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Mirrors, mirrors on the wall ... the ubiquitous multiple reflection error

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ABSTRACT

Participants decided when somebody, Janine, could see their face in a horizontal row of adjacent mirrors mounted flat on the same wall. They saw real mirrors and a shop-dummy representing Janine. Such coplanar mirrors reflect different, non-overlapping areas of a scene. However, almost everybody made an unexpected error: they claimed that Janine would see her face reflected in multiple mirrors simultaneously. They therefore responded as if each mirror showed similar information and thus grossly overestimated how much each mirror revealed. Further studies established that this multiple reflection error also occurred for vertical rows of mirrors and for different areas of a single, large mirror. The error was even common if the participant themselves sat in front of a set of covered-up mirrors and indicated where they would be able to see their own reflection. In the latter case, people often made multiple reflection errors despite having seen all the mirrors uncovered immediately before they responded. People's gross overestimation of how much of a scene a mirror reflects and their inability to learn to correct this false belief explains why, despite a lifetime's experience of mirrors, they incorrectly think they will see themselves in all nearby mirrors.

1. Introduction

Visual perspective-taking involves predicting what you would see from a different location. It is important in many situations, such as hiding from predators and in knowing what another person would see from another position (Amorim, 2003; Kessler & Thomson, 2010; Lambrey et al., 2008; Michelon & Zacks, 2006; Tversky & Hard, 2009). Perspective-taking is often a prerequisite for making important inferences, especially about other people's beliefs and knowledge, and to anticipate people's actions. The basic rules of perspective-taking are acquired early in development, by about 5 years (Flavell, Flavell, Green, & Wilcox, 1981). However, some aspects of perspective-taking remain difficult even for adults (Kessler & Thomson, 2010). The present studies used a novel task involving mirrors to test whether people can predict their own or another person's view of the world if they cannot simply follow the direct line of sight of the observer.

Recent studies have established that people make several striking and systematic errors when they are asked to predict what someone could see reflected in a mirror. The present experiments are the first to test what people think someone could see in more than one mirror. This task was designed to provide an implicit measure of where people thought a reflection would be located (for example, whether people knew that you first see your own reflection appear on the side of a mirror nearest to yourself). People were tested in a realistic, embodied situation, in a room with real mirrors and with a lifelike dummy, Janine, representing the person looking at the mirrors. Their beliefs about mirror reflections were thus examined in a simple, concrete situation in which their egocentric perspective was privileged and they could see real mirror reflections which allowed them to test their assumptions about mirror optics.

Some errors that people make when reasoning about reflections occur even when they are actually shown a

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mirror. For example, people trying to locate an object's projection on a mirror are strongly biased towards its virtual location, even if they are shown the projection immediately before responding (Lawson, 2010). Also, people grossly overestimate the projected size of objects visible to them on the surface of a mirror (Lawson, Bertamini, & Liu, 2007). These errors show that although projections on mirrors exist as shapes that are located on a surface that is well-defined by its frame, these projections are not perceived by us as being like physical objects existing in the world.

In other cases, though, showing people a real mirror eliminates an error that most people would otherwise make. For example, many people incorrectly believe that they will be able to see themselves reflected in a mirror when they are standing to the side of it. However, if they are allowed to approach a mirror in which they can see their own reflection, they realise that they can only see their reflection when they are standing directly in front of the mirror (Lawson & Bertamini, 2006). This early error suggests that many people overestimate how much of a scene they can see reflected in a mirror, even though everyday experience provides ample evidence to disprove this belief. This overestimation belief was the focus of the present study.

In the current experiments, a simple heuristic always provided the correct response to the task. A person can see themselves in a given mirror when, and only when, they are standing directly in front of that mirror. If people used this heuristic then they should only ever say that someone can see themselves in a maximum of one of a set of coplanar mirrors. However, studies of the early error suggest that many people do not know this heuristic (Croucher, Bertamini, & Hecht, 2002; Lawson & Bertamini, 2006).

Experiment 1 examined what people thought that someone could see in a set of three mirrors. Most people incorrectly indicated that somebody looking at a row of horizontal mirrors could see their face reflected in two or more of the mirrors at the same time. Experiments 2–4 generalised this finding to a single, large horizontal mirror divided into sub-areas, to a row of vertical mirrors, and to explicitly responding that somebody could see their face reflected in multiple mirrors simultaneously. Finally, Experiment 5 found that the same multiple reflection error occurred even when the participant was themselves sitting in front of a set of covered mirrors so that perspective-taking was not required. Here, errors were reduced (but not eliminated) if they saw the mirrors uncovered immediately before they responded.

Fig. 1. Janine (on a trolley) at her first position in Experiment 1, as seen from the participant's viewpoint. The three small mirrors (labelled above and below as A, B and C) are hung flat on the wall on the left.

