to be imagined as a mirror. Both the Away and Toward conditions were used as before.

Results and Discussion

The mean distances from the correct answer and the one-sample t-test values are shown superimposed on scale drawings of the room in Figure 7. Once again, whether the participants moved away from or toward the mirror made no difference to distance from the edge of the mirror, $t(40.83) = -1.34$, $p = .187$ (adjusted for unequal variances), and there were no gender differences, $t(46) = 0.24$, $p = .814$. It can be seen (Figure 7) that the distributions of responses are very similar across the different conditions. Table 3 shows the mean distances from the side wall, as well as the mean distance from the mirror's edge (this gives a measure of the distance moved that is independent of the mirror width used). A one-way ANOVA showed no difference between the four conditions for distance from the mirror's edge, $F(3, 92) = 0.64$, $p = .593$, but was borderline significant for position of the response in the room, as measured by distance from the wall, $F(3, 92) = 2.69$, $p = .051$. This suggests mirror width did make some difference. There was a trend that on average, people moved farther from the wall as the mirror's edge became farther away, and, correspondingly, there was a significant positive correlation between mirror width and the distance of the response from the wall, $r(96) = 0.25$, $p = .016$. A possible explanation could be that, as we hypothesized, responses are directly proportional to mirror width but are extended laterally. However, it is possible that the trend resulted solely from the participants who were getting the answer correct in each condition.

At the end of the experiment, the experimenter asked each participant to describe how they thought about the task. There were 43% who gave no response or said they had guessed or did not

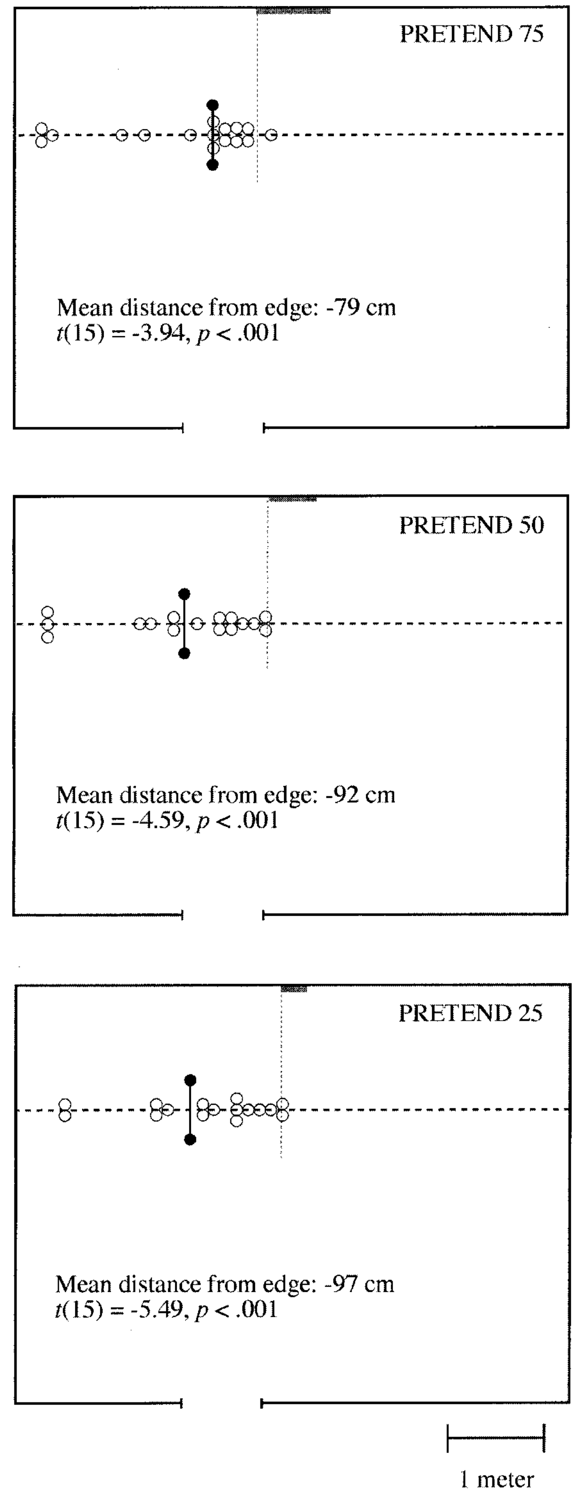


Figure 7. Results of Experiment 5, superimposed on scale drawings of the room. Open circles represent individual responses, dumbbells are the means of the responses, and thin dotted lines are the correct answers. The mean lateral distances from the mirror edges are shown and can be compared as the mirror becomes narrower (from 75, to 50, to 25 cm).

