
Errors in judging information about reflections in mirrors

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Abstract. We investigated people's perception and knowledge of planar mirror reflections. People were accurate at deciding when they could first see their reflection as they approached a mirror from the side, but only if their reflection was visible. Most people stopped too early if the mirror was covered up. People also overestimated the size of the reflection of their face on the surface of a mirror if they were shown a covered mirror. Their accuracy improved somewhat if their reflection was visible but, unlike the first task, they still made striking errors. Perceptual feedback thus improved performance at predicting the behaviour of mirror reflections in both tasks but failed to eliminate errors in the second task. The overestimation of reflection size was not face-specific as it generalised to novel stimuli (paper ellipses) and it was found with both a matching response and for verbal size estimations. The early error in the first task appears to be due to an inaccurate belief that can be overridden by perceptual feedback. The overestimation in the second task is primarily caused by a powerful size-constancy effect.

1 Introduction

Research in the area of naive physics deals with people's beliefs about the physical world with particular attention paid to systematic errors that people make. For example, many people make important errors in describing the behaviour of projectiles, falling objects, and the surface level of liquids (eg Hecht and Bertamini 2000; Kaiser et al 1992; McCloskey 1983; Robert and Harel 1996). In most studies mechanical systems have been investigated. However, recent research has turned to the area of naive optics (Cottrell and Winer 1994; Winer et al 1996). Of particular relevance to the present studies is work by Bertamini and colleagues on people's understanding of the reflective properties of planar mirrors (Bertamini et al 2003a, 2003b; Bertamini and Parks 2005; Croucher et al 2002; Hecht et al 2005; Jones and Bertamini 2006).

Bertamini and colleagues have reported three common errors. First, if people are told to imagine that they are approaching a mirror from the side, many people believe that they would see their reflection before they could actually do so (Bertamini et al 2003b; Croucher et al 2002). The observer's line of sight must be perpendicular to the surface of the mirror for the reflection to be visible, so the observer must at least reach the near edge of the mirror to see his/her reflection. The belief that you can see your reflection before this point is the *early error*. This error is present for paper-and-pencil tasks, for a positioning task in a real room with a pretend mirror, and for animated computer graphic displays (Bertamini et al 2003b; Croucher et al 2002; Hecht et al 2005).

Second, Bertamini and Parks (2005) confirmed earlier informal reports (eg Gombrich 1960; Gregory 1997) that people markedly overestimated what size the reflection of their face would be as they looked at it on the surface of a mirror. In fact, the reflection is exactly half the width (and half the height, so quarter the area) of the observer's actual face—see figure 1. However, most people estimate the reflection to be around the same size as their actual face. This is the *size overestimation error*.

Third, Bertamini and Parks (2005) found that most people believed that their reflection in the mirror would appear smaller as they moved farther from the mirror.

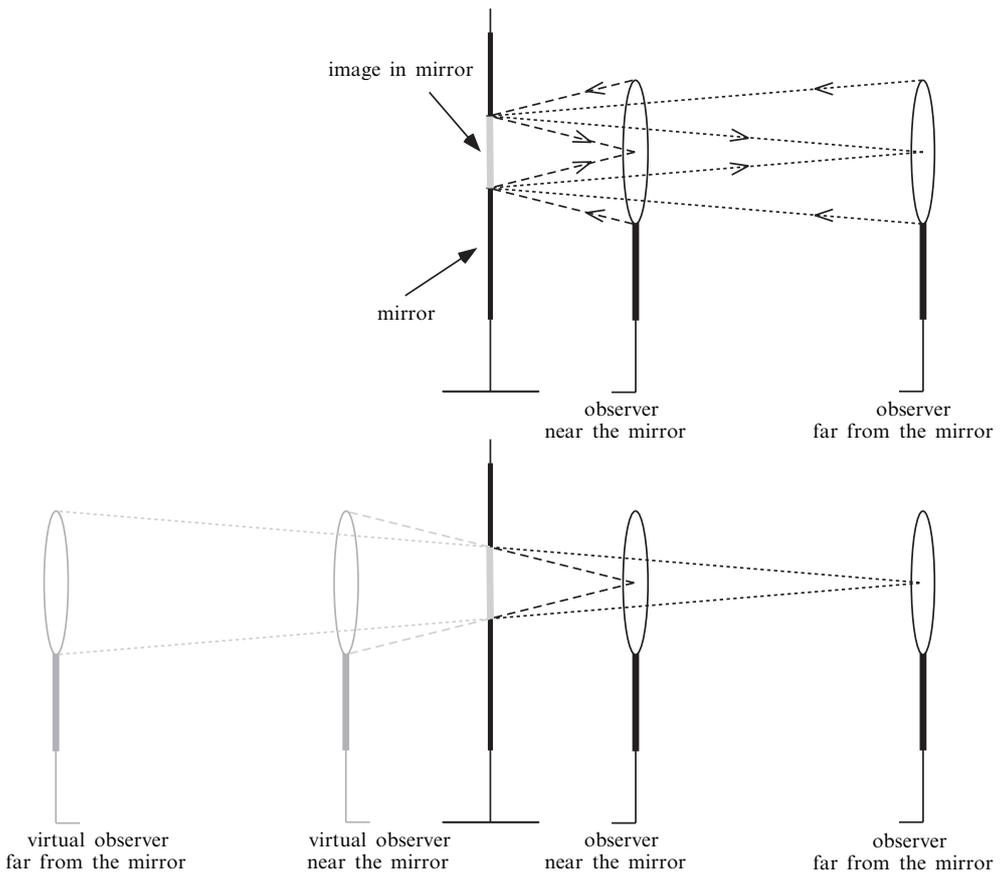


Figure 1. The image of an observer's face on the surface of a mirror is half the size of the observer's actual face, regardless of his/her distance from the mirror. The top diagram illustrates how light reflected from the top and bottom of the observer's face reflects off the mirror before entering the eye. For a plane mirror, the angle of incidence of light equals the angle of reflection, relative to the normal. The lower diagram illustrates the position of the virtual observer (in light grey). The virtual observer is always the same distance behind the mirror as the real observer is in front of the mirror. This virtual object is like a real object seen through a window, where the image on the surface of the mirror is analogous to the image on the surface of the window. We drew the observer's eye in the centre of the face. However, the image of the face would still be half the size of the actual face if his/her eye was at the top of the face.

This is the *distance error*. In fact the reflection of an observer's face on the surface of the mirror is the same size irrespective of the distance from the mirror, see figure 1.

These three errors are large and directional, so they are unlikely to be due merely to a difficulty in responding accurately. However, Bertamini and colleagues did not test whether people would continue to produce these errors when they could see their reflection in a real mirror. It is important to establish this to understand the nature of these errors. This is the aim of the current studies.

One reason for people's errors in understanding the properties of the physical world may be that people acquire and maintain incorrect beliefs despite having real-world opportunities to correct their misunderstanding. The information tested may be readily available in everyday life but the correct response is not remembered. If this is the case, then providing people with rich, perceptual information whilst they do a task should improve their ability to discriminate natural from incorrect, unnatural situations. For example, when questioned about reflections in the absence of a real mirror, some people

expect their reflection in the mirror to be visible irrespective of viewpoint. If so, then increasing the perceptual realism of the task, for example by allowing people to see their reflections in a real mirror, should improve performance. Hecht et al (2005) have confirmed that this is the case. Errors may even be eliminated if the inaccurate belief can be overridden by contradictory perceptual evidence.

The pattern of some of the errors reported in the naive physics literature is consistent with this account. For example, when people made judgments about the movement of pendulums or objects free-falling from aeroplanes (Kaiser et al 1992), or the trajectory of balls (Kaiser et al 1985), animation improved performance relative to static depictions of alternatives. With mirrors, some people expect that an object on one side in the world is located on the opposite side in the virtual world (a left–right reversal heuristic; for example, people may believe that, as they approach a mirror from the right, they will first see their reflection appear from the left of the mirror). However, when shown a mirror in which left and right are reversed they do not find this natural (Bertamini et al 2003a). In these studies, improvements occurred even if people were merely presented with a number of alternatives, only one of which corresponded to the real-world situation. In other cases, performance may only improve if more direct perceptual support is provided, such as showing people only the correct answer. For instance, in studies requiring people to draw functionally important parts of a bicycle, people continued to make errors even when they had to choose between realistic stimuli (Lawson 2006a, 2006b). However, people were accurate when they were allowed to copy directly from a real bicycle.

An alternative source of erroneous beliefs about the physical world may be misperceptions in everyday life. As an example, it is clear why someone may mistakenly believe that sticks bend when they are placed in water: this is what it looks like. In this case, the persons' inaccurate belief could only be corrected by providing nonvisual input (eg tactile information) or by telling them about the refraction of light in water. It would not be corrected by additional visual experience because the visual evidence supports the incorrect belief. On this account, errors are caused by perceptual phenomena.