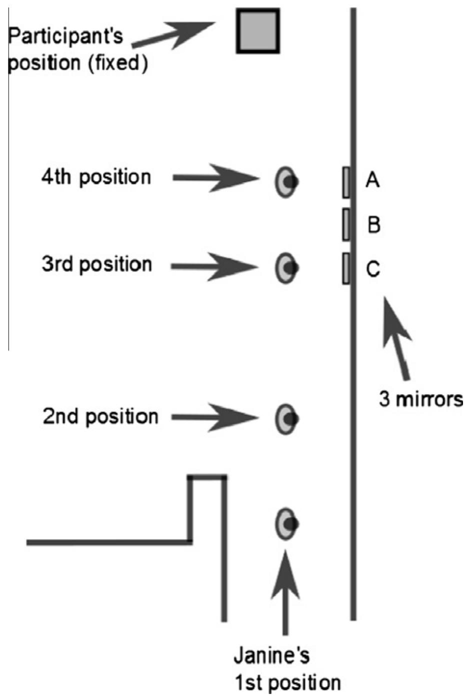

Fig. 2. A bird's eye diagram showing Janine's four positions in Experiment 1 relative to the position of the participant and the horizontal row of three mirrors (A, B and C). The correct response was that Janine could only see herself reflected in mirror C from the third position and in mirror A from the fourth position.

2. Experiment 1

In Experiment 1 people decided in which, if any, of three mirrors another person (Janine) would be able to see her face reflected from four different positions, see Figs. 1 and 2. Coplanar mirrors each reflect different areas of a scene and Janine would only see her reflection in a mirror if she was standing directly in front of it. The task was designed to detect mis-localisations of reflections without needing to ask people to explicitly state where on a mirror a reflection would appear, which they find a difficult and confusing task (Lawson, 2010).

2.1. Method

2.1.1. Participants

Eighteen students from the University of Liverpool took part in the study. Different participants from the same population were tested in Experiments 2, 3, 4 and 6, with most being young, female undergraduates (of the 153 people tested overall, 81% were female and the mean age was 20).

2.1.2. Design and materials

Three rectangular mirrors (30 cm wide × 45 cm high) labelled A, B and C were hung in a horizontal row with a 15 cm gap between each mirror, see Figs. 1 and 2. Janine was put on a 14 cm high trolley so that she could be moved to each of four positions, which were marked in tape on the floor. The top of Janine's head (193 cm) was taller than that of most of the participants but it was below the top of the mirrors (200 cm). Participants stood in the same, marked position throughout the experiment.

2.1.3. Procedure

At each of Janine's positions, participants were asked whether she could see her face reflected in each of the three mirrors in turn. Participants were instructed that it did not matter what else Janine could see in the mirror, such as the room or other parts of her body. They were also told that if they thought that she could see most of her face (but that a part would not be visible in the mirror) then they should still say she could see her face but not if they thought she could only see a little bit of her face (an ear or some hair but not the nose). They were also told to imagine that Janine could turn her head freely to look in any direction.

2.2. Results

People were extremely poor at predicting when Janine could see herself in the mirrors. Only one participant out of 18 was correct on all 12 questions (3 mirrors × 4 positions). Errors were overwhelmingly due to people overestimating when Janine would see herself. The correct response was "yes" for just 2/12 questions but there was an average of 6.1/12 "yes" responses, threefold too many. Multiple reflection responses were always wrong and occurred when participants said "yes" to more than one of the three mirrors at a given position.[1]

Importantly, people did not respond indiscriminately. Only 1/20 of the two mirror errors claimed that Janine could see her face reflected in the two end mirrors but not the central mirror; the remaining 19/20 two mirror errors involved two adjacent mirrors. Also, Fig. 3 shows that most responses were multiple reflection errors in positions 3 and 4 but not in positions 1 and 2. McNemar tests using the binomial distribution and a significance level of 0.05 revealed there were significantly fewer multiple reflection errors for position 1 than 2, and for position 2 than 3, but with no difference between positions 3 and 4. Thus most multiple reflection errors occurred when people were near to the mirrors, see Fig. 2.

2.3. Discussion

In Experiment 1 an unexpected pattern of results dominated performance: the multiple reflection error in which most people said that Janine could see herself in *all* the mirrors that she was close to. This gross overestimation of what is visible in coplanar mirrors meant that it was difficult to use the results to pinpoint where people thought someone would see their face reflected, which had been the original aim of the experiment. Instead of saying that Janine would first see her face in an end mirror (A or C) many people said that she would see her face in all three mirrors simultaneously as soon as she was close to the mirrors.

Although the multiple reflection error was not anticipated it is consistent with the early error in which people believe that they can see their reflection even when they are standing to the side of a mirror (Croucher et al., 2002; Lawson & Bertamini, 2006). Specifically, the multiple reflection and the early errors both provide evidence for an overestimation belief: people think that a mirror will show far more of a scene than it actually does. If people believe that they will usually see most of a room reflected in a small mirror then a logical consequence is that they will also think that much the same information will be reflected in a second, adjacent, coplanar mirror. This reasoning would lead them to incorrectly predict that if you are standing near to these mirrors then your face will be reflected in both of them.