Table 3
Experiments 4 and 5: Mean Lateral Distances From the Mirror Edge, Standard Errors of the Means, and Mean Lateral Distances From the Side Wall for the Four Different Mirror Widths, Showing the Relationship Between Mirror Width and Responses

Group	*N*	Mean distance from edge (cm)	*SEM*	Mean distance from wall (cm)
120-cm mirror (Exp. 4)	48	−71	10.33	166
75-cm mirror	16	−79	19.93	171
50-cm mirror	16	−92	19.97	174
25-cm mirror	16	−97	17.69	181

Note. Values are rounded to the nearest centimeter. Exp. = experiment.

know, which suggests that the largest group of responses were purely naive. There were 24%, all of whom were approximately correct, who said they could not see themselves when past the mirror's edge, or that they had tried to work out the angles of the light reflected. Most of the remainder either said that they would see themselves in the opposite side of the mirror, i.e., their position in the room would be different in the reflected world (6 participants out of 48), or that there is a certain angle where one can see oneself (4 out of 48). Out of 48 participants, 10 people (22%) were conscious of some logical reason for their incorrect response, suggesting there may be a variety of implicit theories contributing to our findings; these may unfortunately not be elicited by questioning, but will require carefully designed experiments.

General Discussion

Mirrors have fascinated people, including psychologists, for a long time. We have started an overdue empirical investigation into the intuitive understanding of mirror reflection, a new field which is part of what we call naive optics. In summary, we found that many participants made significant errors when asked to indicate where an observer would be able to see a target in a mirror.

Perhaps it is appropriate to look for multiple explanations for our findings, because different subgroups of people may have adopted different strategies or heuristics. In Experiments 1A, 2, and 3, we can point to different clusters of responses. The existence of various subgroups was confirmed by the interviews in Experiment 5, although about 50% of people were unable or unwilling to explain the exact logic of their answer. It is important to first note that some responses were correct, and they probably included those observers who could solve the task on the basis of their knowledge and also those who picked the edge of the mirror because it was a salient location on paper or in the room. The fact that putting participants into a real room did not help them but rather increased errors suggests that a schematic drawing better elicits knowledge of the law of reflection (perhaps because of similarity to the ray diagrams used to teach optics in schools and textbooks).

The most common response among the errors was an overestimation of what is visible. A large proportion of our participants (in fact, a clear majority in the experiments conducted in a real room) believed that they could see themselves in a mirror before they actually would. Most of these participants chose a location at some small but significant distance from the edge of the mirror. When the question was about a second character (i.e., the cat in Experiments 1A, 2, and 3), performance did not improve or only appeared to improve if the correct answer happened to be somewhere before the edge of the mirror (in the Far tasks). Below are some possible explanations of this overestimation.

Are Mirrors Conceived as Pictures?

First, we present four hypotheses that arise when we assume that mirrors are mistakenly treated as if they were pictures. When solving the paper-and-pencil tasks that involved perspective taking, observers might have imagined the mirror to act the same as a picture that has captured the object in front of it, at which the observer can then look.

Egocentric mirror rotation hypothesis. People may suffer from an egocentric bias when conceptualizing mirrors and think that the mirror is rotated toward the hypothetical vantage point more than indicated in the drawing. This is akin to the differential rotation effect reported by Goldstein (1979, 1987), who demonstrated a dissociation between the observer's rotation with respect to a picture and the spatial layout of the picture. As a consequence, the gaze of a portrait in a picture gallery appears to follow the visitor around. People's lack of sensitivity to the angle of pictures is also illustrated by the finding that movies and photographs appear surprisingly distortion-free when seen from oblique viewing angles (Cutting, 1987). Assuming an observer-centric rotation bias in our experiments would explain the overestimation of when the cat would appear in Tiger-Tiger-Near as well as the underestimation in Tiger-Tiger-Far. However, the mirror was clearly presented as mounted flat on the wall. If anything, the correct alignment was emphasized in our paper-and-pencil items by the dashed pathway along which the moving individual walked and on which the stationary individual stood, which was obviously parallel to the mirror's surface. But people may not have taken the actual surface orientation of the mirror into account, because in real life, what is seen in a mirror is not perceived as attached to the mirror surface but extends in depth: This is consistent with performance being poorer in Experiments 4 and 5.

