Journal of Experimental Psychology:
Human Perception and Performance
2007, Vol. 33, No. 5, 1027–1044

0096-1523/07/$12.00 DOI: 10.1037/0096-1523.33.5.1027

Overestimation of the Projected Size of Objects on the Surface of Mirrors and Windows

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Four experiments investigated judgments of the size of projections of objects on the glass surface of mirrors and windows. The authors tested different ways of explaining the task to overcome the difficulty that people had in understanding what the projection was, and they varied the distance of the observer and the object to the mirror or window and varied the size of the mirror. The authors compared estimations of projected size with estimations of the physical size of the object that produced the projection. For both mirrors and windows, observers accurately judged the physical size of objects but greatly overestimated the projected size of the same objects. Indeed, judgments of projected size were more similar to physical than to projected size. People were also questioned verbally about their knowledge of projected size relative to physical size. The errors produced for these conceptual questions were similar to those found in the perceptual estimation tasks. Together, these results suggest that projections of objects on mirrors and windows are treated in the same way and that observers cannot perceive such projections as distal objects.

Keywords: mirror, window, size constancy, projection

Imagine, on a steamed-up mirror, clearing just enough space to see your own face. As Gombrich (1960) pointed out, you will probably be surprised to find that a rather small area of the mirror needs to be cleared. You are likely to be surprised because most people believe that a mirror the same size as their face (or their body) is needed to see all of their face (or body) in it. In fact, the projection of your face on the surface of the mirror is just half the width of your physical face and quarter of its area (see Figure 1). This phenomenon is so striking that you are invited to try this demonstration to appreciate its power.

The first empirical study of this issue was by Bertamini and Parks (2005). They investigated what people believe about projections on mirrors. They found that people expect the projection of their face on a mirror to be about the same size as their actual face when they are standing close to the mirror, consistent with Gombrich's (1960) observation. However, most people also believe that their projection gets smaller if they move farther back from the mirror (see also Bertamini, Lawson, & Liu, in press). Again, this belief is false: The projection of your face is half the width and half the height of your physical face irrespective of your distance from a mirror. Finally, people found these questions difficult, though their answers were not random.

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This research was supported by Economic and Social Research Council Fellowship RES-000-27-0162 to Rebecca Lawson and by a China Scholarship Council fellowship to Dan Liu. We thank the Visual Perception Lab Group at the University of Liverpool for helpful discussions.

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Rather than investigating what people believe about projection size (i.e., their conceptual knowledge), Lawson and Bertamini (2006) investigated how well people can judge projection size whilst standing in front of a planar mirror (i.e., their perceptual knowledge). Observers estimated the size of the projection of their face and of paper ovals. In both cases, although the projections were visible, observers still greatly overestimated their size. In contrast, physical size estimates for the same objects seen using a mirror were quite accurate for both matching responses and verbal estimates in centimeters, replicating Higashiyama and Shimono (2004).

In the experiments reported here, people estimated the physical size of bamboo sticks of different lengths and also estimated the size of the projections of these same sticks. We compared estimates when people looked at projections on the glass surface of mirrors and of windows. What emerged is an important lesson about what people can perceive as a distal object within their visual world.

Size Constancy

It is probably uncontroversial to say that, when looking at a mirror, observers see virtual objects beyond the mirror surface. When observers see the reflection of their face, the size of their virtual face exactly matches the physical size of their face. However, the 3-D virtual object and its 2-D projection on the mirror surface are different stimuli that have different sizes. We are interested in whether size constancy applies to 2-D projections as well as to 3-D virtual objects.

The human visual system is typically said to achieve size constancy such that the perceived size of a distal object does not change with viewing distance. Thus, a given object does not seem smaller when it is farther away. Size constancy has also been termed phenomenal regression to the real object (Thouless, 1931)

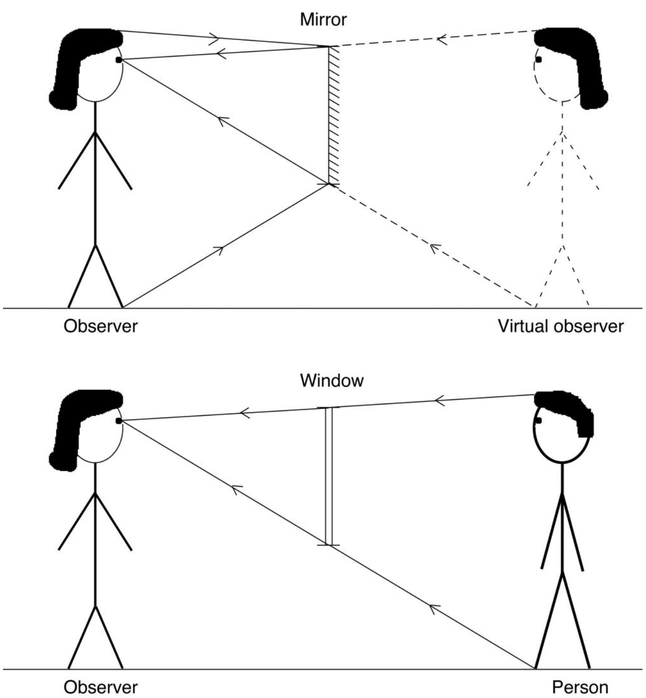

Figure 1. The top diagram shows that an observer standing in front of a mirror can see the full length of their own body in a mirror that is just half of their height. The dotted lines indicate the virtual observer visible in the mirror. In the bottom diagram, an observer stands in front of a window and another person stands at the same distance behind the window. This illustrates that the observer can see the full length of the other person through a window that is just half the height of that person. In both diagrams, the height of the projection seen by the observer is the full height of the mirror or window, and the lines with arrows indicate rays of light.

and transformation to the intermediate object (Brunswik, 1933), since size constancy is not perfect because more distant objects do appear smaller (Carlson, 1960, 1977; Foley, Ribeiro-Filho, & Da Silva, 2004; Lawson & Bertamini, 2006; Ross & Plug, 1998). Size constancy appears to be automatic (Goldfarb & Tzelgov, 2005), is probably achieved early in processing (Murray, Boyaci, & Kersten, 2006), and occurs despite the size of the retinal image produced by an object varying greatly with viewing distance. However, there can be large and systematic failures of size constancy when people estimate 3-D lengths (Loomis & Philbeck, 1999; Norman, Todd, Perotti, & Tittle, 1996) or even lengths in the frontoparallel plane (Koh & Charman, 1999; Ross & Plug, 1998). In addition, people can access information about the visual angle of proximal stimuli, particularly if they are given training with feedback (McKee & Smallman, 1998), so some visual information can be extracted independent of the achievement of size constancy. Perceived size has been reported to be a compromise between physical size and angular (retinal) size (Koh & Charman, 1999; Thouless, 1931), but estimates are close to those based on size constancy with binocular vision and rich cues to depth (as was the case in the present experiments, with an unrestricted field of view of a well-lit, rich environment). In contrast, estimates are increasingly based on angular size as cues to depth are removed (Koh & Charman, 1999; Lichten & Lurie, 1950; Over, 1960). Overall, then, a distal object in an observer's everyday environment generally appears to be the same size irrespective of viewing distance, even though information other than this fixed size can be extracted by the observer if the conditions are right.

Central to this study is the issue of what is treated as a distal object by the visual system in the case of size constancy. Distal objects are real, physical objects. However, certain stimuli that do not exist physically are perceived to be distal objects by the human visual system. Size constancy can be achieved for such stimuli, for instance for virtual objects seen in a mirror (Higashiyama & Shimono, 2004) or even for objects shown in a realistic animation at the cinema. In other words, objects generally appear to have a constant size if they are perceived as distal objects by the observer. Can projections on transparent surfaces such as mirrors or windows be functionally equivalent to distal objects to our visual system? Such projections are not physical objects, but then neither are virtual objects. The four experiments reported here examined this question. We conclude that these projections cannot be perceived as distal objects.

Projections Cannot Be Perceived as Distal Objects

We propose that the systematic errors made in estimating projection size (Lawson & Bertamini, 2006) occur because a projection cannot be treated as a distal object. This is a strong statement that goes beyond saying simply that projections tend to be overlooked because they do not attract an observer's attention. To test our claim, we have tried to direct observers' attention to projections of objects. These attempts have largely failed. One exception to this is if observers are explicitly taught a strategy of closing one eye and lining up the top and bottom of the projection with a matching stimulus. In this case, their estimates of projection size are quite accurate (Lawson & Bertamini, 2006), demonstrating that the necessary information is present in projections and can be acted on. However, this still does not mean that observers using such a strategy perceive these projections as distal objects, just as using a ruler to discover that the lines in the Müller–Lyer illusion are the same length does not stop observers from seeing the illusion. This issue—the extent to which people can perceive information on a 2-D surface when that information derives from the real, 3-D world—is closely linked to the debate in the picture perception literature on the dual nature of pictures (Hecht, Schwartz, & Atherton, 2003). We leave further discussion of this topic to the General Discussion.

We suggest that there is no percept for the 2-D projection on the surface of a mirror or a window. This fits well with the phenomenology and the fact that even understanding questions about projections is difficult. To believe that a projection must be perceived because the information is present in the stimulus would be to commit the stimulus error (Koffka, 1935). Nevertheless, it is worth discussing why it is interesting that projections on mirrors and windows are not perceived. A projection on a surface perceived as transparent can have high contrast, it can occupy a large proportion of the visual field, it can be located in the frontoparallel plane (meaning that slant perception is not an issue), it can be pointed to accurately, it can be marked on the surface using a felt-tip pen (a new object is created in so doing), it can be captured in a photograph, it has a corresponding stimulation on the retina, and it can be understood as something that exists at an intellectual level so it does not conflict with an observer's belief system. Intuitively, one might expect these conditions to be sufficient for the projection to be perceived. They are not. A projection is not a distal object, and it is not perceived as such any more than retinal images are.

Experiments 3 and 4 provided a key test of whether projection size is available to observers. Here, we kept physical object size constant and changed the position of the observer. As a result, projection size differed with viewing distance. If estimates of projection size varied with viewing position, this would suggest that observers could detect changes in projection size, even if imperfectly. Conversely, if only physical size was available to observers, there should be no difference in judgments of projection size with viewing distance. Our results confirm the latter hypothesis.

Alternative Explanations of the Overestimation of Projection Size

We have outlined above our explanation of why Lawson and Bertamini (2006) found that observers grossly overestimated projection size. However, let us now consider whether there are other possible reasons for these errors.

1. Faces Are Special

Faces are highly familiar stimuli with a standard size. If this is important, then it should be easier to judge projection size for unfamiliar objects. Bertamini and Parks (2005) only questioned people about the projection of their face. However, Lawson and Bertamini (2006) tested oval shapes as well as faces and found similar results for these nonface stimuli. Nevertheless, the ovals were similar in size and 2-D shape to faces, so it is important to investigate estimates of the projections of other objects. In an unpublished pilot study we asked about the projection size of bodies and found results consistent with those for faces.[1] In the experiments reported here, we showed bamboo sticks in the frontoparallel plane. The use of sticks also clarified which size estimate (stick length) was required, whereas for faces, bodies, and ovals, observers could have matched height, width, or area.