Some of the systematic errors reported in naive physics research can, at least partly, be explained by this latter, perceptual account. For example, McCloskey et al (1983) found that many people indicated that objects appeared to fall straight down when dropped from a moving carrier, even when they were shown animations of natural, parabolic trajectories. People made these errors even when the correct answer was shown to them. In this case, capture of attention by a misleading frame of reference (the moving carrier) appears to bias perception. In their final study, this misperception even occurred for some people who knew that the trajectory would be parabolic in the real world. People misperceived the event in spite of possessing an accurate belief about how the object should have moved. Similarly, Sholl and Liben (1995) reported a misperception that the water surface is tilted when people were actually shown water in a tilted container. Again, this misperception persisted even for some people who knew that the water surface should be horizontal. McCloskey et al (1980) also noted that objects set in motion in the real world eventually stop even when no external force appears to act on them, so that it is not surprising that people often do not understand the principle of inertia.

Here, we report four studies in which we examined whether people's early errors, distance errors, and overestimation errors with planar mirrors were reduced or eliminated by allowing people to look at reflections in real mirrors. Early errors in the walking task were eliminated by providing visual feedback. This suggests that many people have an inaccurate belief about when they can see their reflection. Surprisingly, this false belief is maintained in the face of contradictory feedback available when people look at planar mirrors under everyday conditions. People strikingly overestimated the size of reflections on the surface of mirrors, even when they were given visual feedback. This suggests that people's inaccurate beliefs about the size of reflections

in mirrors was caused by a powerful perceptual phenomenon. In brief, it is extremely hard to judge the size of an image (even when it lies on a physical object like the glass surface of a mirror or a window) rather than judging the actual size of the object itself. This testifies to the remarkable power of size constancy (Ross and Plug 1998). People's size judgments reflected the actual, physical size of objects, although they were instructed to estimate image size (Baird and Wagner 1991).

2 Experiment 1

The first experiment comprised two parts. In the first, people were asked to approach a mirror from the side and stop when they would first be able to see themselves in it. The correct response is to stop at a point perpendicular to the near edge of the mirror. Group A did the task while the mirror was covered with paper. Based on the results of Bertamini et al (2003b), Croucher et al (2002), and Hecht et al (2005), we expected many in group A to make early errors indicating that they believed that they would see themselves in the mirror before they actually could.

Group B did the same task as group A, but the paper covering the mirror was removed. If an early error was found for group B as well as for group A, this would indicate that the information needed to respond accurately in this task is not available or is not salient in the real-world, so the early error is due to a perceptual phenomenon. Conversely, if the early error was eliminated in group B, it would suggest that the early error was due to a misunderstanding that could be corrected by perceptual evidence.

In the second part of experiment 1, people estimated the size of the reflection of their face in a mirror. They chose a paper ellipse that, if placed directly on the surface of the mirror, would just cover up their reflection so that they could no longer see their face. The correct ellipse is half the width, and half the height, of the observer's face, irrespective of his/her distance from the mirror. However, Bertamini and Parks (2005) found that people usually thought that their reflection would be about the same size as their face if they were near to the mirror and that their reflection would become smaller as they moved farther from the mirror.

Group A did the first size-estimation trial standing near a covered mirror. They selected a matching ellipse by holding ellipses up one at a time next to the covered mirror—see figure 2. People were expected to incorrectly select large (face-sized) ellipses, replicating the overestimation error. The paper covering the mirror was then removed and the test was repeated. If increased perceptual feedback improved performance then people should select smaller ellipses on the second trial (with their reflection visible) relative to the first trial (with the mirror covered). This would support the first account that the overestimation was due to an incorrect belief that could be corrected by direct experience. However, if people selected large, face-sized ellipses on both trials, this would support the second, perceptual account. Finally, group A repeated the test a third time, but they were now allowed to place the ellipses directly onto the surface of the mirror, to further increase the perceptual information provided.

For group B, the first size-estimation trial was identical to that of group A, except that their reflection was visible. This permitted a between-group comparison of the effect of making people's reflection visible on people's initial estimations of reflection size. The second trial for group B was identical to the first, except that the person stood farther from the mirror. If people produced the distance error, they would choose smaller ellipses in this second, far trial relative to the first, near trial. Bertamini and Parks (2005) found that around three-quarters of people believed that their reflection in a mirror becomes smaller as they move farther from the mirror. Most people stated that this was because things get smaller with distance. Bertamini and Parks investigated this issue by asking people to imagine what happened to their reflection as

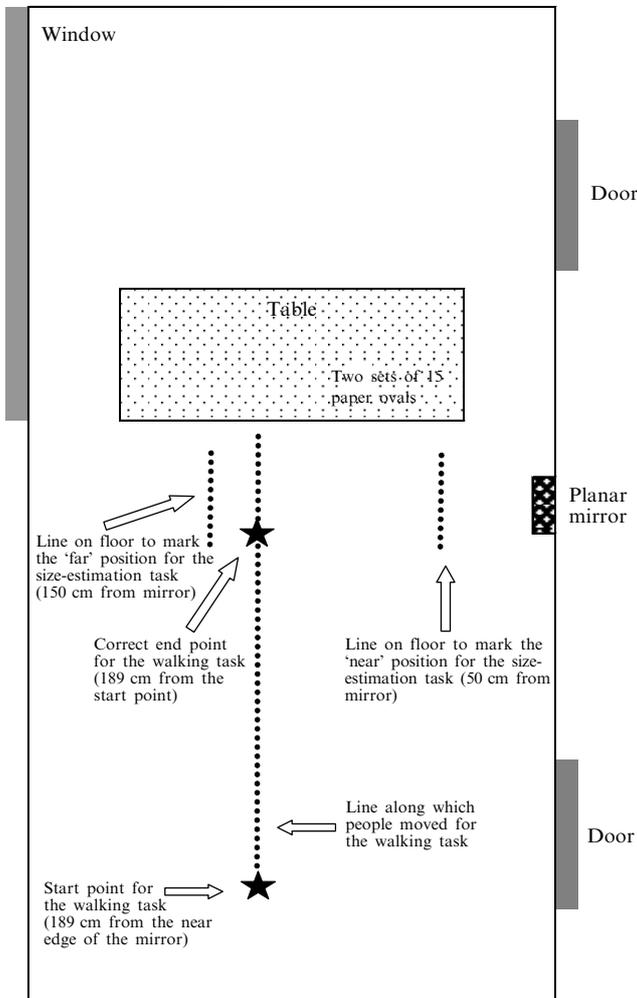


Figure 2. Experimental setup in experiments 1, 2, 3, and 4 showing the positions of the observer relative to the mirror for the walking task (experiment 1 only) and the size-estimation task. The far position was used only in experiment 1.

they moved farther from a pretend mirror. In contrast, in the present study people looked at their reflection as they stood near or far from the mirror. We therefore examined whether the distance error persisted in the face of perceptual feedback.

For all of these tasks, it may seem strange to expect that people should have any difficulty judging what is visible in a mirror while looking at it. However, as discussed in the introduction, sometimes perception itself is misleading. It is therefore necessary to determine empirically whether people's errors in understanding the behaviour of reflections on the surface of mirrors has a perceptual or a conceptual basis.

2.1 Method

2.1.1 Participants. Twenty-eight female students aged from 18 to 25 years from the University of Liverpool took part in the study for course credit.

2.1.2 Materials. A planar mirror (30 cm wide \times 44 cm high with a 2.25 cm diameter wooden frame) was placed on a wall with the top of the mirror 173 cm above the floor (see figure 2). Two sets (one white and one blue) of 15 paper ellipses were placed on a table. In each set, the smallest ellipse was 7 cm long and each successive ellipse was

1.5 cm longer (8.5 cm, 10 cm, etc) with the largest ellipse being 28 cm long. The aspect ratio of all of the ellipses was 0.64. This was chosen to approximate the aspect ratio of faces, though it turned out to be somewhat low. The ellipses were labelled with arbitrary codes and the sizes in each set were mixed up before each trial. Two sets of ellipses were used and a different set was used on each trial so that people could not remember which ellipse they had chosen on the previous trial. Brown tape marked the floor at the start point and the line behind which participants moved in the walking task, and also the near and far positions for the ellipse-matching task.

2.1.3 Design. All participants completed a single trial in the walking task and then three trials in the size-estimation task. Group A did the walking task and the first trial of the size-estimation task with the mirror covered by a sheet of paper. The mirror was then uncovered, so their reflection was visible, before they did the second and third trials of the size-estimation task. Group A did all three trials of the size-estimation task standing in the near position in front of the mirror. Group B did the walking task and all three trials of the size-estimation task with the mirror uncovered. They did the first and the third trials of the size-estimation task standing in the near position and the second trial standing in the far position.

2.1.4 Procedure. All participants began by standing at the starting point of the walking task (see figure 2), facing the wall with the mirror. They were told to look at the mirror and then to shuffle sideways parallel to the wall, keeping just behind the line on the floor, until they could first see one of their eyes in the mirror (group B) or until they thought that they would first be able to see one of their eyes in the mirror (group A). If they asked, they were told that they could move their heads to look in any direction. When they stopped moving, they were asked to stand with their feet together and the distance from the starting point to the point between their feet was measured. Participants were then asked why they had decided to stop at that point. Those in group B were also asked whether they had known before they started to move where they would stop or whether they had used their reflections in the mirror to decide when to stop. This completed the walking task. Note that Croucher et al (2002) found that the early error did not differ if people began by moving towards the mirror (as in the present study) or if they started from the centre of the mirror and moved away.