An alternative reason for some errors in Experiment 1 was that people misjudged Janine's position relative to the mirrors. Participants should only have responded "yes" when Janine was standing directly in front of a given mirror. If people knew this but were unsure about Janine's position, they might, for example, have said "yes" to B only in the third position, although here Janine was standing in front of C, see Fig. 2. However, first, this account does not explain most of the errors since there were few single, incorrect "yes" responses. Instead, people were much more likely to make multiple reflection errors. These were necessarily wrong regardless of Janine's position. The mirrors were separated by more than Janine's face-width so, irrespective of her position, she could only see her face in at most one mirror. Second, 20 people's ability to judge Janine's position relative to the mirrors was tested directly in a control study using the same set-up as Experiment 1. People found it so easy to decide if Janine was standing in front of a given mirror that some had to be reassured that they had not misunderstood the task. Everybody was correct for positions 1 and 2 and 19/20 were correct for positions 3 and 4, with one person saying that Janine was never directly in front of a mirror.

A second issue in Experiment 1 relates to Janine being represented by a shop dummy rather than a real person.

[1] For simplicity, this paper focuses on multiple reflection errors and it ignores much of the richness of the data. For example, correct versus incorrect 0 and 1 mirror responses in Experiments 1–3 are not distinguished. In addition, the pattern of errors made is not discussed yet this should indicate whether people believe that someone's reflection would first appear on the near or far side of a mirror as they approached it. Also performance may differ when people can versus cannot see Janine's face reflected in a mirror. Such detailed, additional analyses plus extra data will be reported in a longer companion paper (Lawson, in preparation).

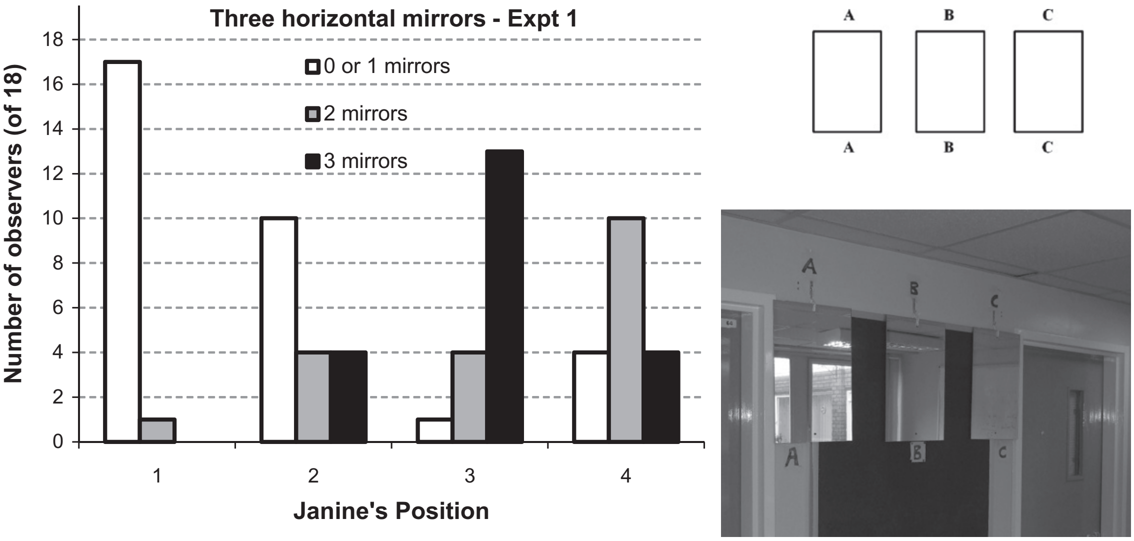

Fig. 3. Results of Experiment 1 and, on the right, icons representing the row of three horizontal mirrors shown and, below, a photograph showing the mirrors. The correct response was always 0 mirrors (positions 1 and 2) or 1 mirror (C in position 3; A in position 4). All 2 and 3 mirror responses were multiple reflection errors.

This was done to avoid Janine indicating to the participant that she could see them, for example by changes in her facial expression. However, a potential disadvantage of this was that Janine did not move her head to look towards the mirrors. People are known to use head and body orientation as well as gaze direction to determine where another person is attending (Langton, Watt, & Bruce, 2000). However, participants were explicitly told to imagine that Janine could move her head. Furthermore, if they had taken Janine's head orientation into account they should have been *less* likely to make multiple reflection errors because Janine did not always look towards a given mirror.

3. Experiment 2

A limitation of Experiment 1 is that the three mirrors may not have been perceived as being perfectly coplanar. During debriefing, some people recalled seeing multiple reflections of themselves in mirrors at angles to each other, like dressing table mirrors. Here, each mirror reflects your face from a different view. This is rare in everyday life whereas multiple, coplanar mirrors are common, for example in public toilets. Nevertheless, experiences of angled mirrors may be more salient to people. In Experiment 2A, we addressed this issue by using a single, large mirror that was divided into by tape into three separate – but necessarily coplanar – areas, A, B and C. In Experiment 2B the tape was removed so there was no discontinuity between the areas. If the multiple reflection errors made in Experiment 1 resulted from people thinking that mirrors A, B and C were angled relative to each other then no such errors should occur in Experiment 2.