2. Mirrors Are Special

People find mirrors fascinating, but planar mirrors are mainly used just to view oneself from a standard distance. Furthermore, projections on concave and convex mirrors (such as car mirrors) have different properties than planar mirrors, and this diversity might confuse people. To test this possibility, we compared projection estimates for windows as well as for mirrors. People are highly familiar with windows in their everyday environment, and windows are often used to gain information about objects on the far side that have different sizes and are placed at varying distances. For example, everyone knows that they can see a large tree through a standard-size window, so they should easily be able to deduce that the projection of the tree on the surface of the window must be much smaller than the physical tree.

In the first three experiments, we compared physical and projection size estimates for windows and mirrors across two matched groups of observers. The mirror and window groups saw visually similar stimuli, and the correct response was identical for both groups across both tasks. We predicted that both groups would produce the same pattern of results—namely, accurate physical estimates but overestimates of projection size. The surface of a mirror is specular, but it is perceived as a transparent sheet through which observers can see solid shapes at a distance, just as for windows.

If, however, the overestimation of projection size reported by Lawson and Bertamini (2006) was produced by an error specific to mirrors, then performance should be more accurate for windows. Evidence for a difference between performance for mirrors and windows was reported by Croucher, Bertamini, and Hecht (2002). They found that an erroneous belief about mirror projections, which produced the so-called early error, did not occur for people's conceptual beliefs about projections on windows.

3. Both the Projection and the Virtual Object Are Seen, and Cross-Talk Occurs Between These Two Percepts

It has been suggested that in a mirror there is a dual percept—the projection on the mirror surface and the virtual object—with both percepts arising from a single, unified representation (Niederée & Heyer, 2003). Hence, when a size judgment is made, the two percepts may be coupled. Here, the size estimate of one may be influenced by the perceived size of the other. However, we know of no evidence to suggest that virtual objects are perceived to be smaller than they are, so they do not seem to be influenced by the size of the projection (which is always smaller). On the contrary, Higashiyama and Shimono (2004) found that physical estimates were accurate for unfamiliar objects seen only via their reflection in a mirror. Nevertheless, we reexamined this possibility in the present studies.

4. Misperceived Distance

Carlson (1977) noted that, to achieve size constancy, distance must be perceived accurately. If cues to stimulus distance are gradually removed, an observer's size estimates change gradually from being based on physical size (so size constancy is achieved) to being based on the angular (retinal) size of the stimulus (Koh & Charman, 1999). Since observers here and in Lawson and Ber-

[1] Observers were either shown a diagram of the upper body of a person facing a wall or a diagram showing the whole body (see http://www.liv.ac.uk/vp/projects/projections.html). Observers imagined themselves as the person in the diagram and drew a rectangle to show what height a mirror on the wall would need to be for them to see all of their face or all of their body in it. To check if they had understood this drawing task, we also asked them to mark on a scale what height of mirror they would need to see the full length of their face or of their body. This scale, which ranged from 25% to 150% in 25% steps, was in proportion to their own height, so 25% meant a mirror that was a quarter of their height. Almost everybody indicated that a mirror the same height as their face (or body) would be needed to see all of their face (or body) in it, whereas the correct response would have been a mirror of half that height. The 20 observers given the face diagram drew a mirror 102% of the depicted height of their face and indicated a height that was 91% of their face height on the scale. The 20 observers shown the body diagram drew a mirror 107% of the depicted height of their body and indicated a height that was 104% of their body height on the scale.

tamini (2006) estimated physical and projection size in a cluttered, well-lit room, there were many different cues to specify viewing distance, so it should have been perceived accurately.

However, when judging projection size, people may mislocate the projection on a mirror to the distance of the virtual object. This distance overestimation would lead to size being overestimated. The idea of a causal link between perceived size and perceived distance is known as the size–distance invariance hypothesis (McCready, 1985; Ross & Plug, 1998). It seems reasonable to suggest that the mirror is perceived as an aperture with nothing located at the distance of the aperture itself, so only the distance of the virtual object is perceived. As in the previous scenario, this hypothesis implies two percepts (the virtual object and the projection of that object) but with the latter percept being misplaced in space. We know of no corroborating evidence in favor of such duality. Moreover, the distance of the glass surface of the mirror from the observer was perceived accurately (see Experiment 4), so, at least at a conceptual level, people know the distance of the projection.

One further, interesting prediction from this hypothesis, not tested in this study, is that if only the *distance* of the projection on the surface of the mirror is misperceived, its *shape* should be perceived accurately. For instance, if the observer looks straight at the mirror and sees reflected in it a circular disc placed at an angle to the mirror, he or she should accurately perceive the elliptical shape of its projection. The observer should only misperceive the distance and, consequently, the size of its projection. However, we predict that, because the virtual object but not the projection is perceived, observers will report that the projection of the disc is more circular than it is.

5. The Projection Is Not Usually Perceived, But it Can Be Perceived

If people perceive 3-D virtual objects, it does not necessarily mean that virtual objects are the only things that they can perceive in a mirror. Instead, this may simply be the default (and most useful) way that people see things in a mirror. Presumably, one could see the size of the projection if one marked its outline with a felt-tip pen on the mirror surface. But that implies that to see the projection one needs to add to it something that is physically present or, in other words, something extra that is not just a projection. This suggests that if only the projection is present, its size cannot be perceived. In our experience, even when people know that they are estimating information about the projection, not the virtual object, and even when they understand why the projection of their face is only half the height of their physical face, they still perceive their projection to be much larger than this. Nevertheless, it is important to explore ways in which observers can be encouraged to focus on the projection itself. We attempted this in several different ways in the present experiments.

6. Misunderstanding What the Question Is About

This possibility is closely related to the previous one. There is no doubt that asking questions about projections is fraught with danger. People may simply judge the size of the physical 3-D object even though the question was about the 2-D projection of that object on the surface of the mirror. From our standpoint, this difficulty is further testimony to the fact that a projection cannot be perceived as a distal object. Detailed instructions were used in all of the present experiments to clarify to observers what we meant by a projection. For instance, in Experiment 3 we asked observers to place a tape measure on the surface of the mirror to measure the size of a projection as part of their pretest training.

Experiment 1

Lawson and Bertamini (2006) found that people grossly overestimate projection size on mirrors, whilst Higashiyama and Shimono (2004) reported that physical estimates for objects seen only as reflections in a planar mirror were accurate. However, no previous study has directly compared physical and projected size estimates using mirrors, nor has this situation been contrasted to that of estimating physical and projected size using windows.

Observers stood in front of a mirror or a window, and a bamboo stick was held so it was visible in the mirror or window (see Figure 2). For the mirror group, the stick was held over the observer's head, and it appeared over their virtual head in the mirror. For the window group, the stick was held over the head of an assistant in a courtyard outside the window. In a series of trials, observers judged the physical length of different sticks. This physical task is quite easy, and we expected similar results for the mirror group and the window group.

In the projection task, observers judged the length of the projection of the stick on the surface of the mirror or window. The stick and the observer were always the same distance from the mirror or window, so the projected length of the stick was always half of its physical length (see Figure 1). Lawson and Bertamini (2006) reported that projection size was estimated at between around 0.70 and 1.20 of the physical size of a given object (where 0.50 was correct and 1.0 indicates that projection size was estimated as equal to physical size). The only exception was when observers were explicitly told to use a monocular, lining-up strategy to align the top and bottom of the projection with a matching oval, in which case projection estimates were quite accurate. We predicted that both mirror and window observers would greatly overestimate projection size because they were unable to treat projections as distal objects.

A third, physical on glass task was included to check whether any difference between physical and projection size estimates was attributable to the projection on the surface of the mirror or window (at a viewing distance of 2 m) being both smaller and optically closer to the observer than the physical object producing the projection (which was at a viewing distance of 4 m). Sticks in the physical on glass task were placed directly onto the surface of the mirror or window and so were at the same viewing distance (2 m) as projections in the projection task and the sticks tested included the same lengths as the projections in the projection task. Thus, the size and location of stimuli in the physical on glass task matched those in the projection task and were dissimilar to those in the physical task. Nevertheless, on the basis of earlier research (Higashiyama & Shimono, 2004; Lawson & Bertamini, 2006), we predicted that size estimations in both of the physical tasks would be accurate, unlike the projection task.

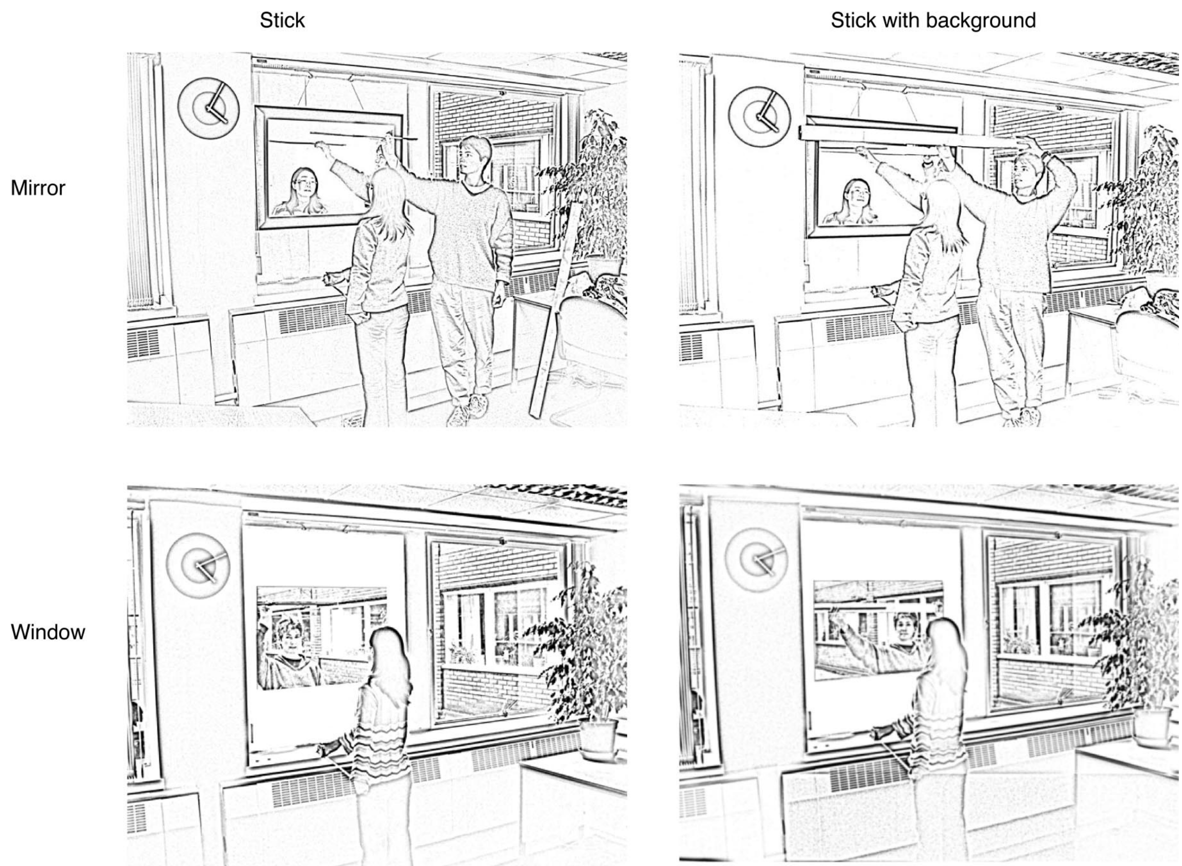

Figure 2. Line drawings depicting an observer (holding the measuring tape on her left side) and an assistant (holding the bamboo stick) in the mirror task and the window task. In Experiments 1 and 2 (left-hand panels), the assistant stood in the center of the window in the window task. In Experiments 3 and 4 (right-hand panels), the stick was held in front of a paper-covered plank, and the assistant stood to the side of the window in both tasks. Nonexperimental windows were left uncovered. The room shown here was used in Experiments 3 and 4, and the observer is standing in the near position (0.5 m from the glass); Experiments 1 and 2 were conducted in similar, adjacent rooms.