In the first trial of the size-estimation task, all participants stood facing the mirror with their feet just behind the tape marking the near position (50 cm from the mirror). The mirror was covered for group A and uncovered for group B. Participants were shown one set of fifteen ellipses and were told that they only varied in size. A small and large ellipse were selected to demonstrate this. The set of ellipses used (white or blue) alternated for each participant and on every trial. Participants were instructed to select the smallest ellipse which would, if it were placed directly on the surface of the mirror, just cover up their face, so that they would no longer see the reflection of their face in the mirror. They were not allowed to place ellipses on the mirror. Instead, they were told to hold up one ellipse at a time against the wall to the side of the mirror. They could pick as many ellipses as they wished and could re-select ellipses before making a decision.

In the second trial, group A repeated the first trial, except that the paper covering the mirror was removed so that they could see their reflection. This trial was therefore identical to the first trial for group B. In group B, participants moved to stand behind the tape marking the far position (150 cm from the mirror). They repeated the first trial, except that they were now so far from the mirror that their arms were not long enough to put the ellipses on the wall. Instead they were told to imagine how large the ellipses would be if they were placed on the wall next to the mirror. Both groups

were reminded that they should choose the smallest ellipse that would just cover up their face in the mirror if they were placed on the surface of the mirror.

The third trial was identical for both groups. Participants stood in the near position and saw the uncovered mirror. The task was the same as in the first trial except that the participants were told to place the ellipses directly on the surface of the mirror (rather than on the wall next to the mirror).

The maximum width and height of the participants' face was then measured by the experimenter with a rigid ruler held next to the face. Finally participants were asked two questions. First, the experimenter stood in the near position and said "imagine that I have an indelible felt-tip pen in my hand and that I draw an outline of my face on the surface of the mirror". The experimenter then stood in the far position and said "imagine that I now have a super-long arm so that I can reach out to the mirror from here and that I draw a second ellipse around the outline of my face. Will that second outline be bigger, smaller, or the same size as the first outline that I drew in the near position?". Second, each participant was asked "when you are standing in the near position, what size is the reflection of your face on the surface of the mirror relative to the actual size of your face?".

2.2 Results

2.2.1 Walking task. An analysis of variance (ANOVA) was conducted on stopping distance from the near edge of the mirror with group as a between-participants factor (see figure 3). Overall, group A stopped significantly short of the near edge of the mirror (range -91 cm to $+4$ cm; $t_{13} = -4.19$, $p < 0.001$), unlike group B (range -3 cm to $+4$ cm, $t_{13} = 1.06$, ns). Most people in group A made an early error, whereas none did in group B. Perceptual feedback therefore eliminated the early error, supporting the inaccurate-belief account of the early error.

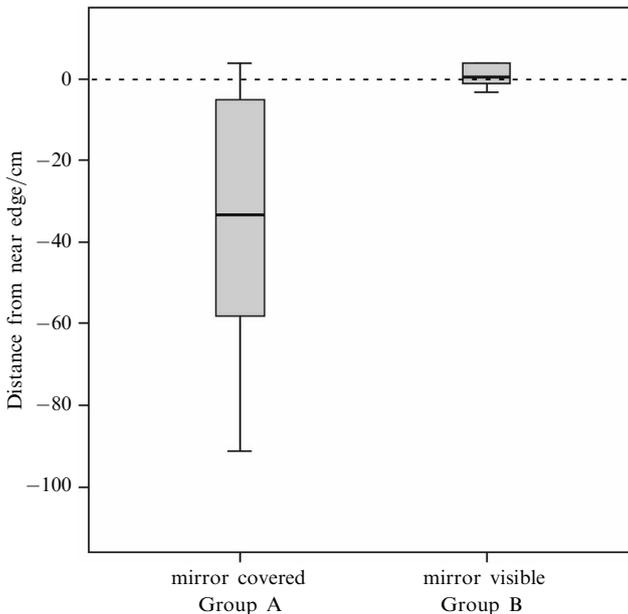


Figure 3. Box plot of the results in the walking task for the distance stopped from the near edge of the mirror (in cm) for the fourteen participants in group A (on the left; mean = -34.4 cm; standard deviation = 30.7 cm) and the fourteen participants in group B (on the right; mean = $+0.7$ cm; standard deviation = 2.5 cm) in experiment 1. The correct response (0 cm) is marked with a dashed line. Negative distances indicate an early error with participants stopping before the near edge of the mirror.

In group B, most (12/14) participants reported that they looked at their reflection in the mirror to decide when to stop. Some participants spontaneously remarked that they would have stopped earlier if the mirror had been covered up. In group A, five people responded accurately (from -5 cm to $+4$ cm) and all five also correctly responded that each would first be able to see her eye when she was level with the near edge of the mirror. The remaining nine participants made an early error (from -91 cm to -15 cm). They provided a variety of reasons to explain why they would be able to see their reflection at the chosen point (eg visualisation; angle of reflection; memory of seeing their reflection in a familiar mirror).

2.2.2 Size-estimation task. The width of the ellipse selected by the participant on each trial was divided by the actual, experimenter-measured width of that participant's face to calculate the proportion of the width of her face that would be covered by the chosen ellipse.⁽¹⁾ If the correct ellipse had been selected, the proportion would be 0.5 since a person's reflection is exactly half the width (and half the height, so quarter the area) of her actual face. If the participant selected an ellipse the same size as her face, the proportion would be 1. ANOVAs were conducted on these proportions (see figure 4). The mean actual face width (and height) measurements were for group A 14.6 cm wide (19.6 cm high) and for group B 14.1 cm wide (20.2 cm high).

In an ANOVA for the first-trial data with groups as the only between-participants factor, there was no significant difference between group A (1.06) and group B (0.98) in the proportion of the width of the face which would be covered by the chosen ellipse ($F_{1,26} = 1.97$, ns). Thus overestimation was as large for group B, who could see their reflection, as for group A, where paper covered the mirror. The proportion on this first trial (1.02) was not significantly different from 1 ($t_{27} = 0.66$, ns), and it was significantly larger than 0.5, the correct answer ($t_{27} = 18.21$, $p < 0.001$). The results for group A confirmed those of Bertamini and Parks (2005): when people had to imagine seeing their reflection in a mirror, they grossly overestimated their size. Surprisingly, this overestimation was as severe for group B, though this group could see their reflection, supporting the perceptual account of this error.

This issue was re-examined in a repeated-measures ANOVA for group A only. Overestimation was significantly greater when the mirror was covered (1.06) in the first trial than when the observer's reflection was visible (0.85) in the second trial ($F_{1,13} = 17.21$, $p < 0.001$). The proportion when the mirror was covered (1.06) was not significantly different from 1 ($t_{13} = 1.84$, ns). In contrast, the proportion when the observer's reflection was visible (0.85) was significantly less than 1 ($t_{13} = -2.52$, $p < 0.03$), though it was still significantly larger than 0.5, the correct answer ($t_{13} = 5.86$, $p < 0.001$). For group A, uncovering the mirror modestly improved performance but a strong overestimation persisted. This suggests that the overestimation is largely resistant to correction from perceptual feedback, supporting the perceptual account. A modest improvement did occur when people could see their reflection. This was significant for the within-participants

⁽¹⁾ Calculations were based on face width because the mean width-to-height ratio of the actual faces of participants (0.72) in experiment 1 was greater than that of the paper ellipses (0.64). Since the ellipses were thus slightly longer and narrower than most participant's faces, if participants selected ellipses which just covered the width of their face, these ellipses would usually cover slightly more than the length of their face. Basing calculations on width reduced the likelihood of detecting overestimations of reflection size (ie it worked to reduce the predicted overestimation). To illustrate this, if a participant's face was 20 cm long and 14 cm wide, if reflection width was matched correctly he/she would select an ellipse 7 cm wide and this would be 10.94 cm long, so 0.94 cm too long. If the participants matched on reflection height, they would have chosen an ellipse 10 cm long and this would be only 6.4 cm wide, so 0.6 cm too narrow. Importantly, most people made large size overestimations, regardless of whether widths, heights, or areas were considered. Also, in their first study Bertamini and Parks (2005) found that people overestimated height and width to a similarly large extent when people judged the size of their reflection in a (non-visible) mirror.