3.1. Method

In both Experiments 2A and 2B 18 participants were tested using the same method as Experiment 1 except that the row of three mirrors was replaced by one (120 cm wide $\times$ 45 cm high) mirror with the same overall dimensions as the horizontal row of mirrors used in Experiment 1. In Experiment 2A two areas of black tape, each 15 cm wide, were used to divide this mirror into three (30 cm wide $\times$ 45 cm high) areas labelled A, B and C, see Fig. 4. In Experiment 2B this tape was removed.

3.2. Results and discussion

No participant produced the correct response to all 12 questions in Experiment 2A and only 2/18 in Experiment 2B. As in Experiment 1, almost all errors were due to people overestimating what Janine could see in the mirror. An independent samples Kruskal–Wallis test of the total number of "yes" responses for each participant revealed no significant difference between Experiments 1 (mean 6.1), 2A (7.0) and 2B (6.6), $H(2) = 1.983$, $p > 0.37$. In each case there were over three times too many "yes" responses. Fig. 4 shows that most responses were multiple reflection errors in positions 3 and 4 but not in positions 1 and 2. McNemar tests using the binomial distribution and a significance level of 0.05 for Experiments 2A and 2B separately revealed there were significantly fewer multiple reflection errors for positions 1 than 2 (significant for Experiment 2A only), and for positions 2 than 3, but no difference between positions 3 and 4.

Thus a similar pattern of multiple reflection errors occurred for a single, large mirror as for three, small mirrors. This provides strong evidence against the claim that the cause of these errors in Experiment 1 was people misperceiving the relative angle of the three mirrors. Participants in Experiment 2 could see that areas A, B and C were coplanar and reflected different, non-overlapping parts of the room. However, they failed to realise the implications of this for predicting what Janine would see in the mirror. Removing the tape from the mirror in Experiment 2B made it explicit that the mirror reflected a single, coherent and