Capture hypothesis. Observers might conceive of a mirror as a device that creates an instantaneous picture by capturing whatever is in front of it. In other words, observers fail to do ray tracing and instead assume that the object in front of the mirror is first captured or thrown onto the mirror in the shortest straight path. Then the mirror is treated the same as a picture, and the object thus affixed to the mirror becomes visible the moment the observer enters the room (see Figure 2). There is some evidence that students (14–15 years) believe that mirrors have an inherent ability to create images and that the visual inspection of these images is an entirely separate process (Langley et al., 1997). The responses of those observers who thought that the object would be visible as soon as they entered the door in Experiments 1A, 2, and 3 fit this capture hypothesis. Obviously, if this effect is understood as a bias, it could also explain a shift of the responses away from the edge of the mirror. Consistent with this hypothesis, in Experiment 5, some people reported the belief that as long as one can look at the mirror, one can see oneself. This hypothesis predicts that the position of the observer is irrelevant, and it is therefore in agreement with the similarity of the responses in Experiments 1A, 2, and 3, when the observer position was changed (Near and Far).

Boundary extension hypothesis. Observers may overestimate what a mirror contains, similar to the pervasive distortion effect in which the spatial extent of a previously presented image is overestimated (Intraub, Bender, & Mangels, 1992; Intraub, Gottesman, Willey, & Zuk, 1996). Boundary extension may be described as either a memory or a perception effect, but Intraub et al. (1996) found that it is actually greatest for immediate recall, so it is not the same as a memory averaging or regression toward a prototype. When put in a mirror context, observers may perform an instantaneous boundary extension. This would account partially for our general overestimation effect. Boundary extension is similar to amodal completion (see Kanizsa, 1979) in that the edges of a photograph are occlusion edges, and people fill in the parts of a scene that are perceived to be missing. Mirrors, similar to photographs, have occlusion edges, so boundary extension could also occur for mirrors. However, boundary extension fails to account for the lack of overestimation for windows in Experiment 2, although windows also provide occlusion edges to a scene. With regard to the interviews of Experiment 5, some participants reported that there was a fixed zone of visibility extending to either side of the mirror that does not alter in position as the observer moves. This self-report fits the data very well, including the similarity of responses in the Near and Far conditions.

Whereas Hypotheses 1 and 3 have trouble explaining the extreme cases for which objects are believed to appear in the mirror as soon as the mirror itself comes into view, all three hypotheses do not explain the restriction of the overestimation to the horizontal plane, that is, the absence of errors in the Rope scenario. This leads us to a fourth hypothesis.

Left–right reversal hypothesis. Some participants in Experiment 5 said that their position in the scene would be reversed in a mirror (see Corballis, 2000; Gardner, 1964; Gregory, 1998). A mistaken belief in a left–right reversal caused by the mirror could also explain the lack of overestimation in the Rope scenario. As mentioned in the introduction, Gregory (1998) suggested that people perform an incorrect mental transformation between the scene and its mirror image, which is probably due to the experience of mirror writing and seeing one's own face in mirrors, for which objects seem to be left–right but not top–bottom reversed. According to Gregory, the actual transformation in these situations takes place through a fourth dimension (for a three-dimensional world), which may be beyond people's understanding or imagination. Gregory suggests that people may confuse this impenetrable rotation with a simple rotation in 3-D space (around the vertical axis), exchanging left and right. This is consistent with the asymmetry we found between items presented as top and side views (Experiments 1A and 3). Also, some participants in Experiment 5 said that they would see themselves in the wrong side of the mirror, as if their reflection were walking in the opposite direction to them. This is an example of people adopting the wrong heuristic, or "common superstition" as Linksz (1950) puts it. It is beyond the scope of this article, and certainly beyond our data, to take sides in the mirror reversal debate (see Gregory, 1998, for a review). However, naive beliefs about reversal may explain the differences between the Top and Rope responses.