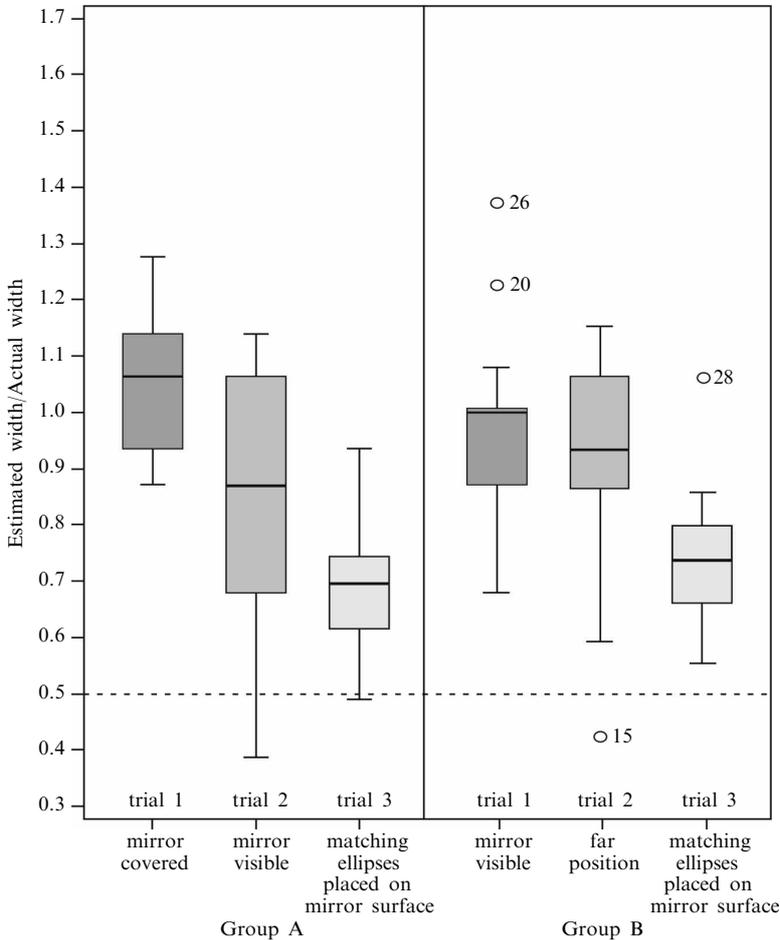


Figure 4. Box plot of the participant's estimated width of the reflection of his/her face divided by the actual width of that participant's face for the three trials completed by group A (on the left) and group B (on the right) in experiment 1. Unless otherwise specified, the mirror was visible and was seen binocularly from the near position, and people held up the matching ellipses on the wall next to the mirror. The correct response (0.5) is marked with a dashed line.

comparison for group A and there was a non-significant trend in the same direction for the between-participants comparison for the first-trial data. This provides evidence for a secondary role for the inaccurate-belief account in explaining the overestimation.

In a repeated-measures ANOVA for group B only, the overestimation was significantly larger when people stood in the near position (0.98) in the first trial than when they stood in the far position (0.90) in the second trial ($F_{1,13} = 4.81, p < 0.05$). There was therefore some evidence that people made the distance error in this task. However, the proportion in the far position (0.90) was not significantly different from 1 ($t_{13} = -1.82, ns$), and it was significantly larger than 0.5, the correct answer ($t_{13} = 7.32, p < 0.001$). Similarly, the proportion in the near position (0.98) was not significantly different from 1 ($t_{13} = -0.43, ns$), and it was significantly larger than 0.5 ($t_{13} = 10.36, p < 0.001$).

When questioned at the end of the study, most people (79%) thought that the reflection of their face on the surface of the mirror would be smaller when they looked at it from the far position than from the near position. This was true for both group A (12/14) and group B (10/14). As in Bertamini and Parks (2005), when asked explicitly, most people produced the distance error. Only three people thought that their reflection

would be the same size from both positions (the correct answer) and three thought that their reflection would be larger from the far position. However, at most, the distance error only weakly influenced people's size overestimations: on average group B chose only slightly smaller ellipses from the far position than from the near position. Even in the far position, people selected ellipses that were much too large. Furthermore, people's explicit beliefs about what would happen to their reflection as they moved farther from the mirror failed to predict their responses on the ellipse-matching task. Of the nine people in group B who selected a smaller ellipse from the far position, six said their reflection would be smaller in the far position, but two said they would be the same size, and one said her reflection would be larger. Of the five people who selected a larger ellipse or the same-sized ellipse from the far position, just one said her reflection would be larger in the far position whilst four said their reflection would be smaller.

Finally, a mixed ANOVA was used to analyse data from group B in the first trial (with the ellipses placed on the wall next to the mirror) and the third trial (with the ellipses placed directly on the surface of the mirror) and from group A in the second trial (ellipses next to the mirror) and third trial (ellipses on the mirror). In all four of these conditions, people's reflections were visible and they stood in the near position. The width of the chosen ellipses as a proportion of the width of their faces was significantly larger when the ellipses were put on the wall next to the mirror (0.92) than when they were placed directly on the mirror (0.72) ($F_{1,26} = 43.83$, $p < 0.001$). There was no significant difference between group B (0.87) and group A (0.77) ($F_{1,26} = 3.00$, ns), and no interaction between group and where the ellipses were placed ($F_{1,26} = 1.38$, ns). The proportion when the ellipse was placed on the mirror (0.72) was significantly smaller than 1 ($t_{27} = -12.12$, $p < 0.001$), but it was still significantly larger than the correct answer of 0.5 ($t_{27} = 9.59$, $p < 0.001$). Performance was thus more accurate when the ellipse was placed directly on the surface of the mirror. Nevertheless, to our surprise, both groups continued to overestimate the size of their reflection by over 40%.

When questioned at the end of the study, most people thought that the reflection of their face was smaller than their actual face size, though few were confident about this. Of the twenty-eight people, twenty-three (82%) said that their reflection was smaller, four gave confused responses that could not be interpreted, and one thought that her reflection was larger than her actual face. Most people had some insight into the size of their reflection after completing the study, but they did not explicitly know that their reflection was half the width of their actual face.

2.3 Discussion

The results for the walking task were straightforward. We replicated the early error (Bertamini et al 2003b; Croucher et al 2002; Hecht et al 2005) for group A who were tested with a covered mirror: most people stopped before the near edge of the mirror. In contrast, allowing people to see their reflection in a real mirror (group B) eliminated the early error. The early error is therefore due to an inaccurate belief rather than a perceptual phenomenon. Bertamini et al (2003b) explored a number of reasons why many people believe they can see their reflection before they can do so. It is surprising that the early error is so common, despite the prevalence of evidence contradicting it in everyday situations, and despite people's success at using that evidence, as demonstrated by group B here.

Hecht et al (2005) showed dynamic, computer-generated scenes to observers and found only small early errors in the walking task. These errors were an order of magnitude less than those reported in more conceptual, pen-and-paper tasks. They argued that this was due to the increased perceptual information in their task. However, Croucher et al (2002) tested people who moved in a real room with a pretend mirror (a paper-covered

whiteboard), whilst here we tested people moving in a real room with a real (but covered) mirror. Large early errors were found in both cases, yet perceptual information was presumably more realistic than in the scenes shown on computers to Hecht et al's seated observers. Also, unlike experiment 1 here, Hecht et al did not directly manipulate the amount of perceptual information available within the study. An alternative explanation of Hecht et al's finding of a significant but minimal early error is that their studies tested a selected population. They tested just seven people in their second study, and all but one had university-level maths, physics, or engineering training. Their results may not accurately reflect the magnitude of the early error in the general population. In support of this account, note that, in experiment 1, five of the fourteen participants in group A responded accurately, so here, too, a sizeable minority of people did not produce the early error. Our results indicate that, so long as the reflection in the mirror is not visible, a strong early error occurs for many people, even if all other perceptual information about the task is maximised.

In contrast to the results from the walking task, visual feedback from seeing an uncovered mirror did not eliminate size overestimation. There was a large error in every condition tested. In the first trial, both groups A and B chose ellipses which were about the same size as their faces, so about twice as wide (and twice as high) as they should have been. There was some evidence that visual feedback improved performance, but only modestly. For group A, uncovering the mirror improved their performance such that they selected ellipses that were significantly smaller than their faces. Nevertheless, they still chose ellipses that were much too large. Also, when people placed the ellipses directly on the surface of the mirror, the ellipses chosen were smaller than when the ellipses were held beside the mirror. Nevertheless they were still around 40% larger than their reflections. These results support the perceptual account as the main reason for people's overestimation, as performance was largely resistant to correction from perceptual feedback. The somewhat reduced overestimation error when people could see their reflection in a real mirror provides evidence for a secondary role for the inaccurate-belief account.

When explicitly questioned, most people (79%) stated that the reflection of their face on the surface of the mirror would become smaller as they moved farther from the mirror, confirming Bertamini and Parks's (2005) report of a distance error. However, this belief had little influence on group B's ellipse-matching performance: there was only a small reduction in overestimation when they were tested in the far, relative to the near, position. Furthermore this reduction was not consistently linked to people's explicitly reported beliefs about how the size of a reflection changes as the observer moves away from a mirror. The lack of difference between the near and far positions is surprising. In the near condition, observers matched two images seen side by side, so the retinal images should be the same size for the correct match. This was not true for the far position. The explanation seems to be that in both cases observers' judgments are strongly biased by size constancy. If people match to the actual size of their faces, which is invariant with viewing distance, then performance in the near and far positions should be similar. Nevertheless it is possible that people's ellipse-matching estimates would alter more if distances greater than 150 cm were tested.

The distance error probably results from people inappropriately applying a (generally correct) belief about the retinal size of images, namely that things appear smaller when they are seen from farther away. However, an overestimation is caused by inappropriately applying size constancy when people are asked to judge the size of a reflection (rather than to judge the actual, physical size of an object). Here retinal size is largely ignored. Most people produced both overestimation and distance errors indicating that they do not have a coherent, consistent understanding of optics. People's understanding of mechanics has similarly been found to be simplistic, incoherent, and inconsistent.

In conclusion, perceptual feedback improved performance at predicting the behaviour of mirror reflections in both the walking distance and the size-estimation tasks. However, the improvement was modest in the latter task, whereas errors were eliminated in the former task. We therefore found evidence to support the inaccurate-belief account as the sole reason for errors in the walking task, and as a secondary explanation for errors in the size-estimation task, whilst the perceptual hypothesis provided the main account for errors in the size-estimation task.