Method

Observers

Thirty-six students (6 male) from the University of Liverpool, Liverpool, United Kingdom, took part in the experiment for course credit. Half were assigned to the mirror group and half to the window group.

Design and Materials

For the window group, a window in the experimental testing room was partly covered with white paper to leave a rectangular aperture (87 cm wide × 58 cm high) through which a courtyard was visible. For the mirror group, this aperture was covered by a planar mirror (87 cm wide × 58 cm high, with an 8-cm diameter black frame). The sticks were shown centered horizontally within this aperture. In the physical and projection tasks, observers used a retractable measuring tape to estimate the size of five bamboo sticks of the following lengths: 10 cm, 20 cm, 40 cm, 60 cm, and 80 cm. In the physical on glass task, people estimated the same five sticks plus a 5-cm stick and a 30-cm stick. All observers completed three stick estimation tasks. Within the mirror and window groups, subgroups of 6 observers completed each of three different task orders: physical, projection, then physical on glass estimates; or projection, physical on glass, then physical estimates; or physical on glass, physical, then projection estimates.

Procedure

Observers estimated the length of each stick by pulling out the tape to the appropriate length and then reading off this length in centimeters. They pulled out the tape perpendicular to the aperture so that observers in the mirror group could not look at the reflection of their arm position to help them to estimate length (see Figure 2). The sticks were held horizontally and were shown in a pseudorandom order across observers and tasks.

Observers in the window group stood in the experimental room facing the center of the window and 2 m from it. The assistant stood outside in the courtyard, opposite the observer. For the physical and projection tasks, the assistant stood 2 m from the window and held one stick at a time over her own head. In the physical on glass task, the assistant stood to the side of the window and held each stick directly against the glass.

Observers in the mirror group stood in the experimental room facing the center of the mirror and 2 m from it. For the physical and projection tasks, the assistant stood next to the observer and held one stick at a time above the observer's head. In the physical on glass task, the assistant stood to the side of the mirror and held each stick directly against the glass.

For the two physical estimation tasks, observers reported physical length. They were told that this was the length that would be measured if a tape was placed directly against the stick. For the projection task, observers reported the length of the projection of each stick on the surface of the mirror or window.[2] It was emphasized that this was a different task than estimating physical length. Observers often initially had some difficulty in understanding what they had to estimate, so the experimenter spent time repeating and elaborating the explanation. Observers were given two practice trials before starting the experiment. They estimated the physical width of a table (73 cm) and then a metal bracket (10 cm). They pulled out the tape to their estimated distance. The experimenter then held the tape against the table or bracket and told them the correct length.

Results

For the main analyses of all four experiments, each length estimate was divided by the physical length of the stick. In Experiment 1, the correct proportion was 1.0 for physical size estimates and 0.50 for projection size estimates. Proportions were analyzed because the variance of estimates increased systematically with stick length. For example, in Experiment 1 the standard deviations for the 10-cm and 80-cm sticks for physical estimates were 3.2 cm and 15.0 cm, respectively; whilst for projection estimates they were 3.9 cm and 16.1 cm, respectively; and for physical on glass estimates they were 2.0 cm and 13.6 cm, respectively. Standard mixed design analyses of variance and additional statistical tests were conducted on these proportions in all four experiments reported here. Since our results were clear, we have not reported these analyses in full.

The effect of task was significant, $F(2, 68) = 39.35$, $p = .00$, but that of group (mirror or window) was not. Most important, the Group × Task interaction was not significant, $F(2, 68) = 0.83$, $p = .44$ (see Figure 3). Participants were always close to the correct proportion of 1.0 when estimating physical length. Mean physical estimates were 1.07 for the mirror group and 1.04 for the window group, whilst physical on glass estimates were 0.98 and 1.00, respectively. In contrast, projected lengths were grossly overestimated for both the mirror group (0.83) and the window group (0.79).

Length also influenced the accuracy of estimates, $F(4, 136) = 34.12$, $p = .00$. Estimates relative to physical length were greatest for shorter sticks (1.09 for 10-cm sticks, 1.03 for 20-cm sticks, 0.90 for 40-cm sticks, and 0.87 for 60-cm and 80-cm sticks). The same pattern occurred for both groups and for both physical and projected size estimates (see the Appendix). It is important to establish whether observers' overestimation of projections could be a confound attributable to their overestimation of the length of smaller stimuli. Since the projected length of a given stick was always half of its physical length, people's estimates of projection size may have been relatively large because they were always estimating the length of a smaller stimulus in the projection task than in the physical task. We addressed this issue by conducting two additional analyses.

First, we compared projection estimates with physical on glass estimates for the five stimulus lengths tested (5, 10, 20, 30, and 40 cm), which were identical for both tasks. Here, projection estimates were divided by the actual projected length (not the physical length of the stick, as in the analyses described above). The correct proportion was therefore 1.0 for both the physical on glass and projection tasks in this analysis. Task was significant, $F(1, 34) = 75.63$, $p = .00$. Estimates were 1.06 in the physical task and 1.62 in the projection task. Thus, for estimates of stimuli of identical length, physical estimates were accurate, whereas projected size was grossly overestimated.

Second, we conducted an analysis similar to the first in which we compared estimates of the projected size of the three stimulus lengths (10, 20, and 40 cm), which were common to all three tasks. Again, task was significant, $F(2, 68) = 60.65$, $p = .00$. Estimates were 1.12 in the physical task, 1.02 in the physical on glass task, and 1.57 in the projection task. As in the first analysis, for stimuli of the same length, physical estimates were accurate, whereas projected size was grossly overestimated. Thus, the overestimation of projected size was not merely an artifact of overestimations of smaller stimuli (see the Appendix).

After completing the three tasks, observers were asked what strategy they had used when they estimated projected lengths. Around half of the observers in each group (11 for the mirror group, 8 for the window group) said that they had tried to imagine a line on the surface of the window or mirror or that they had imagined the tape laid out on its surface. They had then tried to estimate the length of this line. Just 2 people in each group mentioned using the frame around the mirror or the paper around the window or other cues beyond the surface of the window or mirror to help them to estimate projections. Projected length estimates were more accurate for these 4 observers (0.64), whilst their physical estimates (0.93) and physical on glass estimates (0.96) remained accurate. Estimating the proportion of the width of the mirror or window covered by the projection should be a simple and successful way to estimate projected length because the width of

[2] In this article, we refer to the size of an object on the surface of the glass of a mirror or window as the *projected size* of that object. However, in Experiments 1–3, our observers were instructed to estimate the size of the image of an object (for mirrors or windows) or the reflection of an object (for mirrors only). These terms were used because they are more familiar, but we did not assume that they would be correctly interpreted. Instead, since we were aware that people might not at first understand what they were supposed to do when they were asked to estimate projected size, we took time to explain the task and we used concrete examples. For example, in the first three studies we told them to imagine that they could use a felt-tip pen or lipstick to mark the extent of the stick on the glass surface and to estimate the length of that line. Furthermore, in Experiment 3, people directly measured the projected size of a stick before they began the projection task. Finally, in Experiment 4, observers were told to estimate the minimum width of a mirror that would be needed to see all of a given stick in it. Here, it was not necessary to use the terms projection, image or reflection to explain the task.

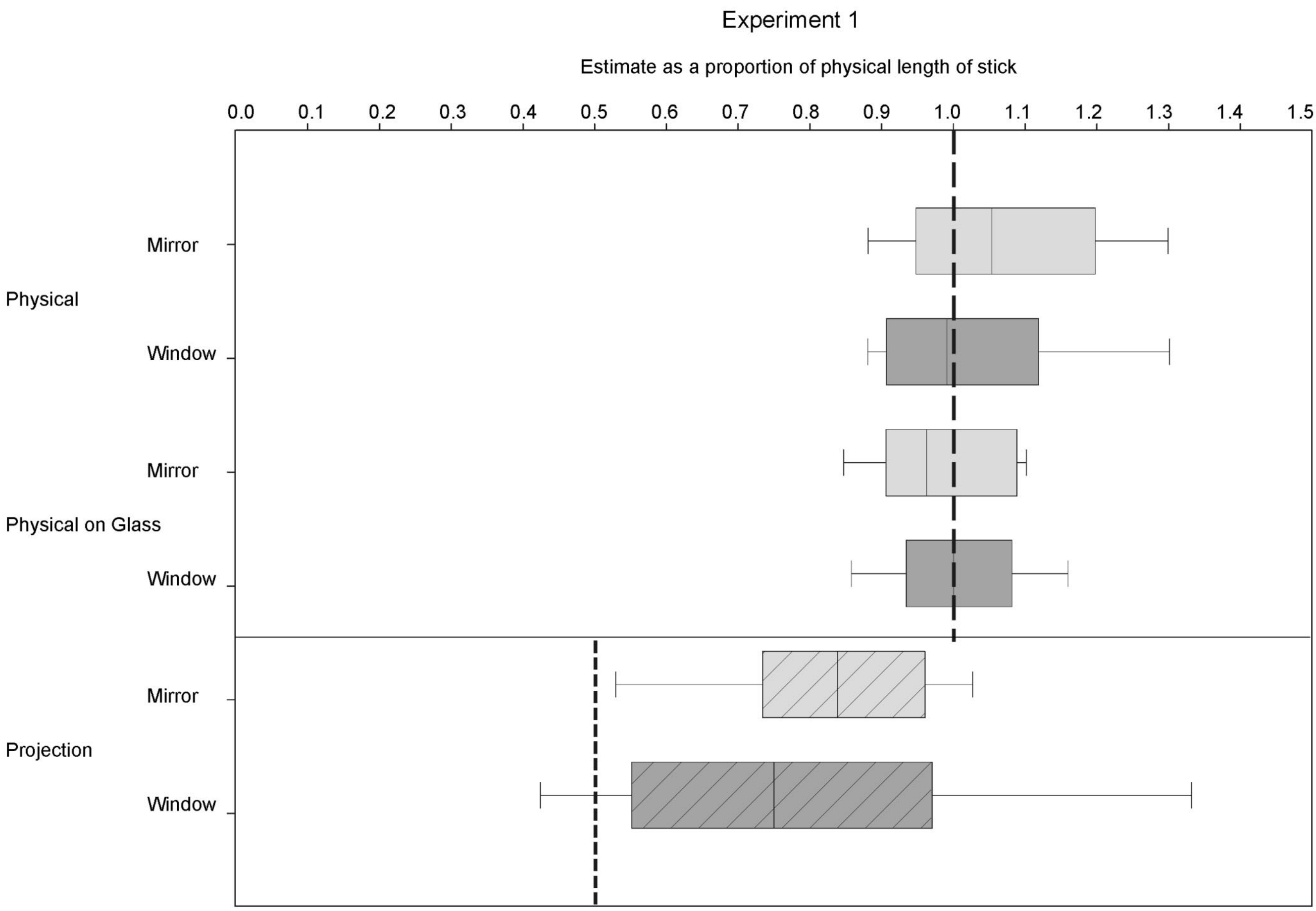

Figure 3. Box plots of the physical, physical on glass, and projection size estimates in Experiment 1, plotted for the mirror group and the window group. Each box indicates the 25th, 50th (median), and 75th percentiles, and the error bars show the 10th and 90th percentiles. The correct response was 1.0 for the two physical tasks and 0.5 for the projection task, as indicated by the dashed lines.

the mirror or window can be judged accurately. That such an indirect strategy is necessary supports our claim that projected length cannot be judged directly. Furthermore, that so few observers used this strategy suggests that most people were unaware of their errors in estimating projected length.