Heuristics and Naive Optics

The above four hypotheses can and should be tested explicitly. However, as mentioned before, the large individual differences in our data suggest that different observers use different heuristics when answering the mirror question that we presented to them. Such differential use of heuristics is consistent with performance in other naive physics problems that require the processing of more than one variable and are thus too complex to be understood intuitively (see Gilden & Proffitt's [1989] analysis of extended body dynamics). In other words, observers start making errors when one perceptual heuristic is no longer able to produce a correct answer, or when they mistakenly conceive of a simple problem as requiring more than one heuristic (but see Hecht, 1996). Can this one-heuristic explanation account for the variance in our findings?

The first issue to resolve is to classify which types of complexities create problems for people in the case of mirrors. For example, on the basis of the results of Experiment 1A, we could say that adding a second character (the cat) makes the task harder, but it could equally be argued that the condition where only Jane is present should be more complex because both the point of observation and the object observed are moving. We do not have enough evidence to resolve this issue at the moment, but it is interesting to contrast two aspects of the phenomenon. People's extensive experience moving in the horizontal relative to a mirror may have led to a representation of mirror effects that are mistakenly complex. Moreover, this very experience may prevent recourse to the simple geometric solution. That is, people's experience exerts a cost because it is not connected cognitively with geometrical solutions, but is perceived as more complex than it actually is (Gilden & Proffitt, 1989; Proffitt & Gilden, 1989), particularly when the observer and the target are not the same individual. Movement in the vertical dimension (i.e., the Rope scenario), on the other hand, is sufficiently removed from real-life experiences to elicit geometrical solutions in the same way that our tasks in Experiment 1B did.

Another heuristic that might come into play when judging mirror images is the extramission belief cited in the introduction. Winer and colleagues (Winer, Cottrell, Karefilaki, & Chronister, 1996; Winer, Cottrell, Karefilaki, & Gregg, 1996) found the extramission belief to be revealed more frequently with the use of graphical tasks compared with the use of verbal tasks. They suggested that many people possess accurate declarative knowledge about perception while they use a naive theory for solving perception-related problems. We have not tried a purely verbal questioning approach, but the interview data from Experiment 5 showed that about 50% of the participants could not report specific reasons for their answers. The extramission belief may be part of how people reason about mirrors, but it does not, in itself, explain the overestimation effect, as it is unclear how it could influence predictions about geometry. Moreover, the extramission belief may be very volatile and depend on the phrasing of the question. Langley et al. (1997) asked 14- to 15-year-old students to draw a connection between a light source object and the eye, and they found that only 7% showed any evidence at all for this belief.

Finally, Langley et al. (1997) has suggested that people's experience of actively looking at objects shifts their answers to questions about optics toward what they call *component-specific prop-*

erties. In the case of mirrors, observers may attribute to them the magical ability to make objects visible, and therefore people neglect to think in terms of light propagation and reflection.

Conclusion

Having entertained a variety of possible explanations, we believe that the findings are best characterized as an extension of what is visible (boundary extension). The overestimation effect is robust across psychology and physics students and across gender, but it remains confined to the horizontal plane. No overestimation of what is visible above and below a mirror was detected in the task in which the observer was climbing a rope in front of a mirror. This is interesting, because moving in the horizontal relative to the mirror (e.g., walking across a room) is a more common experience than moving vertically (e.g., climbing a rope). The overestimation is therefore unlikely to be due to lack of understanding of the task or lack of experience with mirrors. To the contrary, expertise seems to exert a cost in that people do not apply abstract geometric knowledge to such familiar situations as mirrors in the horizontal plane. This seemingly paradoxical effect of experience is not unique (Hecht & Proffitt, 1995). Notwithstanding these effects, our student population knew, at least at an abstract level, about the law of reflection, in that they drew equal angles when asked about a ray of light reflected by a mirror (Experiment 1B). In general, we also noticed no problem in verbally reporting knowledge of the law of reflection when talking informally with students. This suggests that what people expect to be visible in a mirror is not derived from this declarative knowledge but rather from naive theories or heuristics.

Our experiments constitute a first stage in our study of naive optics, and we are now studying other aspects, including not only further investigation of naive theories of mirror reflection, but also problems involving refraction and dynamic situations. By dynamic situations we mean computer animations in which mirrors are presented in moving contexts, as in the present experiments, but the reflection in the mirror is a simulation and may be consistent with different expectations. By doing this, we will discover whether perceptual knowledge (i.e., recognizing possible and impossible events) is consistent with the predictive overestimation revealed by the paper-and-pencil and the pretend mirror tasks.

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