3 Experiment 2

Experiment 2 was conducted to examine a number of reasons why, in experiment 1, people overestimated the size of the reflection of their face even when they could see their reflection. First, we checked that people did not always overestimate the size of elliptical shapes. People estimated the size of a real, cardboard ellipse that was approximately half the width and half the height of their face, and so was about the size of the reflection of their face on the surface of the mirror. This tested the accuracy of people's estimation of the size of real objects rather than of reflections. We expected people to be accurate and not to systematically deviate from the correct answer. If so, this would suggest that the overestimation observed in experiment 1 was either due to errors in estimating the size of faces or to errors in estimating the size of reflections in mirrors.

Second, we investigated whether overestimation was specific to estimating faces or generalised to other, novel objects. A paper ellipse that was approximately the same size as a face was placed next to the observer's head. The observer saw the reflection of this ellipse in the mirror that he or she was facing. This reflection was about the same size as the reflection of the face. If the observer could accurately estimate the size of the reflection of this novel ellipse it would suggest that size constancy for faces produced the overestimation in experiment 1. When people see the reflections of faces in mirrors, they may find it difficult to discount their knowledge of the actual size of faces. This could explain why, in experiment 1, people usually selected ellipses that were about the size of their faces. In contrast, if people continued to overestimate when they tried to match the size of the reflection of a novel, test ellipse, it would indicate that they had a general difficulty in estimating the size of reflections on the surface of a mirror.

On the third trial in experiment 2, people estimated the sizes of the reflection of their face. We predicted that a clear overestimation would be found here, as this trial replicated the first trial in experiment 1 for group B. This trial provided a within-participants control to test whether size estimation for reflections of novel ellipses (tested in the first two trials) was more accurate than that for reflections of faces.

Finally, the fourth trial repeated the third except that people closed one eye as they were matching the ellipses. This tested whether people's responses were more accurate when faces were viewed monocularly rather than binocularly. If size overestimation is linked to size constancy, reducing depth information may reduce size constancy and hence the overestimation error (Holway and Boring 1941; Kaneko and Uchikawa 1997; Koh and Charman 1999). Monocular viewing moves one step towards reducing the reflection to a flat picture. Analogously, we naturally close one eye when trying to frame a photograph to flatten what we see, to get a better idea of how the photograph will look.

3.1 Method

3.1.1 *Participants.* There were eighteen students (six male and twelve female) aged from 18 to 43 years from the University of Liverpool who took part in the study for course credit.

3.1.2 *Materials.* These were identical to those in experiment 1, except that, in addition, two test ellipses were used: a small, orange ellipse (7.25 cm wide \times 10 cm high) and a larger, green ellipse (14.5 cm wide \times 20 cm high). The 0.725 aspect ratio of these test

ellipses was slightly greater than that for the sets of blue and white matching ellipses (0.64), but was equal to that of the faces of participants in experiment 1 (0.72). The green ellipse was approximately the same size as a face whilst the orange ellipse was approximately half the width and half the height of a face. The orange ellipse was therefore about the same size as the reflection of a person's face.

3.1.3 Design and procedure. All participants completed four trials standing in the near position (see figure 2). The general procedure was identical to the first trial for group B in experiment 1. In the first trial, participants estimated the actual size of the orange ellipse. The experimenter held this ellipse at head height on the wall next to the mirror. Participants held up the matching ellipses on the wall on the opposite side of the mirror. In the second trial, participants estimated the size of the reflection of the green ellipse. The experimenter held this ellipse next to the participant's face so that he/she could see its reflection in the mirror. In the third and fourth trials, participants estimated the size of the reflection of their face on the surface of the mirror. They did this binocularly in the third trial and monocularly in the fourth trial. The experimenter then measured the maximum width and height of the participant's face using a rigid ruler held next to the face.

3.2 Results

The width of the ellipse selected by each participant was divided by the actual width of the test ellipse (for the first two trials) or by the actual width of that participant's face (for the last two trials) to calculate the proportion of the width of the ellipse or his/her face that would be covered by the chosen ellipse (see figure 5). If participants had responded accurately, then this proportion would be 1 on the first trial (when they matched to the actual, physical ellipse) and 0.5 on the other three trials (when they matched to a reflection on the surface of the mirror).

On the first trial, participants estimated the actual size of the half-face-sized, orange test ellipse. The proportion of the width of this test ellipse that would be covered by the chosen ellipse (0.96) was not significantly different from the correct response of 1 ($t_{17} = -1.76$, ns). Thus participants could accurately estimate the physical size of ellipses seen directly.

On the second trial, participants estimated the size of the reflection of the face-sized, green test ellipse on the surface of the mirror. The proportion of the width of this test ellipse that would be covered by the chosen ellipse (0.86) was significantly larger than the correct response of 0.5 ($t_{17} = 13.98$, $p < 0.001$). This ratio was, though, significantly less than 1 ($t_{17} = -5.22$, $p < 0.001$), so estimates were smaller than the actual size of the ellipse. People grossly overestimated the size of the reflection of this test ellipse, demonstrating that overestimation of reflections is not restricted to faces.

On the third trial, participants estimated the size of the reflection of their face on the surface of the mirror. The proportion of the width of their face that would be covered by the chosen ellipse (1.21) was significantly larger than the correct response of 0.5 ($t_{17} = 16.15$, $p < 0.001$). Indeed these estimates were significantly greater than 1 ($t_{17} = 4.81$, $p < 0.001$). A repeated-measures ANOVA comparing estimates on the second and third trials revealed that people overestimated the size of the reflection of their face more than of the face-sized test ellipse ($F_{1,17} = 59.07$, $p < 0.001$). This suggests that there may be a face-specific overestimation over and above people's general overestimation of the size of reflections.

The fourth trial was identical to the third, except that participants estimated the size of their reflection monocularly rather than binocularly. The proportion of the width of their face that would be covered by the chosen ellipse (1.16) was significantly larger than the correct response of 0.5 ($t_{17} = 13.73$, $p < 0.001$). As on the third trial, this proportion was also significantly greater than 1 ($t_{17} = 3.32$, $p < 0.005$). A repeated-measures ANOVA

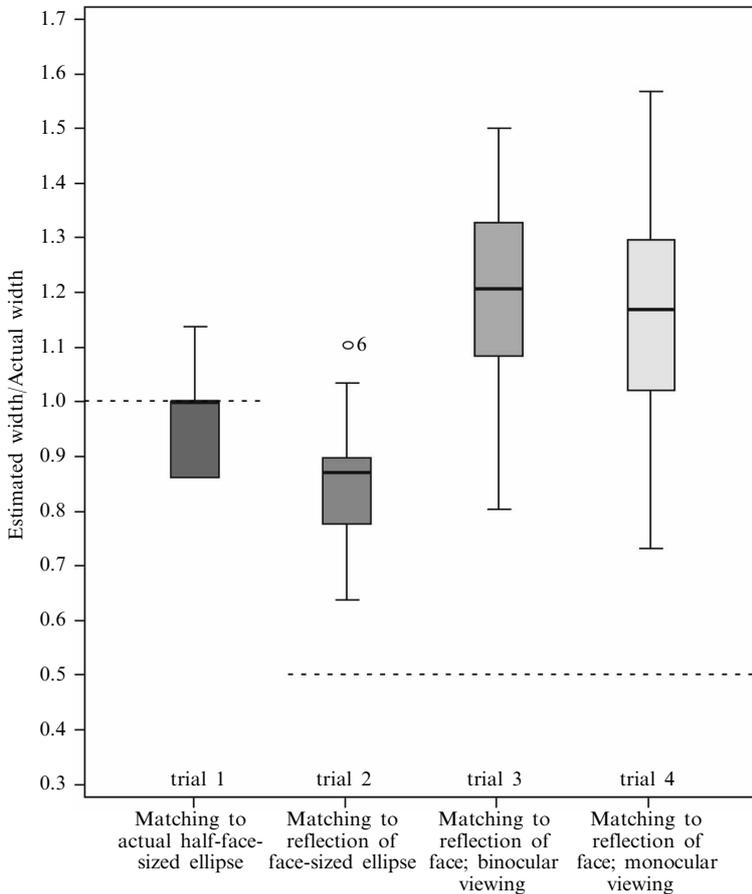


Figure 5. Box plot of estimated width of stimulus divided by actual width of object (an ellipse in the first two trials; the observer's face in the last two trials) in experiment 2. Unless otherwise specified, the mirror was visible and was seen binocularly from the near position, and people held up the matching ellipses on the wall next to the mirror. The correct response is marked with a dashed line and was 1 on the first trial and 0.5 on the next three trials.

comparing estimates on the third and fourth trials found that overestimations did not reduce significantly when people viewed their reflections monocularly rather than binocularly ($F_{1,17} = 2.40$, ns).

3.3 Discussion

In experiment 2 people accurately estimated the size of a real, test ellipse. This indicates that the overestimation found in experiment 1 was not due to problems in estimating size per se. In contrast, people grossly overestimated the size of the reflection of a test ellipse on the surface of a mirror. This indicates that much of their overestimation results from a problem in estimating the size of reflections of any object. However, the overestimation was still greater when people estimated the size of the reflection of their face compared to the reflection of a test ellipse. This latter effect may be because faces have a known, standard size, unlike the test ellipses (Kato and Higashiyama 1998). If so, then greater overestimation should also occur for other familiar objects such as horses and chairs. Alternatively, the increased overestimation could be restricted to estimations of the size of body parts or only of faces. Further research will be necessary to test these possibilities. Finally, no difference was found between binocular and monocular size estimation. Reducing the depth cues thus failed to significantly reduce overestimation, though there was a trend in this direction.