Discussion

First, the results of Experiment 1 revealed that projected sizes on mirrors are grossly and systematically overestimated (replicating Lawson & Bertamini, 2006), whilst physical sizes are estimated quite accurately (replicating Higashiyama & Shimono, 2004). In Lawson and Bertamini (2006), observers overestimated the projected size of faces and paper ovals. The present results extend these findings to sticks, for which there is no ambiguity as to whether width, length, or area is to be estimated. Second, the same pattern of results was found for windows as for mirrors. This supports our hypothesis that the same mechanism underlies the errors in both cases—namely, people's inability to treat projections as distal objects. We further tested this hypothesis in Experiment 2.

Further support for this account came from the comparison of results for the projection task and the physical on glass task for stimuli of the same size (i.e., for sticks in the projection task that were twice as long as the matched sticks in the physical on glass task) and viewed from the same distance. Here, although the retinal input was closely matched and both the size and location of the stimuli to be estimated were equated, people performed very differently. They overestimated projected size whilst accurately estimating physical size.

Experiment 2

In Experiment 2, we again compared physical and projection estimates, but in addition we manipulated the distance of the observer and the stick from the surface of the mirror or the window. We extended the viewing distance from the mirror or window from 2 m in Experiment 1 to 6 m in the far viewing condition of Experiment 2 and contrasted this to a near viewing condition of 1.5 m. If, as we propose, people are unable to perceive the size of projections, then they should similarly overestimate projected size in both the near and far viewing positions. In contrast, their physical estimates should be quite accurate for both viewing positions, because of size constancy.

Standing at the far viewing position may, however, encourage people to realize that the projection is much smaller than the physical object producing the projection. Bertamini and Parks (2005), Bertamini et al. (in press), and Lawson and Bertamini (2006) all found that most observers believe that the projection of their face on a mirror would be smaller if they stood farther from the mirror (note that this belief is incorrect). For windows, it is even more likely that people will give projected size estimates from the far position that are much smaller than their physical size estimates. All observers are highly familiar with seeing large objects through relatively small windows, and people should be reminded of this commonplace observation when they stand 6 m from the window and see through it a stick that is 12 m from them. Finally, if people reason differently about the optics of mirrors and windows (e.g., Croucher et al., 2002), then manipulating viewing distance may provide a means of detecting such differences.

Lawson and Bertamini (2006) varied viewing distance when observers had to estimate projected size on a mirror. They found a small improvement in projected size estimates (from 0.98 to 0.90) from the near to the far position. Importantly, though, estimates were much greater than the correct proportion of 0.50 in both cases. However, this earlier study only tested viewing distances of 0.5 m and 1.5 m from the mirror surface. Furthermore, near estimates were always made before far estimates, and the study did not test physical size estimates or include a window group. Experiment 2 tested a wider range of viewing distances for both physical and projection estimates for a mirror group and a window group.

Method

Observers

Forty-eight students (8 male) from the University of Liverpool took part in the experiment for course credit. Half were assigned to the mirror group and half to the window group.

Design, Materials, and Procedure

These were identical to Experiment 1 except for the following points. The experiment was conducted in a larger room, though the dimensions of the window and mirror remained the same. Observers in both the window and mirror groups completed four tasks in one of four task orders: near then far physical and then near then far projection, near then far projection and then near then far physical; far then near physical and then far then near projection, or far then near projection and then far then near physical. For each group, a subset of 6 observers was assigned to each task order. In the near tasks, the observer and the assistant stood 1.5 m from the window or mirror. In the far tasks, the observer and the assistant stood 6 m from the window or mirror.

Results

Each length estimate was divided by the physical length of the stick. The correct proportion was 1.0 for physical estimates and 0.50 for projection estimates. Physical estimates (1.07) were greater than projection estimates (0.79), $F(1, 46) = 114.41$, $p = .00$. In contrast to Experiment 1, group was also significant, $F(1, 46) = 13.43$, $p = .00$, with window estimates (0.85) being smaller than mirror estimates (1.02). This was likely due to a slight distortion of the mirror surface that was noticeable at the far distance. More important, the Group × Task interaction was not significant, $F(1, 46) = 0.01$, $p = .93$ (see Figure 4). For both groups, physical estimates were greater than projection estimates, which, in turn, were much greater than the correct proportion of 0.50. Mirror estimates were greater than window estimates for both the physical tasks (1.16 compared with 0.99) and the projection tasks (0.88 compared with 0.71).

The Task × Group × Distance interaction was significant, $F(1, 46) = 5.58$, $p = .02$, so we conducted separate analyses for physical and projection estimates. For physical estimates, the Group × Distance interaction was significant, $F(1, 46) = 15.54$, $p = .00$. In post hoc Newman–Keuls analyses, for the window group near (0.98) and far (1.00) estimates were not significantly different, whereas for the mirror group near estimates (1.07) were less than far estimates (1.25). As noted above, distortions of the reflection in the mirror were visible from the far but not the near position and were the likely cause of these mirror group overestimates of physical size. For projection estimates, window estimates (0.71) were smaller than mirror estimates (0.88), $F(1, 46) = 9.68$, $p = .00$. However, distance was not significant, with similar estimates from the near (0.81) and far (0.78) positions, and the Group × Distance interaction was also not significant. Most important, projected size was overestimated in every condition (see Figure 4).

After completing the perceptual estimates, people were asked two questions whilst they stood in the near position. First, they were asked whether the projection of an object on the surface of the window or mirror was bigger, smaller, or the same size as the physical object. Here, 72% correctly said smaller, 24% said same size, and 4% said larger. More people were accurate in the window group (86%, 14%, and 0%, respectively) than in the mirror group (58%, 33%, and 8%, respectively), but both groups showed the same pattern of response.

Second, they were asked whether the projection of an object from the far position was bigger, smaller, or the same size as its projection from the near position. Here, 85% of observers said smaller, and only 15% correctly said same size. Responses were similar for the window group (17% correct) and the mirror group (12% correct). However, at debriefing it became clear that some people misinterpreted this question and said smaller because they knew that the retinal image of an object was smaller from the far position. In Experiment 3, we clarified this question.

Discussion

In Experiment 2, replicating Experiment 1, both the mirror and window groups greatly overestimated projection size. Importantly, there was no evidence that estimates of projected size improved when observers stood farther from the mirror or the window. When the distance from the projection to the observer was 6 m (Experiment 2, far distance), 2 m (Experiment 1), and 1.5 m (Experiment 2, near distance), the mirror group judged projections to be 0.86, 0.83, and 0.90 of physical size, respectively, whilst the window group estimated projections to be

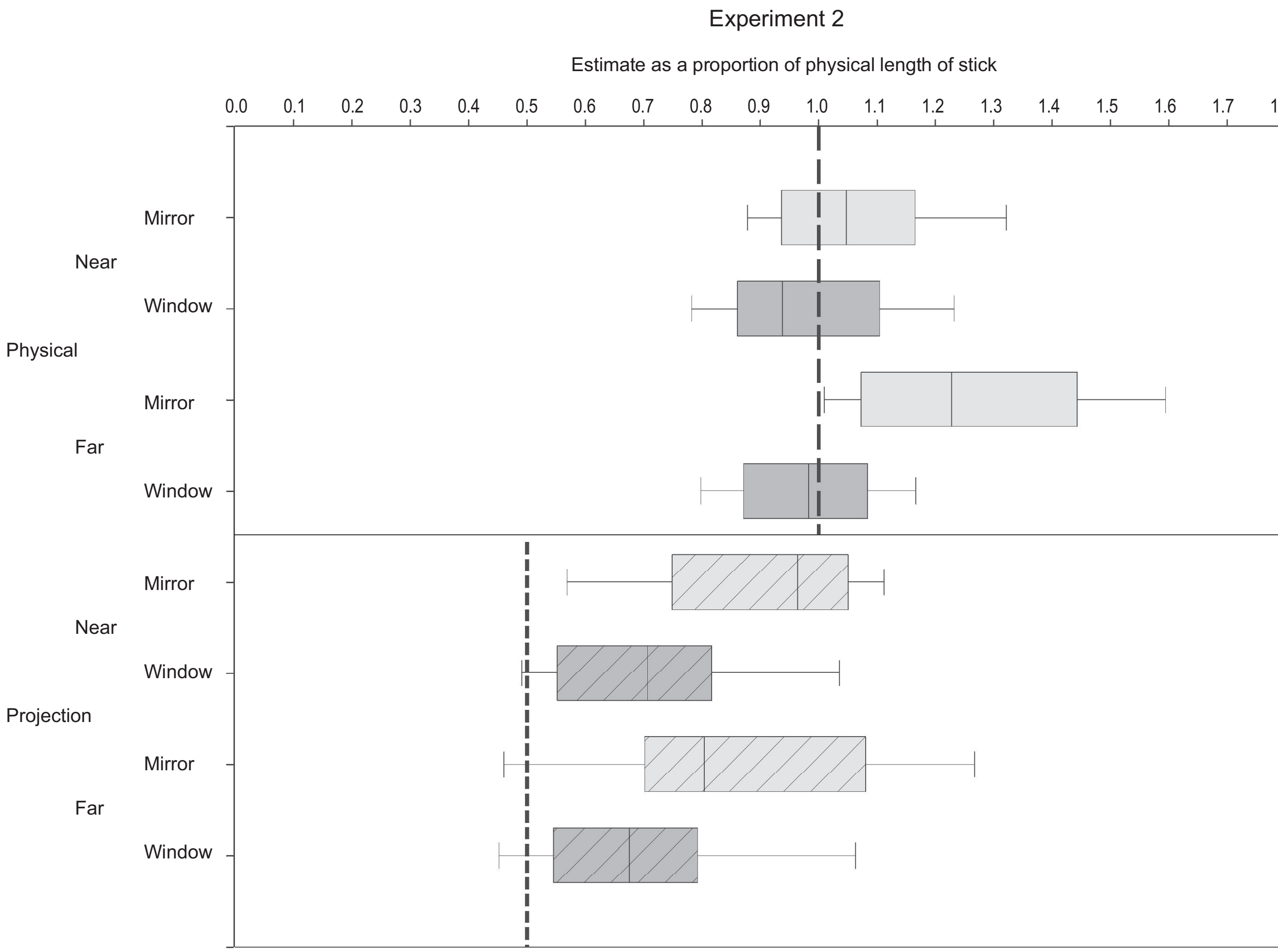

Figure 4. Box plots of the physical and projection size estimates in Experiment 2, plotted for the mirror group and the window group for the near and far positions separately. Each box indicates the 25th, 50th (median), and 75th percentiles, and the error bars show the 10th and 90th percentiles. The correct response was 1.0 for the physical task and 0.5 for the projection task, as indicated by the dashed lines.