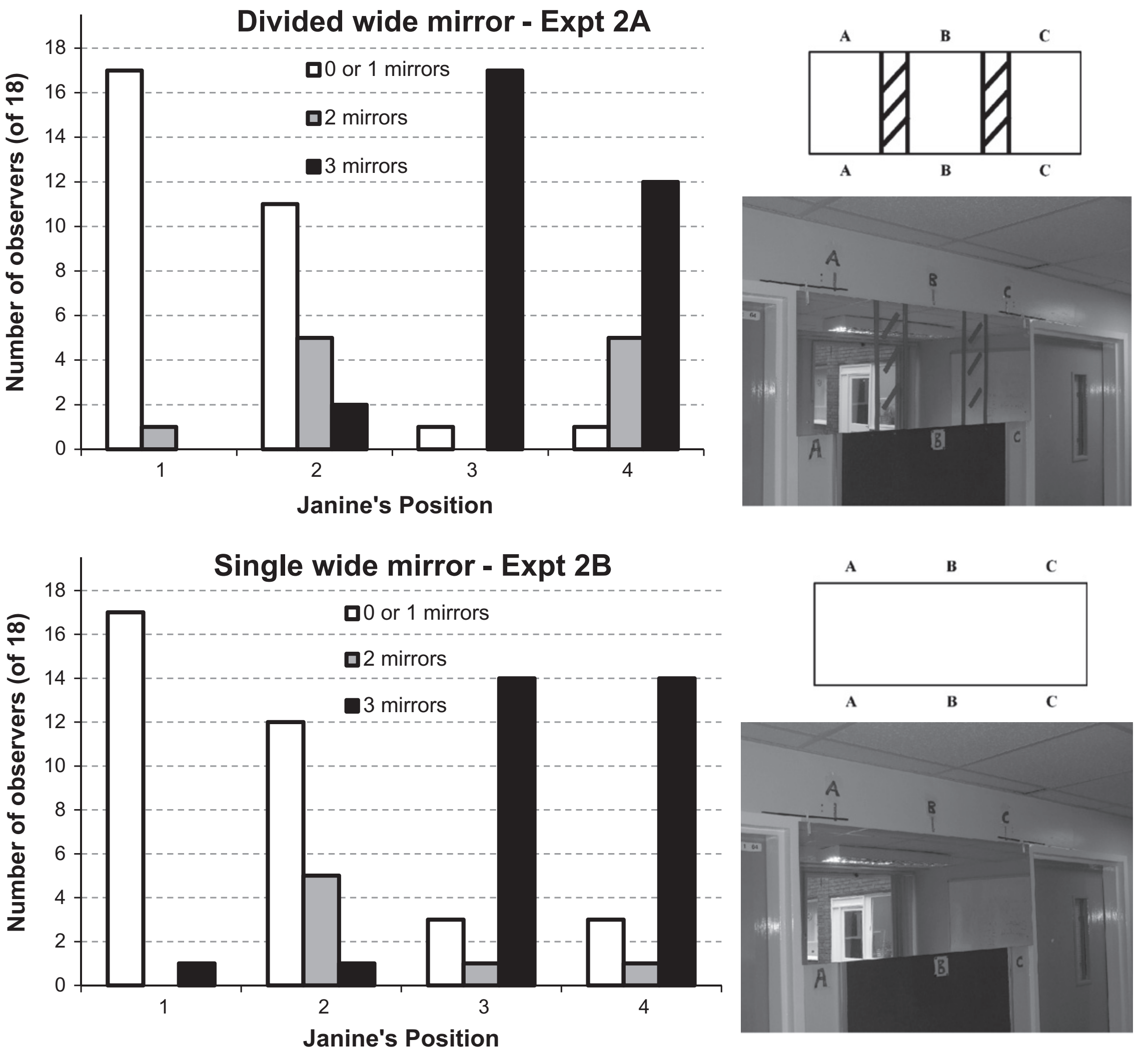

Fig. 4. Results of Experiment 2A and, below, Experiment 2B with icons on the right representing the mirror configurations and, below these, a photograph showing the mirrors. The correct response was always 0 or 1 mirrors. All 2 and 3 mirror responses were multiple reflection errors.

uninterrupted scene but had the disadvantage that the edges of each area were not defined. However, these results were very similar to those of Experiment 2A so this did not seem to be an important factor.

The multiple reflection error is unlikely to have arisen from everyday perceptual experience since we rarely see ourselves reflected simultaneously in multiple mirrors and we never see multiple, overlapping views of the same scene reflected within the same mirror. One solution to the conundrum of why, nevertheless, there is such a strong and pervasive overestimation of what is visible in a mirror could be that people misunderstand the effects of head and eye movements. During debriefing, some participants said that they thought that Janine would be able to see different information if she turned her head or her eyes to look in different directions. For example, they suggested that if Janine was in the third position she could see herself in A if she looked at A, in B if she looked at B, and in C if she looked at C. They could easily have tested this egocentric reflection hypothesis during the study by looking at A then B then C and noting that changing their head and eye position did not alter what they saw reflected in the mirrors. However, their comments indicated that they had failed to hypothesis-test their understanding of mirrors in this way. This false belief about the effect of head and eye movements on reflections may arise because moving your eyes or head always alters what is visible for direct gaze. This error may also, in part, arise from people failing to understand the importance of the observer's viewpoint in determining what is visible reflected in a mirror. However, the results of Experiments 1 and 2 show that people do not simply think that mirrors reveal the same information irrespective of an observer's position. Instead, people made many more multiple reflection errors when Janine was near to the mirrors (positions 3 and 4) than when she was further away (positions 1 and 2).

4. Experiment 3

Multiple reflection errors were ubiquitous whether areas A, B and C were defined by separate mirrors (Experiment 1) or by tape on a single, wide mirror (Experiment 2A) or only by labels above a single, wide mirror (Experiment 2B). However, in all three cases A, B and C were arranged horizontally. In Experiment 3, three small mirrors were instead hung in a vertical row to test whether this eliminated multiple reflection errors. Consistent with the multiple reflection error, many people think that someone approaching a mirror from the side will first see their reflection before they are directly in front of it (Croucher et al., 2002; Lawson & Bertamini, 2006). However, Croucher et al. (2002) found no such early error when someone was shown moving in a lift or climbing a rope so that they approached the mirror from above or below. Their pen and paper studies suggest that people may only have a horizontal, not a vertical, bias to overestimate what is reflected in a mirror. If the multiple reflection error is caused by the same overestimation false belief as the early error then it should not occur for vertically arranged mirrors.

4.1. Method

Eighteen participants were tested using the same method as Experiment 1 except for the following points. The three mirrors were oriented horizontally (45 cm wide by 30 cm high) and were placed in a vertical row with a 15 cm gap between each mirror, see Fig. 5. The row was centred horizontally at the middle of where mirror B was hung in Experiment 1. The top of the upper mirror was level with the top of the mirrors in Experiment 1. Janine could not see herself in A, B or C from any of the four positions so the correct response was always "no". An extra position was included to check that "yes" responses were made correctly. This extra position was midway between positions 3 and 4 and from it Janine could see herself in A only. Results from this position are not, though, reported since all participants incorrectly responded "yes" to questions posed at the four standard positions and the results for the extra position were similar to those for positions 3 and 4. In particular, all participants said that Janine could see herself in A from both position 3 and the extra position.

4.2. Results and discussion

People were poor at predicting what Janine could see in vertically arranged mirrors, making an average of 4.2/12 "yes" responses, all of which were wrong. They thus overestimated what Janine would see downwards as well as sideways. This contrasts to the findings of Croucher et al. (2002) who reported only a horizontal, not a vertical early error. The reason for this discrepancy is addressed in Section 7. Fig. 5 shows that, again, most responses were multiple reflection errors in positions 3 and 4 but not in positions 1 and 2. McNemar tests using the binomial distribution and a significance level of 0.05 revealed there were significantly fewer multiple reflection errors for positions 2 than 3, but no difference between positions 1 and 2 or positions 3 and 4.