4 Experiment 3

Experiments 1 and 2 used an indirect means of estimating size. People were told to select the ellipse that would just cover up the stimulus. This response measure may have biased people to overestimate size if, for example, they believed that their reflection on the surface of the mirror was the same size as their face. People could not see their reflection whilst they chose an ellipse from the table so any inaccurate beliefs may have biased their selection of matching ellipses. In addition, the ellipses had a fixed aspect ratio which would not be identical to that of the observer's face. Experiment 3 was conducted to avoid these problems and to try to replicate the overestimation error with a different response measure. People were asked to directly estimate the width and height of stimuli in centimetres. This verbal estimation task was easier to explain and was more familiar than that of matching ellipses. Nevertheless we predicted that people would continue to overestimate the size of reflections on the surface of mirrors, for both reflections of a test ellipse and reflections of their face.

4.1 Method

4.1.1 *Participants.* There were eighteen students (six male and twelve female) aged from 18 to 20 years from the University of Liverpool who took part in the study for course credit.

4.1.2 *Materials, design, and procedure.* These were identical to those in experiment 2 except that participants responded by verbally estimating the width and height of the stimulus in centimetres rather than by choosing an ellipse that matched the size of the stimulus. As in experiment 2, the stimulus was an actual ellipse in the first trial and was the reflection (of an ellipse or of the observer's face) on the surface of the mirror in the remaining trials. Prior to the second trial, participants were briefly shown a transparent ruler placed on the surface of the mirror and were told to estimate the size of the reflection of the stimulus if it were to be measured with the ruler placed on the surface of the mirror. As in experiments 1 and 2, the explanation of the task took some time as we wanted to minimise the risk of misunderstandings.

4.2 Results

The participant's width estimation was divided by the actual width of the test ellipse (for the first two trials) or by the actual width of that participant's face (for the last two trials) (see figure 6). If participants had responded accurately, this proportion would be 1 on the first trial (when they estimated the actual, physical size of a test ellipse) and 0.5 on the other three trials (when they estimated the size of a reflection on the surface of a mirror).

On the first trial, participants estimated the actual size of the half-face-sized, orange test ellipse. Their estimated width divided by the width of this test ellipse (0.95) was not significantly different from the correct response of 1 ($t_{17} = -1.06$, ns). Replicating experiment 2, people could accurately estimate the size of real objects. Furthermore, as in experiment 2, people tended to slightly underestimate the width of the ellipse, so any error was in the opposite direction to the overestimation of mirror reflection size observed in experiments 1 and 2.

On the second trial, participants estimated the size of the reflection of the face-sized, green test ellipse. Their estimated width divided by the width of this test ellipse (0.74) was significantly larger than the correct response of 0.5 ($t_{17} = 3.40$, $p < 0.004$). This proportion was, though, significantly less than 1 ($t_{17} = -3.59$, $p < 0.002$), so people's estimates were smaller than the actual size of the ellipse. As in experiment 2, people grossly overestimated the size of the reflection of a test ellipse, confirming that the overestimation of reflections is not restricted to faces.

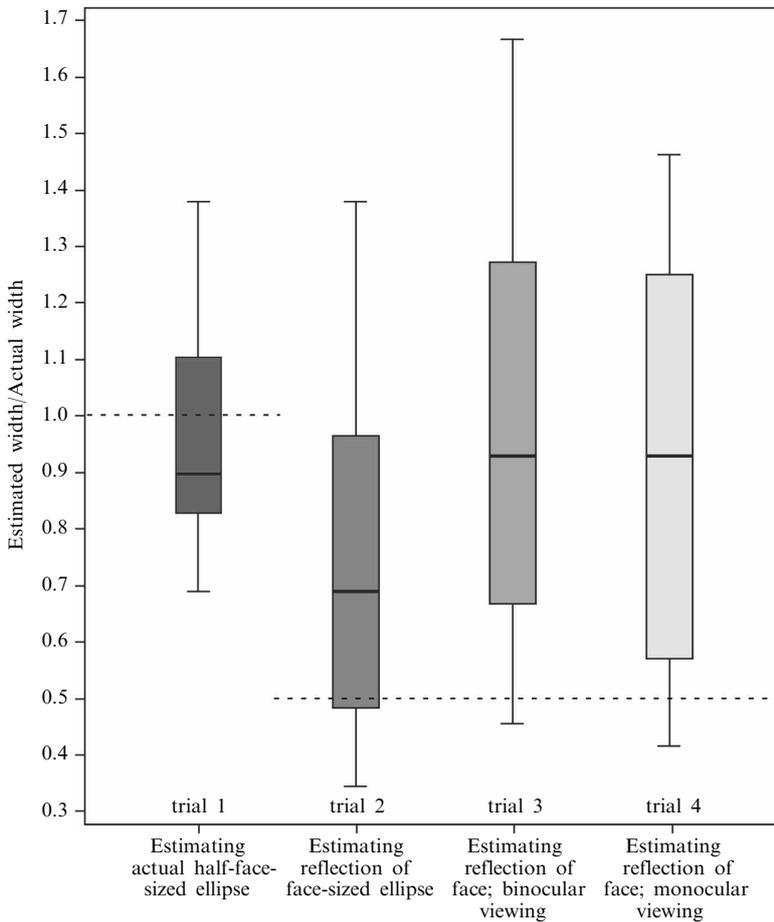


Figure 6. Box plot of estimated width of stimulus divided by actual width of object (an ellipse in the first two trials; the observer's face in the last two trials) in experiment 3. Unless otherwise specified, the mirror was visible and was seen binocularly from the near position, and people estimated sizes in centimetres. The correct response is marked with a dashed line and was 1 on the first trial and 0.5 on the next three trials.

On the third trial, participants estimated the size of their reflection on the surface of the mirror. Their estimated width divided by the width of their face (1.02) was significantly larger than the correct response of 0.5 ($t_{17} = 5.48$, $p < 0.001$), and was not significantly different from 1 ($t_{17} = 0.19$, ns). A repeated-measures ANOVA comparing estimates on the second and third trials revealed that people overestimated the size of the reflection of their face more than of the face-sized test ellipse ($F_{1,17} = 27.31$, $p < 0.001$). Replicating experiment 2, this suggests that there is a face-specific overestimation of reflection size in addition to people's general overestimation of the size of reflections.

The fourth trial was identical to the third, except that participants estimated the size of their reflection monocularly rather than binocularly. Their estimated width divided by the width of their face (0.91) was significantly larger than the correct response of 0.5 ($t_{17} = 4.98$, $p < 0.001$). As on the third trial, this proportion was not significantly different from 1 ($t_{17} = -1.16$, ns). A repeated-measures ANOVA comparing estimates on the third and fourth trials found that overestimations reduced when people viewed their reflections monocularly ($F_{1,17} = 8.45$, $p < 0.01$). This final result contrasts with that found in experiment 2, where monocular viewing did not significantly improve performance, although there was a trend in the same direction.

4.3 Discussion

People's estimates of stimulus size were more variable in experiment 3 than in experiment 2, but otherwise the results largely replicated those of experiment 2. This demonstrates that the overestimation found when people judge the size of reflections on mirrors is not an artifact of the ellipse-matching task used in experiments 1 and 2. When people were asked to verbally estimate size in centimetres they did not overestimate the size of an actual ellipse. However, most people grossly overestimated both the size of the reflection of an ellipse and the size of the reflection of their face.

The finding that, as in experiment 2, people grossly overestimated the size of the reflection of a test ellipse confirms that an important component of the overestimation was due to problems in estimating the size of all reflections in mirrors. However, this overestimation was even larger when people judged the size of their own reflection, replicating the results of experiment 2. Unlike experiment 2, the overestimation reduced significantly when people saw their reflection monocularly rather than binocularly, so performance improved when depth cues were reduced. There are several possible explanations for the face-specific component of the overestimation. For example, in contrast to the novel test ellipses, faces are familiar objects, have a standard size, extend in depth, and the width of a face is relatively difficult to specify. Further research is needed to establish which factors are important in determining the magnitude of the overestimation. Most important here, though, is that people overestimated reflection size in every condition tested in experiments 1, 2, and 3. People hugely overestimated the size of reflections of both test ellipses and faces (seen from near or far, and viewed monocularly or binocularly), and this was true whether they responded by matching ellipses placed next to or on the surface of the mirror or responded by verbally estimating size in centimetres.

5 Experiment 4

The size and consistency of people's overestimation in the previous studies is surprising. In experiment 4 we tested whether people could be explicitly taught a strategy that would eliminate their overestimation. We first attempted to replicate the main findings of experiment 2 by repeating the first three trials. On the critical fourth trial, people were told to use a monocular, lining-up strategy when choosing an ellipse which would just cover up their reflection in the mirror. People were instructed to place their chosen ellipse at the same height on the wall as the top of the reflection of their face and then decide whether the bottom of the ellipse lined up with the bottom of the reflection of their chin. We also tested whether people could accurately measure the size of their reflection using a transparent ruler placed on the surface of the mirror.