0.69, 0.79, and 0.72, respectively. The correct response was 0.50 of physical size in all cases.

Observers were also asked about the size of the projection of an object relative to the physical size of the same object. Most correctly responded that the projection was smaller. This is consistent with their perceptual estimates of projected size, which, as in Experiment 1, were somewhat smaller than their physical estimates (see Figures 3 and 4). However, observers were not asked to quantify the size difference between the projection and the object producing it. The accuracy of their conceptual beliefs was examined more precisely in Experiments 3 and 4.

Finally, observers were asked whether projected size would vary if they moved from the near to the far position. Most said, incorrectly, that the far projection would be smaller, consistent with our earlier findings (Bertamini & Parks, 2005; Lawson & Bertamini, 2006). In contrast, the same observers' perceptual estimates of projected size were not influenced by viewing distance in Experiment 2. Observers may therefore have responded on the basis of different information in the perceptual and conceptual tasks. Alternatively, observers may have misinterpreted this second conceptual question in Experiment 2 as being about the retinal size of an object. Therefore, we posed this question more precisely in Experiment 3, to distinguish between these two possibilities.

Experiment 3

Experiments 1 and 2 revealed that people grossly overestimate projected size on windows as well as on mirrors, though physical size can be estimated accurately. We propose that this is because observers cannot perceive projections as distal objects, so they do not have access to information about projected size. In our first two experiments, the projection plane defined by the surface of the mirror or window was always midway along the path of light between the observer's eye and the target object. In this special case, the projected size of the object is always half of its physical size irrespective of viewing distance (see Figure 5). Thus, in these experiments, as in Lawson and Bertamini (2006), we did not manipulate projected size relative to physical size.

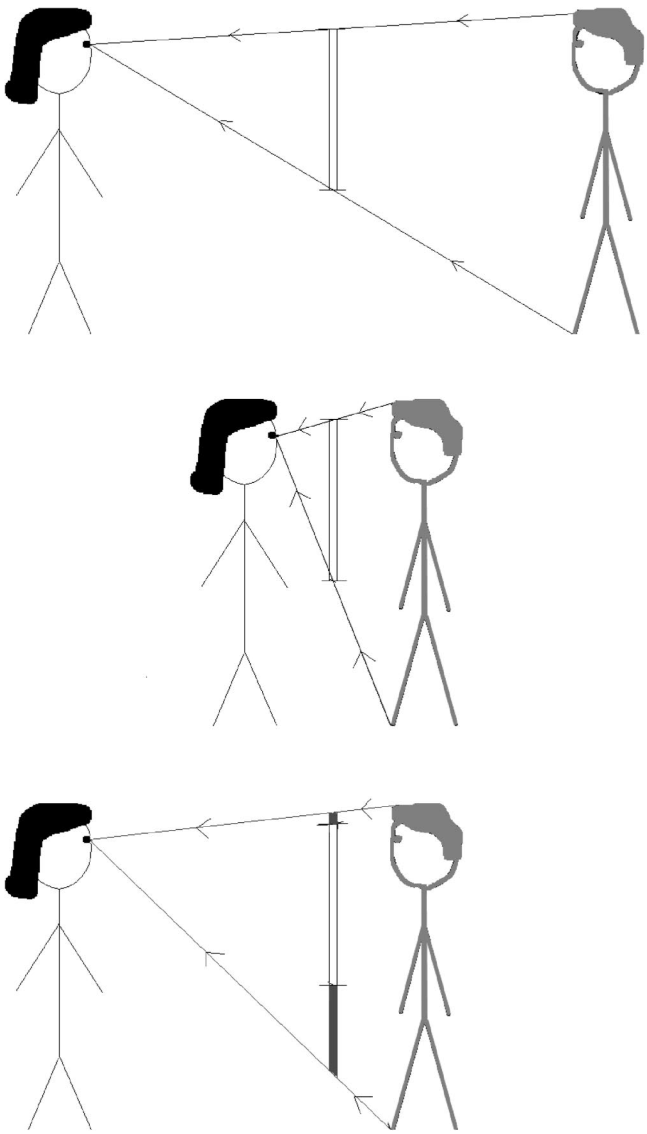

Figure 5. Three diagrams illustrating an observer (on the left) looking through a window (center) at a target object (another person, on the right). The observer can see all of the target through a window that is just half of the target's height, whether the observer is far from (top) or near (middle) the window, provided that the observer and the target are the same distance from the window. However, if the observer moves farther from the window than the target (bottom), then she needs a bigger window to see all of the target (the extra window height required is indicated in black). The same effect occurs for mirrors. The height of the projection of the target seen by the observer is always the full height of the window. Lines with arrows indicate rays of light.

In Experiment 3, we varied viewing distance whilst keeping the object 0.5 m from the projection surface. Here, perhaps counter-intuitively, projected size increases as the observer moves away from the mirror or window (see Figure 5). In the limit, projected size approaches the physical size of an object. In Experiment 3, the projected size was 0.50 of the physical size when the observer was in the near position (0.5 m from the mirror or window), but it increased to 0.86 when the observer moved to the far position (3 m from the mirror or window). This manipulation provided a strong test of whether observers can perceive projected size. If observers estimated projected size as smaller from the near compared with the far position, this would suggest that they could detect a difference between the projections, even if imperfectly. Conversely, if observers can only perceive physical size, there should be no difference in their estimates of projected size across the two viewing positions.

Experiment 3 also extended the conceptual questions posed in Experiment 2. First, in Experiment 2 and earlier studies (Bertamini & Parks, 2005; Lawson & Bertamini, 2006), observers were only asked to give the direction of any size difference between projections and the objects producing them. In Experiment 3, people had to specify the magnitude of this difference (see Figure 6). Second, in Experiment 2, perceptual estimates of projection size were unchanged by viewing distance, but, when asked, people said that far projections were smaller than near projections. In Experiment 3, we examined this apparent discrepancy between perceptual and conceptual knowledge. In this study, the projection was larger in the far position, the retinal size was smaller in the far position, and the physical size was the same in both positions. Responses to whether the far projection was larger, smaller, or the same size as the near projection should then indicate what aspect of the stimulus people were responding to.

Method

Observers

Forty-eight students (8 male) from the University of Liverpool took part in the experiment for course credit. Half were assigned to the mirror group and half to the window group.

Design and Materials

These were identical to Experiment 2, with the exception that the experiment was conducted in a room intermediate in size between those used in Experiments 1 and 2, and people responded to two of the three conceptual questions by drawing lines to represent projections of the stick on a diagram (see Figure 6). The dimensions of the window and mirror were the same.

Procedure for Perceptual Length Estimates

This was identical to Experiment 2 except for the following points. (a) The assistant holding the sticks always stood in the near position whilst the observer made estimates from both the near position (0.5 m from the window or mirror) and the far position (3 m). (b) For all tasks, a plank (7 cm wide and 140 cm long) covered in white paper was held up behind the sticks (see Figure 2). The plank prevented mirror group observers in the far position from seeing the sticks directly; they could only see them using the mirror. The plank was used in all conditions for consistency. (c) The assistant stood to the side of the aperture and held the sticks to one side rather than above her head (see Figure 2). (d) Before starting the physical task, people measured the length of a 68-cm bamboo stick. Before starting the projection task, people measured the length of the projection of a 24-cm stick on the surface of the window (for the window group) or mirror (for the mirror group)

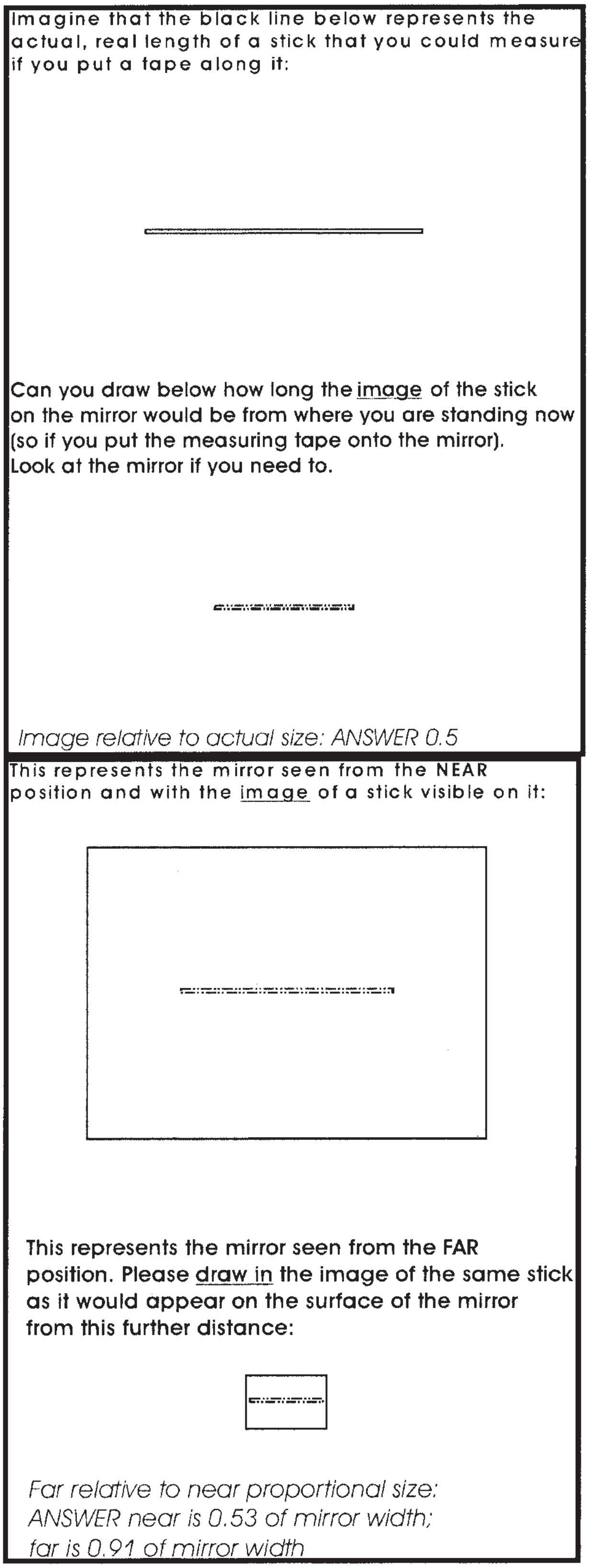

Figure 6. The mirror group version of the conceptual question sheet used in Experiments 3 and 4, with the correct responses filled in.

from the near position by placing the measuring tape directly onto the glass. After responding, observers were told the correct response (68 cm for the physical task; 12 cm for the projection task). This demonstration made it easier to explain the projection task. (e) People were told to pull the tape out upside-down to their estimated length and only then to turn over the tape and read out their estimate. This was done to discourage people from rounding their estimates.