5. Experiment 4

Experiments 1–3 showed that almost everybody makes multiple reflection errors when they are asked successively whether someone can see themselves in a set of nearby mirrors or areas of a single mirror. This is really surprising since in everyday life you rarely see your face reflected in multiple mirrors and you certainly never see your face popping up reflected in several places on the same mirror. However, the nature of the task may have served to over-

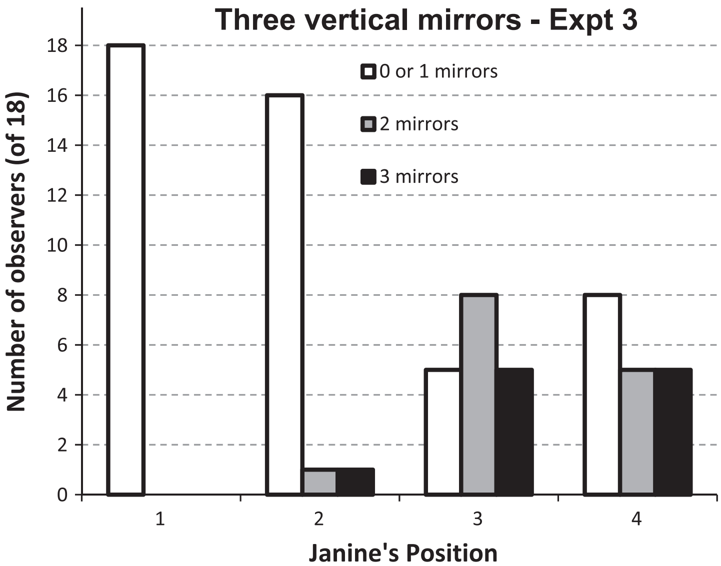

Fig. 5. Results of Experiment 3 and, on the right, a photograph showing the vertical row of mirrors. The correct response was always 0 mirrors. All 2 and 3 mirror responses were multiple reflection errors.

estimate the occurrence of multiple reflection errors. In particular, people did not have to explicitly respond that Janine could see herself in more than one mirror at once. Thus, although people said that Janine could see herself in A and B and C from a given position they may not have realised that this implied that she could see her face in all three mirrors simultaneously. To address this, in Experiment 4 people were asked to draw what they would see of themselves as they looked at a set of five coplanar mirrors. Here, multiple reflection errors had to be made explicitly by drawing faces in more than one mirror. The five mirrors were arranged in a cross so that the rate of vertical and horizontal overestimations could be compared directly.

In Experiment 4 people were also asked to decide what they could see if they were in front of the mirrors rather than deciding what somebody else could see. This might be an easier perspective-taking task. Michelon and Zacks (2006) found that differences in how perspective-taking tasks are framed can influence people's responses. They contrasted performance on a task that could be solved by just following the line of sight of another person (can Janine see a given object?) versus a task that required imagining that you were at Janine's location (is a given object to the left or right of Janine?). The two tasks produced different patterns of performance. For example, only the left-right task was influenced by the difference in orientation between the participant and Janine. Finally, in Experiment 4, people were shown a photograph of a real person looking at the mirrors rather than a shop-dummy with a fixed head position. This was more realistic and may be less confusing.

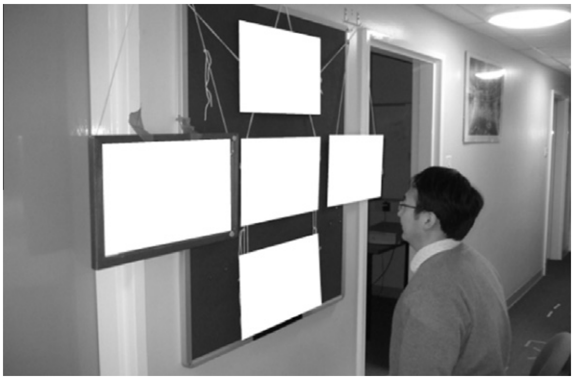

Fig. 6. The photograph shown to participants in Experiment 4. The face of the person shown was opposite the centre of the middle mirror. White quadrilaterals were superimposed over each of the five mirrors to indicate clearly where each was and to avoid distracting participants by showing to them the mirror reflections.