The subjects in experiments 1, 2, and 3 were only young psychology students. To ensure generality, one group in experiment 4 was recruited from a more diverse population of volunteers. The second group were young psychology students but their instructions were altered. We were concerned that the instructions in experiments 1 and 2 to pick the ellipse that would "just cover" a stimulus may have led people to overestimate. This could be, first, due to an anchoring effect, if people started by choosing an ellipse that was definitely large enough to cover the stimulus. Second, if people were unsure which of two ellipses was closest to the size of the stimulus then the instructions would encourage them to choose the larger ellipse. To examine this issue, in experiment 4 the second group was told to pick the ellipse that would "almost completely cover" the stimulus.

5.1 Method

5.1.1 Participants. There were thirty-six participants. In the "just cover" instruction condition there were six male and twelve female volunteers aged from 25 to 69 years. Most were staff at the University of Liverpool but only five were psychologists.

In the “almost completely cover” instruction condition there were six males and twelve females aged from 18 to 28 years. They were undergraduate psychology students who participated for course credit.

5.1.2 Materials, design, and procedure. The first three trials were identical to those in experiment 2, except that the instructions were to find the ellipse that “almost completely covered” the stimulus for the young group of participants. Before the second and third trials it was repeatedly emphasised that we were interested in the reflection of the object on the glass surface of the mirror and not the actual, physical size of the object producing the reflection. After the third trial, people were told that it had been found in previous studies that people often made large errors in the task. The participants were then instructed to use a strategy of lining up the top of their chosen ellipse with the top of the reflection of their face, then checking whether the bottom of the ellipse was level with the bottom of the reflection of their chin. They were also told to close one eye. The third trial was then repeated with a different set of matching ellipses. Next, participants used a transparent ruler placed on the surface of the mirror to measure the width and height of their reflection. They were also asked to estimate the distance from their eye to the surface of the mirror. Finally participants were asked what size their reflection was on the surface of the mirror relative to the actual size of their face. The experimenter then measured the dimensions of each participant’s face using metal callipers. The width was measured from just above each ear, and the height was measured from the chin vertically up to a point level with the top of the skull.

5.2 Results

The width of the ellipse selected by each participant was divided by the actual width of the test ellipse (for the first two trials) or by the actual width of that participant’s face (for the last two trials) to calculate the proportion of the width of the ellipse or his/her face that would be covered by the chosen ellipse (see figure 7). If participants had responded accurately then this proportion would be 1 on the first trial (when they matched to actual, physical ellipses) and 0.5 on the other three trials (when they matched to reflections on the surface of the mirror).

We conducted a mixed ANOVA with trial (1, 2, 3, or 4) as a repeated-measures factor and instructions (“just cover” or “almost cover”) as a between-participants factor on the proportion of the width of the stimulus that would be covered by the participant’s chosen ellipse. As predicted, there was a main effect of trial ($F_{3,102} = 33.768, p < 0.001$). Importantly, though, there was no effect of instructions ($F_{1,34} = 0.199, ns$). There was thus no evidence that the “almost cover” instructions (0.81) led people to choose smaller ellipses than the “just cover” instructions (0.79) that were used in experiments 1 and 2. The trial \times instructions interaction was also not significant ($F_{3,102} = 1.725, ns$). Given that there was no difference between the two groups, their results were pooled for the following analyses.

On the first trial, participants estimated the actual size of the half-face-sized, orange test ellipse. The proportion of the width of this test ellipse that would be covered by the chosen ellipse (0.91) was significantly less than the correct response of 1 ($t_{35} = -7.06, p < 0.001$). Thus, as in experiments 2 and 3, participants slightly underestimated the width of the ellipse. Any error in estimating the size of real objects was therefore in the opposite direction to the overestimation observed with mirror reflections.

On the second trial, participants estimated the size of the reflection of the face-sized, green test ellipse on the surface of the mirror. The proportion of the width of this test ellipse that would be covered by the chosen ellipse (0.82) was significantly larger than the correct response of 0.5 ($t_{35} = 13.62, p < 0.001$). This proportion was, though, significantly less than 1 ($t_{35} = -7.54, p < 0.001$), so estimates were smaller than the actual size of the ellipse. Replicating the results of experiments 2 and 3, people

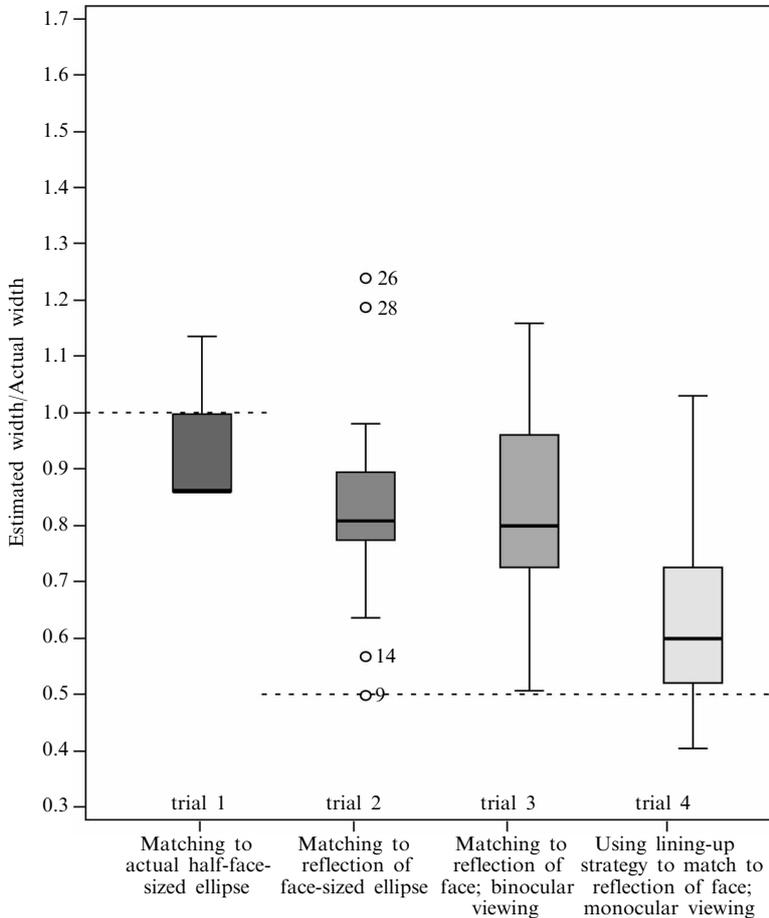


Figure 7. Box plot of estimated width of stimulus divided by actual width of object (an ellipse in the first two trials; the observer's face in the last two trials) in experiment 4. Unless otherwise specified, the mirror was visible and was seen binocularly from the near position, and people held up the matching ellipses on the wall next to the mirror. The correct response is marked with a dashed line and was 1 on the first trial and 0.5 on the next three trials.

grossly overestimated the size of the reflection of a test ellipse, confirming that the overestimation of reflections is not restricted to faces.

On the third trial, participants estimated the size of their reflection on the surface of the mirror. The proportion of the width of their face that would be covered by their chosen ellipse (0.84) was significantly larger than the correct response of 0.5 ($t_{35} = 12.267$, $p < 0.001$), but was significantly less than 1 ($t_{35} = -5.95$, $p < 0.001$). In contrast to the results of experiments 2 and 3, a repeated-measures ANOVA found that people did not overestimate the size of the reflection of their face more than that of the face-sized test ellipse ($F_{1,35} = 0.236$, ns).

The critical fourth trial was identical to the third, except that participants were told to estimate the size of their reflection monocularly and to line up the tops and bottoms of the ellipses with that of their reflection. A repeated-measures ANOVA comparing estimates on the third and fourth trials found that the new strategy significantly reduced overestimations ($F_{1,35} = 82.204$, $p < 0.001$). On the fourth trial, the proportion of the width of their face that would be covered by their chosen ellipse (0.63) was significantly larger than the correct response of 0.5 ($t_{35} = 5.00$, $p < 0.001$), but it was significantly less than 1 ($t_{35} = -13.81$, $p < 0.001$). Explicitly instructing people

to use a monocular, lining-up strategy did greatly reduce the magnitude of errors, though most people continued to overestimate size.

People were accurate at using a transparent ruler to measure the width and height of the reflection of their faces. The ratio of the persons' measurement of the width of their reflection to the physical width of their face as measured by the experimenter (0.46) was slightly (but significantly) less than the correct response of 0.5 ($t_{35} = -4.74$, $p < 0.001$). The ratio of the persons' measurement of the height of their reflection to the physical height of their face as measured by the experimenter (0.50) was not significantly different from the correct response of 0.5 ($t_{35} = -0.44$, ns). People were also quite accurate at estimating the distance from their eyes to the surface of the mirror (mean = 52 cm; standard deviation = 11 cm; the correct response was approximately 55 cm).

Despite judging reflection size quite accurately in the fourth trial, and in spite of accurately measuring their reflection size with a ruler, people were still not confident or accurate at deciding what size the reflection of their faces was relative to the size of their actual faces. Most (29/36) thought that their reflection was smaller than their actual face but six thought that their reflection was the same size, and one thought it was larger. Most people had some insight into the size of their reflection after completing the study, but they did not explicitly know that their reflection was half the width of their actual face.