Procedure for Conceptual Questions

After completing their perceptual size estimates, observers were asked three multipart questions about their conceptual knowledge of the size of projections whilst they stood in the near position. The first question concerned the size of projections of a stick compared with its physical size. Observers looked at an 80-cm stick reflected in the mirror or window and were asked whether the projection of the stick was bigger, smaller, or the same size as the physical stick. They were then shown a 6.7-cm line and told that it represented the physical stick (see Figure 6). Observers drew a line beneath it to indicate the length of the projection of this stick. Finally, they were asked what projection length they had tried to draw, as a proportion of the depicted physical stick length.

For the second question, observers were asked whether the far projection of a stick was bigger than, smaller than, or the same sizeas its near projection. Next, they were shown a diagram representing the near projection of a stick. They then drew a line to indicate the projection of the same stick from the far position (see Figure 6). They were also asked what proportion of the width of the far aperture was occupied by the projection that they had just drawn. Finally, observers tried moving backward and forward between the near and the far position and were again asked whether the far projection of the stick was bigger than, smaller than, or the same size as the near projection.

For the third question, observers stood in the near position with their back to the mirror or the window, facing the experimenter. They were asked whether they could see more, less, or the same amount of the scene in the mirror or window from the far compared with the near position. They then turned to face the mirror or window and moved backward and forward between the near and the far position and were asked this question again. People may find this question about field of view easier to reason about than the previous question about the size of the projection of a particular object (Bertamini et al., in press). People often move forward to see more of the world through a window or an open door. Hence, they may have learned how viewing distance influences the amount of a scene visible through an aperture, even if this knowledge is not applied to questions about projection size.

Results

Perceptual Estimates

Each length estimate was divided by the physical length of the stick. The correct proportion was 1.0 for physical estimates, 0.50 for near projection estimates, and 0.86 for far projection estimates. Physical estimates (1.04) were greater than projection estimates (0.88), $F(1, 46) = 58.69$, $p = .00$. Group was not significant and, most important, neither was the Group × Task interaction, $F(1, 46) = 0.62$, $p = .44$. Physical size estimates were close to the correct proportion of 1.0 for both the mirror group (1.07) and the window group (1.01), whilst projected size was similarly overestimated for the mirror group (0.90) and the window group (0.87).

Neither the Distance × Task nor the Distance × Task × Group interaction was significant (see Figure 7). Most important, far projection estimates (0.89) were similar to near projection estimates (0.87), even though there was a large difference between the correct response for far projections (0.86) and near projections (0.50). Although the far projection estimates were accurate, we do not believe that this was attributable to people accurately perceiving the size of far projections. In Experiment 3, as in Experiments 1 and 2, people estimated projected size at around 0.80 of physical size irrespective of the distance of the observer from the surface of the mirror or the window and irrespective of the actual projected size.

Conceptual Questions

Question 1—projected size compared with physical size. When questioned, 69% of observers said that the projection of the stick was smaller than the physical stick (22% said the same size; 8% said larger). The line that observers then drew to show the projection was 0.88 of the physical stick (the correct proportion here was 0.50). Consistent with this, people then said that the projection was 0.90 of the length of the physical stick, with 67% intending the projection of the stick to be smaller than the physical stick (23% said the same size; 10% said larger). All these responses were similar for the mirror and window groups.

In summary, when asked in three different ways about projected size relative to physical size, most people in both groups correctly responded that the projection was smaller. However, they thought that it was only around 10% smaller (it is 50% smaller), so they grossly overestimated projected size. Their beliefs about projected

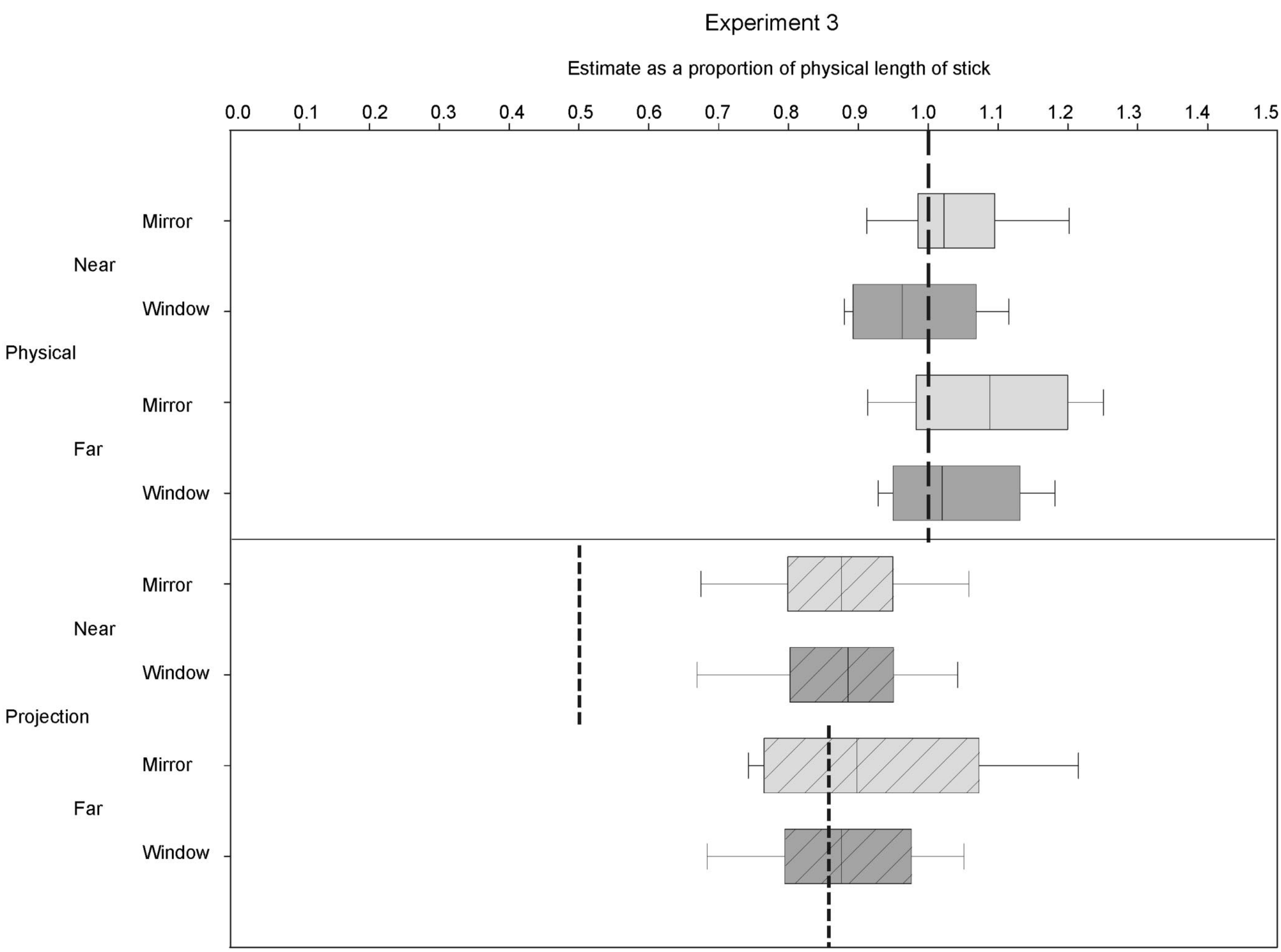

Figure 7. Box plots of the physical and projection size estimates in Experiment 3, plotted for the mirror group and the window group for the near and far positions separately. Each box indicates the 25th, 50th (median), and 75th percentiles, and the error bars show the 10th and 90th percentiles. The correct responses were 1.0 for both the near and far physical tasks, 0.50 for the near projection task, and 0.86 for the far projection task, as indicated by the dashed lines.

size were thus consistent with their errors in the perceptual estimation task.

Question 2—projected size from the near compared with the far position. Initially, 79% said that the projection of a stick was smaller from the far compared with the near position (17% said same size; only 4% correctly said larger), with similar responses for the mirror and window groups. However, the line that they then drew to show the far projection covered about the same proportion of the aperture (0.50; it should have covered 0.90 of its width). Consistent with this, most observers (63%) thought that the far projection would cover the same proportion of the mirror or window as the near projection (31% said smaller; only 6% correctly said larger). Performance improved somewhat after observers had tried moving between the near and far positions: 27% then said same size, 40% said smaller, and 33% correctly said larger.

In summary, when initially asked about the size of the far projection, almost everybody responded smaller than the near projection. However, here and in Experiment 2, this was probably because many people thought the question was about the apparent size of more distant objects. Far fewer people drew the far projection as smaller. Note that this confusion cannot explain the results of the perceptual estimation tasks in Experiments 2 and 3 since estimates of projected size were no different from near and far positions. The next stages of the second question were included to avoid this misinterpretation, yet still hardly anybody correctly responded that the far projection was larger than the near projection. Even after checking their responses by moving backward and forward, only one third of people were correct.

Question 3—scene visible from the near compared with the far position. When observers could not see the mirror or the window, 48% correctly said that less would be seen through the aperture from the far compared with the near position, and 48% said more. Results were similar for the mirror and window groups. After observers had turned to face the mirror or window and could move backward and forward, 100% correctly said that they could see less from the far position.

Thus, posing this question about changes in projections with viewing distance in a familiar context in Question 3 improved performance compared with Question 2, with perfect performance once perceptual feedback was provided. It is unlikely that the improved performance on Question 3 was solely because it followed Question 2, though this may have contributed to increasing accuracy. Instead, we believe that people know how viewing distance influences scene visibility because of their everyday experience with apertures such as windows (Bertamini et al., in press). Furthermore, people probably made better use of perceptual feedback in Question 3 because they adopted a successful strategy. They looked at objects visible near the edge of the mirror or window and noticed that these disappeared as viewing distance increased rather than trying to estimate projected size directly by looking at objects in the middle of the mirror or window.

Discussion

The mirror and window groups both grossly overestimated projected size from the near position, replicating Experiments 1 and 2. Observers directly measured the projected length of a stick by putting a tape on the surface of the mirror or window before they started to estimate projected lengths, but this concrete demonstration of the task did not improve their accuracy.