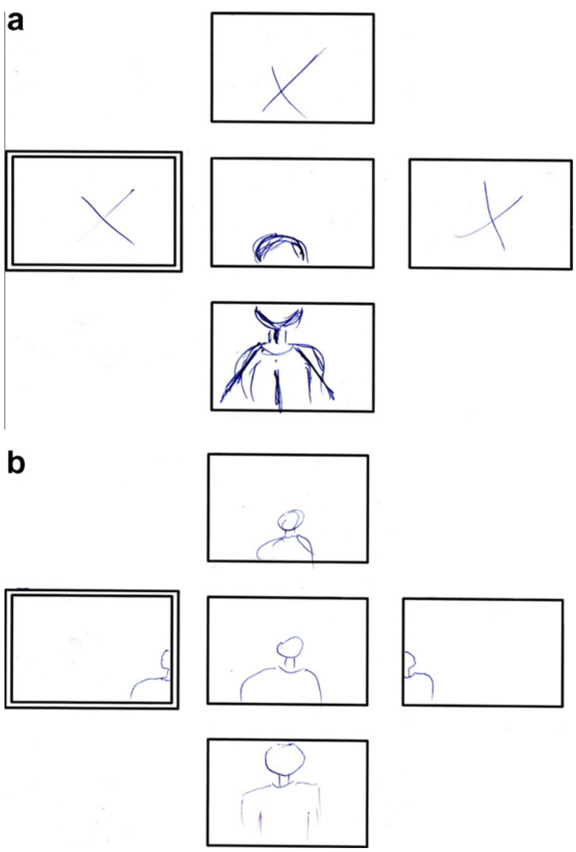

Fig. 7. Sample responses from Experiment 4. (a) A typical two partial head response which scored 1 and was counted as correct (the actual correct response was a full head in the central mirror and no head or partial head in any other mirror). (b) A multiple reflection response scoring 4 (three full heads and two partial heads). Unusually, this shows a greater vertical than horizontal overestimation.

5.1. Method

Prospective students and their parents volunteered to participate on University Open Days ($n = 333$; of the 200 under 35 years old, 81% were female and the mean age was 18; for the over 35 year olds, 65% were female and the mean age was 48). They were each given a questionnaire to fill out which included the multiple mirrors drawing task. They were told to imagine sitting where the person was in the photograph (see Fig. 6), with their head fixed in place, opposite the central mirror, but with their eyes able to move freely. They were given a sheet with five boxes representing the mirrors and were asked to draw what, if anything, they would see of themselves reflected in the five mirrors. The box on the left side had a double line around it (see Fig. 7) to represent the left, framed mirror and participants were told this. They were told to use a stick figure to depict themselves.

5.2. Results and discussion

For each mirror, drawing a full head was scored as 1 and a partial head as 0.5. The mean five mirror total score was 1.6. Total five mirror scores of 1 (either just one full or two partial heads) were counted as correct (48%; white bars in Fig. 8). Few people scored less (13%; grey bars in Fig. 8), with most drawing the top of their head in the middle mirror and only arms and body in the bottom mirror. This would be correct if your eyes were just above the bottom of the central mirror. The remaining responses scored over 1 and were multiple reflection errors (37%; black bars in

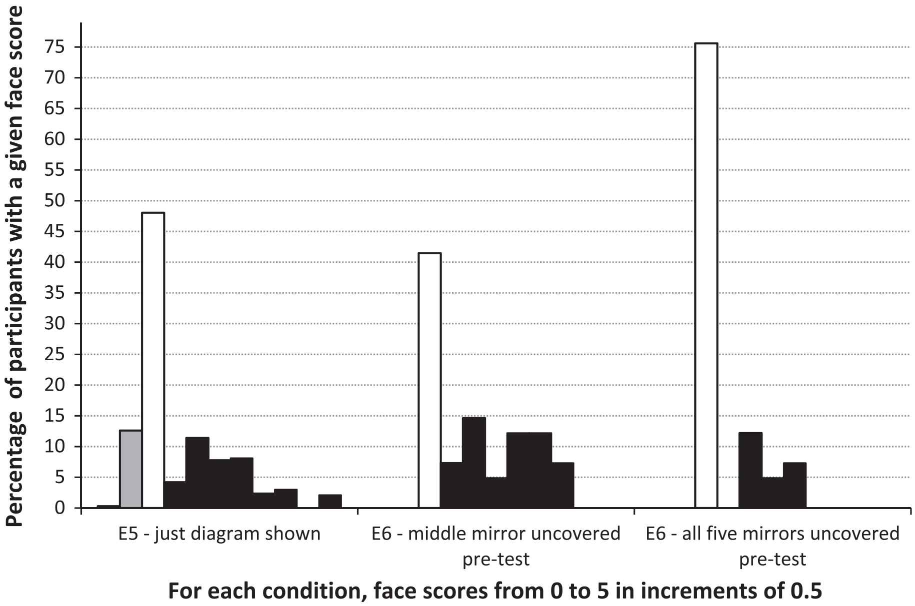

Fig. 8. A graph of the percentage of participants with a given face score (from 0 to 5 in increments of 0.5) in Experiment 4 and in Experiment 5 for the group shown only the middle mirror uncovered and the group shown all five mirrors uncovered before doing the task. Grey bars show responses with too few heads (scores of 0 and 0.5), clear bars show correct responses with one full or two partial heads (scoring 1) and black bars show multiple reflection errors (scores from 1.5 to 5).