Finally, we examined whether there was a sex difference in people's size estimations. In a mixed ANOVA including sex and trial as factors, sex was significant ($F_{1,34} = 8.024$, $p < 0.009$). Male estimates (0.75) were less than those of females (0.83). On the first trial, this sex difference was not significant ($F_{1,35} = 0.749$, ns), with males (0.90) and females (0.92) similarly underestimating the actual size of an ellipse (1.0). In contrast, on the second trial, estimates of the size of the reflection of an ellipse were significantly closer to the correct response of 0.5 for males (0.74) than for females (0.86) ($F_{1,35} = 6.186$, $p < 0.02$). Likewise, on the third trial, estimates of the size of their own reflection were significantly more accurate for males (0.76) than for females (0.88) ($F_{1,35} = 4.722$, $p < 0.04$). On the fourth trial, male estimates (0.59) remained more accurate than female estimates (0.65), but this smaller difference was not significant ($F_{1,35} = 1.474$, ns). Overall, males estimated image size (but not actual size) more accurately than females, but males still did overestimate image size.

5.3 Discussion

The results of the first three trials in experiment 4 largely replicated those of experiments 2 and 3: people were quite accurate at estimating the size of a real ellipse, with any error leading to underestimations rather than overestimations of size. In clear contrast, people markedly overestimated the size of the reflection of both a novel ellipse and of their face. Instructing people to choose the ellipse that "almost completely covered" (rather than that "just covered") their reflection did not reduce overestimation. Finally, performance was much more accurate on the fourth trial when people were instructed to use a monocular, lining-up strategy to perform the task. Nevertheless, even here most people continued to overestimate the size of their reflection on the surface of the mirror. When questioned during debriefing, people denied that they had been confused about what was required in the task—they had simply had difficulty in estimating reflection size on the surface of a mirror.

With sufficient training and feedback, people could probably be taught to estimate reflection size accurately. However, the important point is that this task is extremely difficult for most people, even if they clearly understand what is required and if they are told to use a strategy that should lead to successful performance. Given this, it is unsurprising that few people become aware of the size of reflections as a consequence of their everyday interactions with mirrors.

6 General discussion

The four studies presented here probed the nature of people's failures to understand the reflective properties of planar mirrors. In the walking task investigated in experiment 1, we replicated the results of Bertamini et al (2003b) and Croucher et al (2002): many people believed that they would see their reflection before they could do so as they approached a mirror. Importantly, we found clear evidence that this early error was due to people having an inaccurate belief. The early error was eliminated if people could see an uncovered mirror in which their reflection was visible—see figure 3. This suggests that many people fail to store readily accessible information from their past experience of mirrors. They therefore maintain inaccurate beliefs about mirrors despite experiencing contradictory perceptual evidence. The question that remains to be answered is why so many people make the early error, given its lack of perceptual support. Bertamini et al (2003b) argued that it is difficult to generate the virtual world seen on a mirror from knowledge of the real world, because no rigid transformation in 3-D space can achieve that. People may resort instead to transformations that they can imagine, such as a rotation around a vertical axis. Further research is needed to elucidate the origin and content of the incorrect belief, or beliefs, underpinning the early error.

When explicitly questioned, most people in experiment 1 made a distance error, stating that the reflection of their face in a mirror becomes smaller as they move further away from the mirror (Bertamini and Parks 2005). However, this belief had little influence on people's ellipse-matching performance. Changes in overestimation from the near to the far position were not consistently predicted by people's explicitly reported beliefs about how their reflection size changes with distance. Also there was only a small reduction in overestimation when people judged the size of their reflection from a greater distance from the mirror. Similar to the early error, the distance error may result from an inaccurate belief that is largely unaffected by people's perceptual experience with mirrors. This belief is likely to be derived from the commonplace (and generally accurate) observation that objects appear smaller from farther away.

In contrast to the straightforward results from the walking task, the results of all four studies point to a more complex account of the overestimation error observed in the size-estimation task. Experiment 1 revealed that significant overestimation persisted even when people could see the reflection of their face, so it appeared to be primarily due to a perceptual phenomenon. The results of experiments 2, 3, and 4 revealed that the size of reflections of ellipses was also overestimated, though in experiments 2 and 3 the overestimation for these novel stimuli with no standard size was somewhat less than that for faces. Overall, the results demonstrated that people massively overestimate the size of reflections seen in mirrors—whether reflections of novel ellipses or of faces, whether viewed monocularly or binocularly, and at different distances, and whether responses were made by matching ellipses or by estimating size in centimetres.

Some of the overestimation may have been produced by a bias due to tendency of people to generally adjust down rather than up (Gardiner et al 1989). People's initial size estimates were always too large and people may not have adjusted these estimates down sufficiently. However, this account cannot explain the large overestimations in experiment 3, when people directly estimated size rather than responded by matching ellipses. This account also fails to explain why people overestimated the size of reflections of ellipses but not the actual size of ellipses in experiments 2, 3, and 4.

Higashiyama and Shimono (2004) asked people to estimate the actual, physical size of objects that could not be seen directly but were visible only as reflections in a planar mirror. This task complements that used in the present studies in which people estimated the size of reflections. Higashiyama and Shimono's stimuli were red rectangles and triangles of differing sizes. They found that people were quite accurate at responding, both when they gave verbal estimates of size and with a matching response measure.

Their findings suggest that people accurately achieve physical size constancy for objects seen as reflections in mirrors. The present results suggest that the achievement of size constancy is so powerful and automatic that size information about the reflection itself is difficult for observers to access. This is consistent with Milliken and Jolicoeur's (1992) finding that people remember the perceived rather than the retinal size of objects.

The severity of people's problem in judging the size of reflections that appear on the surface of a mirror may seem surprising. The task is simple and people were accurate at estimating the physical size of objects, whether seen directly (as in the first trial of experiments 2, 3, and 4 here [see also Haber and Levin 2001]) or seen as a reflection in a planar mirror (as in Higashiyama and Shimono 2004). However, estimating the size of a reflection requires people to access information that is ignored in everyday life. It is analogous to seeing a car through a window and being asked to pick the correct size of paper that would obscure your view of the car if the paper were placed on the window. This is a difficult and unnatural task, because we are not usually concerned with the plane upon which this information appears (whether it be the glass surface of a mirror or of a window). This is the case even if, as here, the distance to the image plane can be judged accurately. We usually focus on the information that is (for windows), or appears to be (for mirrors), visible behind that plane. One might say that the frame of the window or the frame of the mirror defines an arbitrary cross section of a visual cone. Even though the cross section is well specified by the frame, it has no perceptual existence.

In the present studies, we carefully and repeatedly explained the size-estimation task to observers, to ensure that they understood that they had to estimate the size of reflections on the surface of the mirror and not the actual, physical size of objects. The fact that it is so hard to explain what is required in this task supports our claim that the size of the reflection is difficult to perceive. In experiment 4, people were explicitly taught a monocular, lining-up strategy to help them to judge size. Their performance improved greatly, but even here there was significant overestimation (see figure 7). Our main conclusion is that estimating the size of reflections is difficult, even if people are given plentiful perceptual information and are taught an effective strategy for estimating reflection size. This result contrasts starkly with the walking task in which every participant in group B was accurate. Here, people readily took advantage of being able to see their reflection in the mirror. They needed no encouragement or instructions about how to use the extra perceptual information to eliminate the early error.

In general, it is known that judgments about 2-D properties of images are affected by their 3-D interpretation, as demonstrated by, for instance, the Ponzo illusion and the tabletop illusion (Shepard 1990). In this study, we asked people how large a reflection was. Despite being clear what the task was, people's initial size estimations were similar to the size of the actual 3-D object, not to the size of the 2-D reflection of the object. Our conclusion is about reflections on the surface of mirrors. However, the phenomenon is probably more general and applies to all situations where an image is uncoupled from its physical source, such as the image that can be traced on the glass pane of a window.

There are clear links from the present findings of size overestimation to earlier research on size constancy, in particular with respect to people's ability to judge size (Ross and Plug 1998). In most such studies, people are asked to estimate the actual, physical size of objects, as in Higashiyama and Shimono's (2004) experiments. However, more relevant to the present work are studies in which people are instructed to judge size based on the visual angle subtended by the object on the retina (Baird and Wagner 1991; Carlson 1977; Gilinsky 1955; Kaneko and Uchikawa 1997). Unfortunately much of this earlier work was plagued by problems and inconsistencies in defining

terms and difficulties in explaining the task to participants (Baird and Wagner 1991; Kaneko and Uchikawa 1997; Ross and Plug 1998). It is easy to instruct people to estimate the actual size of a real object (“what a ruler held against the object would measure”). It is much harder to explain angular or retinal size to a naive observer. An advantage of using mirrors in the present studies is that the instructions were relatively simple and easy to understand, and the distance of the image was clearly specified since the mirror is a physical object. Nevertheless, despite our participants indicating that they clearly understood what was required of them, they still strikingly overestimated the size of reflections. As in Gombrich’s anecdote of the unexpectedly small size of the tracing of one’s face in a steamy mirror (Gombrich 1960), people, instead, expressed surprise when the correct answer was shown to them.

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