Unlike in Experiment 2, when the observer stood in the far position in Experiment 3, the stick was nearer than the observer to the mirror or window. Here, the projected length of an object relative to its physical size (0.86) was much larger than it was in the near position (0.50). However, this variation in projected size did not influence projected size estimates, which were similar for the near (0.87) and far (0.89) positions. This supports our claim that people only perceive the constant, physical size of an object; they cannot perceive changes to its projected size.

When questioned, most people correctly responded that the near projection was smaller than the physical stick, but they drew the projected size as 0.88 (it was 0.50) of physical size. Their responses thus matched their earlier perceptual overestimates of projected size (see Figure 7). People also incorrectly said that the projection of an object would be smaller or the same size from the far compared with the near position. Most people continued to make this conceptual error even after the question was clarified so it could not be misconstrued as being about the size of retinal images and even after they had perceptual feedback. When this question was reframed, about half of the observers correctly said that less of a scene is visible in a mirror or through a window if the observer moves back, and performance was perfect once they had perceptual feedback. People find it easier to reason about field of view than about the projected size of an object (Bertamini et al., in press), consistent with our claim that people cannot perceive projections of objects. Overall, there was no evidence for superior conceptual compared with perceptual knowledge about projected size.

Experiment 4

Most people find it hard to understand what is the projection of an object on a transparent surface. Across the present experiments and Lawson and Bertamini (2006), we tried many ways to explain and test estimates of projected size to try to improve performance. We have used different response measures (matching shapes, using measuring tapes and direct length estimates) as well as different explanations (e.g., describing drawing a line on the glass to mark the extent of the projection [see Footnote 2], as in Experiments 1–3) and demonstrations (e.g., requiring people to measure projections on the surface of the glass, as in Experiment 3). In Experiment 4, we replicated the mirror conditions of Experiment 3, but we used different instructions, which did not use potentially confusing terms such as *images* or *reflections*. People were told to estimate what width a mirror would need to be to just see all of a stick in it. These instructions may be easier to understand, and they also emphasize the importance of the size of the mirror. Both factors might improve estimates of projected size.

Second, in Experiments 1–3, the mirrors and windows used were much larger than the projected size of all of the target objects. People always saw projections within an extensive, distant background, and the context provided by the frame of the mirror or window was always spatially separated from this projection. In Experiment 4, we used a narrow mirror, so projections of the longer sticks extended beyond its frame and were visible next to the frame. The increased saliency of the frame of this narrow mirror might encourage people to focus on the information available at the depth of the mirror frame. This, in turn, could improve people's estimations of projection size. Indeed, people might become explicitly aware that projected size is much less than physical size if they realized that their estimate of the projected size of a stick was greater than the width of the mirror and yet all of the stick could be seen in the mirror.

Third, people were asked to estimate the width of the mirror and its distance from them when they were at the near and far positions. We did this to check that people were not misperceiving the mirror to be wider than it was or to be located farther away from them. As discussed in the introduction, this could, in theory, have led people to overestimate projected size.

Method

Observers

Forty-eight students (8 male) from the University of Liverpool took part in the experiment for course credit. Half were assigned to the narrow mirror group and half to the standard mirror group.

Design, Materials, and Procedure

These were identical to Experiment 3 except for the following points. (a) There was no window group. (b) The standard mirror group saw the same mirror as before, but the narrow mirror group saw a mirror 30 cm wide × 44 cm high, with a 2.5-cm diameter wooden frame. (c) The task instructions for the projection task were changed so that people were asked to estimate how wide the mirror would need to be to just see all of the stick in it. (d) After their last perceptual estimate, people were asked to estimate the width and height of the mirror and their distance from it from where they stood. They then moved to the other viewing position (near or far) and again estimated their distance from the mirror.

Results

Perceptual Estimates

Each length estimate was divided by the physical length of the stick. The correct proportion was 1.0 for physical estimates, 0.50 for near projection estimates, and 0.86 for far projection estimates. Physical estimates (1.03) were accurate and similar to projection estimates (1.01), $F(1, 46) = 0.26$, $p = .60$, and narrow mirror estimates (0.98) were somewhat less than standard mirror estimates (1.06), $F(1, 46) = 5.39$, $p = .025$. However, most important, the Group × Task interaction was not significant, $F(1, 46) = 0.04$, $p = .85$. Physical and projection size estimates were similar for both the narrow mirror group (0.98 and 0.97, respectively) and the standard mirror group (1.07 and 1.06, respectively).

Neither the Distance × Task nor the Distance × Task × Group interaction was significant (see Figure 8). Most important, replicating Experiment 3, far projection estimates (1.04) were similar to near projection estimates (0.98), even though there was a large difference between the correct response for far projections (0.86) and that for near projections (0.50).

Estimates of the width of the mirror were quite accurate for the narrow mirror group (32 cm; it was 29.5 cm) and the standard mirror group (99 cm; it was 87 cm). Only the narrow mirror group estimated distance to the mirror. This was not overestimated from the near position (53 cm; it was 50 cm) or the far position (267 cm; it was 300 cm).

The projected size of the 60-cm stick seen from the near position was 30 cm, and this, in turn, was the same width as the narrow mirror. Thus, when people were deciding what width the mirror would need to be to see all of this stick in it, they should have realized that the mirror was already the correct width, so they just needed to estimate its width. However, estimates of the projected and the physical size of this 60-cm stick were similar for the narrow mirror group (0.81 and 0.87, respectively) and the standard mirror group (0.95 and 0.94, respectively). Thus, even for this special case, the narrow mirror group did not seem to realize that they were overestimating projected size (49 cm) despite their accurate estimates of mirror width (32 cm).

Conceptual Questions

Question 1—projected size compared with physical size. Initially, 75% of observers said that the projection of a stick was smaller than the physical stick (15% said same size; 10% said larger), and observers drew the projection as 0.85 of the physical stick length. Consistent with this, people said the projection was 0.86 of the length of the physical stick. Responses were similar for the standard and narrow mirror groups. Thus, as in Experiment 3, people overestimated projected size as around 0.85 of physical size (the correct proportion was 0.50).

Question 2—projected size from the near compared to the far position. Initially, 79% of the standard mirror group said the far projection of a stick was smaller than its near projection (8% said same size; only 13% correctly said larger), similar to Experiment 3. However, the narrow mirror group was more accurate: 50% said the far projection was smaller, but 46% correctly said it was larger. Thus, although the perceptual estimates of the narrow mirror group were no better than those of the standard mirror group, observers in the narrow mirror group seemed more likely to explicitly understand the effect of viewing distance on projected size. This conclusion was supported by their subsequent responses.

The line drawn by the standard mirror group to show the far projection covered about the same proportion of the mirror as the near projection (0.60; it should have covered 0.90 of its width). However, the narrow mirror group drew a far projection that covered 1.25 of the mirror width. Eleven of this group drew a line extending beyond the depicted width of the far mirror, whereas nobody in the standard mirror group did this.

Finally, the standard mirror group were split amongst those responding that the far projection was the same size (38%), smaller (29%), or larger (33%) than the near projection. Their performance improved somewhat after perceptual feedback: 46% then said same size and 46% correctly said larger. Again, the narrow mirror group was more accurate: Initially, only 25% said that the far projection was the same size as the near projection, and 63% correctly said it was larger; after moving between the near and far positions, only 8% said same size, and 83% correctly said larger.

In summary, the inaccurate responses of the standard mirror group replicated those produced in Experiment 3, with most people believing that the far projection was smaller than or the same size as the near projection of the same object. However, performance was better for the narrow mirror group. More people explicitly noticed changes in projected size when this was made salient by using a mirror that was narrower than the projection of many stimuli. Note, though, that this improved conceptual knowledge did not benefit their perceptual estimates.

Question 3—scene visible from the near compared with the far position. When observers could not see the mirror, 58% correctly said that less would be seen through the mirror from the far than from the near position, and 40% said more. Results were somewhat better for the narrow mirror group (63% said less) than the standard mirror group (54% said less). After observers had turned to face the mirror and could move backward and forward, 100% correctly said that they could see less from the far position, replicating Experiment 3.

Discussion

Instructing people to estimate projected size by estimating the width of a mirror needed to see all of an object failed to improve accuracy. People still grossly overestimated projected size in Experiment 4, so describing the task without mentioning either images or reflections failed to elicit accurate estimates. Furthermore, as in Experiment 3, projected size estimates were similar for the near (1.04) and far (0.98) positions despite the correct responses (0.50 and 0.86) being very different across the two viewing positions. These results support our claim that people cannot perceive changes to projected size. Nevertheless, people could estimate the width and distance of the glass surface of the mirror, so they knew, at least conceptually, the size and distance of the projection surface. Hence, their errors in estimating projected size could not have been a result of their perceiving the mirror to be larger or more distant than it really was.

Perceptual estimates were similar for the standard and the narrow mirror groups. By moving their heads from side to side, the latter group was surprisingly good at estimating the physical length of the longer sticks, which were only partially visible in the narrow mirror. The increased salience of the frame relative to the projec-

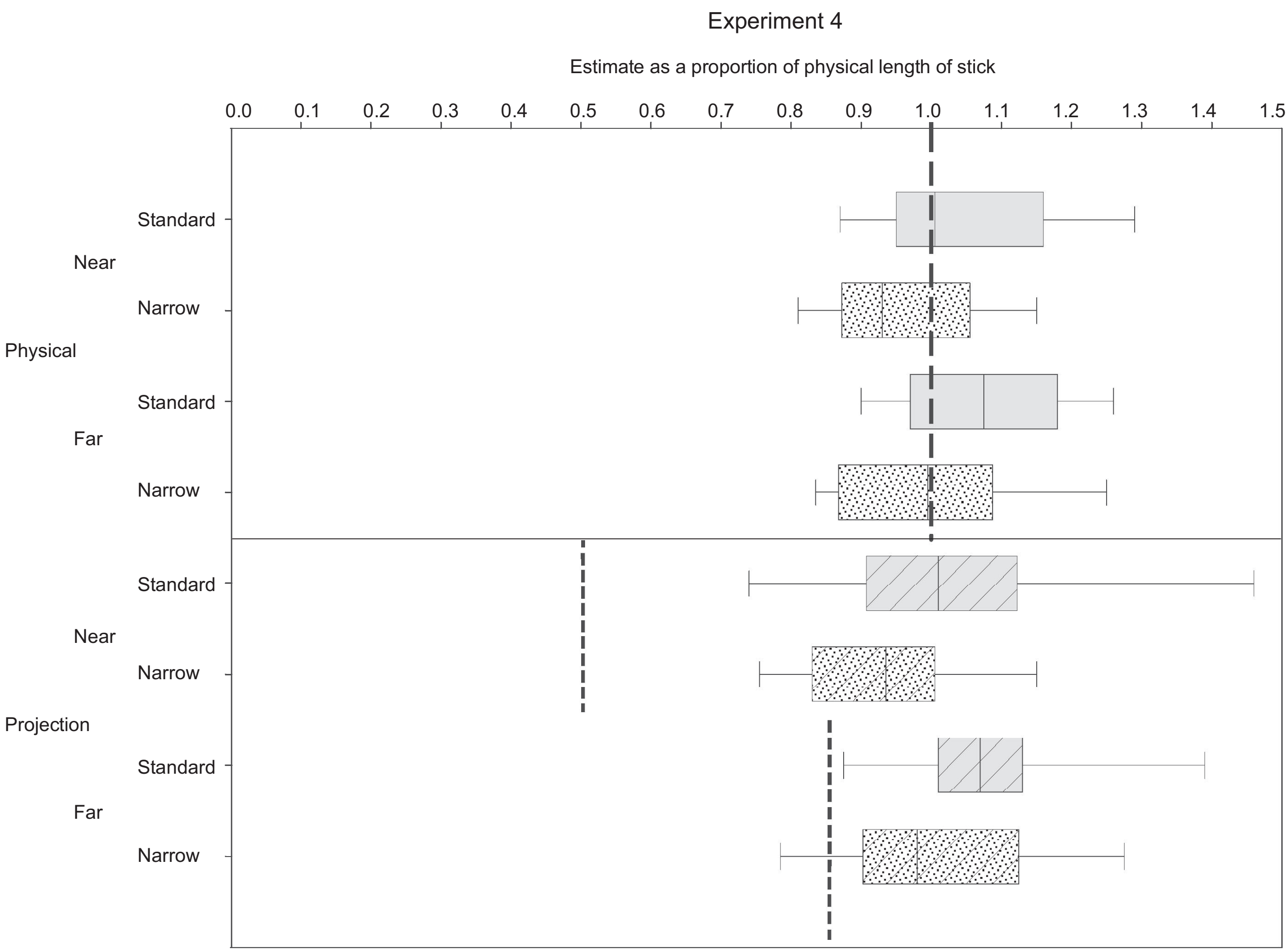

Figure 8. Box plots of the physical and projection size estimates in Experiment 4, plotted for the standard mirror group and the narrow mirror group for the near and far positions separately. Each box indicates the 25th, 50th (median), and 75th percentiles, and the error bars show the 10th and 90th percentiles. The correct responses were 1.0 for both the near and far physical tasks, 0.50 for the near projection task, and 0.86 for the far projection task, as indicated by the dashed lines.

tion on the mirror did not improve estimates of projected size for the narrow mirror group. Furthermore, most responses to the conceptual questions were consistent with people's perceptual estimates of projected size. However, the narrow mirror group was more likely to notice that projections were larger from the far position.

General Discussion

We tested people's ability to estimate information about projections and about physical objects. People can estimate the physical size of objects quite accurately independent of viewing distance. Our experiments demonstrated that people are also good at estimating the physical size of objects seen in mirrors or through windows (see also Higashiyama & Shimono, 2004). However, observers estimated the projection of an object as around 0.80 of the physical size of that object, so in many cases they overestimated projected size by 60% or more. This error occurred even though we took pains to specify what projected size was and we explained the task in different ways. The same pattern of performance was observed whether projections were on mirrors or windows (in Experiments 1–3), for projections at different viewing distances (in Experiments 2–4), or on different sizes of mirror (in Experiment 4); when both the location in depth and size of the projection and the physical object were matched (comparing the physical on glass and projection tasks in Experiment 1); and irrespective of the relative size of the projection to the physical object (in Experiments 3 and 4). Furthermore, when observers were explicitly questioned about their conceptual knowledge of projections on mirrors and windows, their results were largely consistent with their perceptual estimates. Together, these findings provide strong support for our hypothesis that people cannot perceive projections of objects on mirrors or on windows.

If it is impossible for people to perceive the size of a projection, how do we explain the systematic estimates that observers gave? One possibility is that, since observers could not judge projected size, they instead reported the physical size of the object that produced the projection. As a first approximation, this is a good description of what happens. In our experiments, estimates of the projected size of an object were usually closer to its physical than to its projected size. The obligatory achievement of size constancy is consistent with the finding that retinotopic activation in primary visual cortex due to the perceived size of an object changes according to the object's perceived distance (Murray et al., 2006). This suggests that size constancy is achieved early in processing, though the relation of this activity to the conscious perception of object size remains to be determined (Sterzer & Rees, 2006). However, it is likely that other factors influence judgments. For example, observers may try to differentiate physical from projected size estimates when they are asked to produce both. Another factor may be a cognitive adjustment due to a conceptual belief that projections are smaller than the objects producing them. Some observers may also use a successful strategy such as estimating the width of the mirror or window taken up by the projection. Note that it is remarkable that naive observers do not make more use of such strategies (Lawson & Bertamini, 2006), although similar tricks are used by skilled painters and illustrators. For all these reasons, it is not surprising that people's estimates of projected size were consistently smaller than their estimates of physical object size.

As projected size was usually estimated to be between the physical and the projected size of an object, this could be taken as evidence of a compromise or cross-talk between the dual percept of a physical object and its projection (Niederée & Heyer, 2003; Sedgwick, 2003). However, our results provide evidence against this interpretation. First, we found no evidence that the size of physical objects was underestimated, although the projected size was always smaller than the physical object size. Second, in Experiments 3 and 4, an object of constant size produced projections with very different sizes (depending on viewing distance), but estimates of projected size were similar irrespective of distance. Cross-talk would predict larger estimates of projected size for larger projections.

We argued in the introduction that overestimation of projected size on mirrors may be a striking example of an interesting and general phenomenon that informs us about the perception of distal objects. The present results demonstrate that this overestimation is not a special feature of mirrors or of estimation of face size: The sizes of projections of sticks on windows are also difficult to perceive. Indeed, we believe that the same results would have been produced if we had used an empty frame. The glass surface on mirrors and windows is only useful because it allows the projection estimation task to be explained concretely to observers (e.g., by telling them that they could draw around the projection on the glass with a felt-tip pen). The frame is more important because it clearly specifies the location of the projection plane.

The perception of 2-D surfaces depicting 3-D distal objects has been debated extensively by researchers interested in the relation between the perception of pictures and of the real, physical world (Gibson, 1979; Hecht et al., 2003). It is widely accepted that people can generally access two percepts from a picture—a 2-D pigmented surface and a representation of a 3-D scene showing objects at different depths. Niederée and Heyer (2003) suggested that these two types of percept are bound together, rather than merely being available to an observer in parallel (see also Sedgwick, 2003), and that a similar dual percept exists for both mirrors (p. 85) and windows. For example, Niederée and Heyer stated, "think, for example, of a house seen through a window, which at the level of the percept simultaneously appears smaller than the window (proximal mode) and larger than the window (distal mode)" (p. 93). However, Niederée and Heyer provided no empirical support for their claims, and the present experiments provide evidence against them. Our findings suggest that when people see a house through a window, they never perceive a small house on the 2-D glass surface. Hence although people can accurately estimate the physical size of either the window or the house, they cannot accurately extract the size of the projection of the house on the surface of the window.

Although the perception of pictures and photographs is similar in some respects to the perception of projections on the surface of mirrors or windows, there are important differences (Clark, 1996). There is no physical 3-D scene for pictures, unlike for projections on windows or, indirectly, for mirrors. For pictures, the only physical object is the picture itself. Furthermore, pictures are usually perceived as pictures; they rarely produce a trompe l'oeil effect in which they are mistaken for reality (Cutting, 2003; Niederée & Heyer, 2003). The greater realism of the 3-D scene visible in a mirror or through a window probably makes it harder to access information about 2-D projections on mirrors and windows, though this issue remains to be tested empirically. Pictures also show a 3-D scene from a fixed viewpoint, which usually differs from the viewpoint of the observer. Therefore, perception of the 3-D scene can be distorted, though a compensation process has been suggested (Pirenne, 1970; Rosinski & Farber, 1980; but see Cutting, 1987). In contrast, projections on the surface of mirrors and windows alter as the observer moves, and the 3-D scene is always shown from the correct perspective for the observer.

Most research on picture perception has focused on people's ability to extract information about the 3-D physical world rather than the 2-D pictorial world (e.g., Rogers, 2003). However, it has been suggested that well-studied effects such as the Müller–Lyer, Ponzo, and table-top illusions demonstrate failures to access accurate 2-D pictorial information because of an automatic 3-D interpretation of such stimuli (Gregory, 1963, 1998; but see DeLucia & Hochberg, 1991; Zanker & Abdullah, 2004). The present experiments found that in a more extreme (but more naturalistic) situation, observers could not estimate information about projections on a 2-D surface. The difficulty that artists have when they try to realistically represent objects in a 3-D scene onto a flat canvas is analogous to the difficulty that our observers had in estimating information about the projection of a 3-D object on a mirror or a window.

The visual world is populated by objects that people effortlessly perceive as solid shapes. These are experienced as *out there*, and this is what the term *distal* tries to capture. In contrast, although, as here, projections may exist as geometric shapes that are localized in space on a surface that is well defined by its frame, they still have no existence to observers as distal objects. This is counterintuitive only because of the lure of the stimulus error (Koffka, 1935).

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Appendix

Influence of Binocular Viewing on Stimulus Size

Our observers estimated sizes binocularly, so the projection of a stick on the surface of the mirror or window was slightly displaced horizontally for their right relative to their left eye. If the stick and the observer were the same distance from the glass surface and observers used their right eye to estimate the position of the right end of the stick and their left eye for the left end, this length would be longer than the length of the projection visible monocularly by an amount half of their interocular distance (around 3 cm). If this contributed to people's overestimation of projected size, it would only have a substantial effect for the shortest, 10-cm stick. Here, adding 3 cm to the projected size (5 cm) gives 8 cm, which is close to people's estimates. For longer sticks, any effect would be small: For the 80-cm stick, it only increases the projected size of 40 cm to 43 cm. Figure A1 shows the mean estimates of physical size and projected size from the near position, averaged over the eight mirror and window groups tested in the four present experiments. The estimated projected sizes were 0.89, 0.83, 0.84, 0.85, and 0.82 of physical size for the 10-cm, 20-cm, 40-cm, 60-cm, and 80-cm sticks, respectively, so the overestimation of projected size was not just a result of overestimation of the smaller sticks.

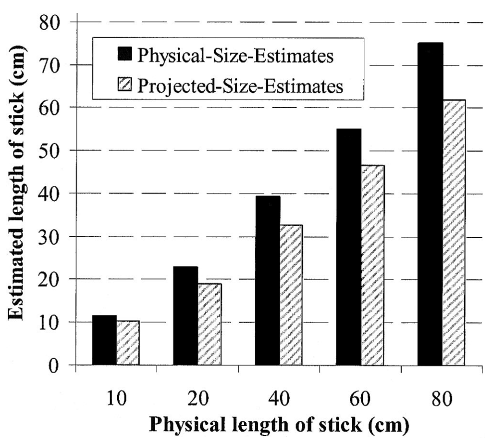

Figure A1. Mean estimates of physical size and projected size from the near position, averaged over the eight mirror and window groups tested in Experiments 1–4. For these conditions, the projected size was always half of the physical length of the stick.

Received August 8, 2006
Revision received January 11, 2007
Accepted February 28, 2007 ■