Fig. 8). Thus many people drew their face as being simultaneously visible in two or more coplanar mirrors. Nevertheless, there were fewer multiple reflection errors than in Experiments 1–3. Here almost everybody (64/72, 89%) made multiple reflection errors when Janine was near the mirrors (positions 3 and 4, which were most similar to the person's position in Experiment 4). Error rates cannot be directly compared across such different tasks. However,

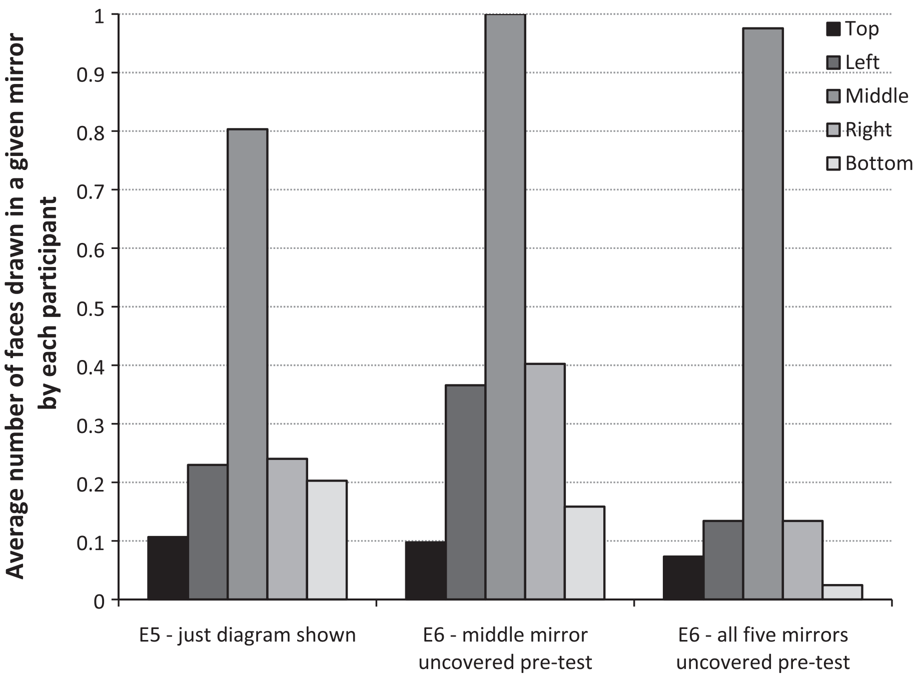

Fig. 9. Graph showing the average number of faces drawn (with 0 if no face was drawn, 0.5 for a partial face and 1 for a full face) in each of the five mirrors in Experiment 4 and in Experiment 5 for the group shown only the middle mirror uncovered and the group shown all five mirrors uncovered before doing the task.

it seems likely that people's overestimation of what a mirror reflects was tempered, in Experiment 4, by having to explicitly report what they would see all at once.

There was a horizontal bias in errors. Using the same face scoring system, most faces were drawn in the middle mirror (51% of the total face score of 527) with similar numbers of left (14%), right (15%) and bottom (13%) faces and rather fewer top faces (7%), see also Fig. 9. However, 120 participants did not draw a full head in the middle mirror with many producing responses like Fig. 7a. This was not a multiple reflection error so including such responses would inflate the estimate of incorrect faces drawn in the bottom mirror. For the remaining 213 participants again most faces were drawn in the middle mirror (53% of the total face score of 401) with similar numbers of left (16%) and right (16%) faces but there were fewer bottom (8%) and top faces (8%). For these participants the mean left and right total score (0.60) was greater than the mean top and bottom total scores (0.29; this difference was significant with a related samples matched pairs Wilcoxon signed rank test, $Z = 6.039$, $p < 0.001$). Notwithstanding this horizontal bias, people also made multiple reflection errors vertically, consistent with the results of Experiment 3 but contrary to Croucher et al.'s (2002) results. This issue will be returned to in Section 7.

6. Experiment 5

The results of Experiments 1–4 appear to put important limitations on recent research which suggests that people can rapidly and involuntarily infer the visual perspective of other people (Frischen, Loach, & Tipper, 2009; Langton et al., 2000; Samson, Apperley, Braithwaite, Andrews, & Bodley Scott, 2010; Thomas, Press, & Haggard, 2006; Tversky & Hard, 2009; Zwickel, 2009; Zwickel & Müller, 2010). For example, Samson et al. (2010) asked participants to make speeded responses to the number of discs that they could see in a display. They were slightly slower at the task when an avatar in the display could see fewer discs than the participant (because some discs were behind the avatar) compared to when the avatar and the participant could see the same number of discs. This cost suggests that people inferred how many discs the avatar could see. This inference was task-irrelevant and seemed to be obligatory since it interfered with producing the correct response when it conflicted with the number of discs that the participant could see. However, inferring what the avatar could see only required following its gaze whereas mirrors reveal information that is not visible directly along a straight line of sight. The present results show that people are poor at predicting what another person can see in a mirror.

In Experiments 1–4 people always had to imagine what they or another person could see from a different position. However, multiple reflection errors may occur even when perspective-taking is not required. This was examined in Experiment 5 using the same multiple mirror drawing task as Experiment 4 except that participants sat in front of a set of covered-up mirrors. If the multiple reflection error is caused by problems in perspective-taking or judging spatial relations it should not occur in this situation. Experiment 5 also tested people's ability to learn about mirror reflections from task-relevant perceptual experience. This was done by showing different groups either only the central mirror uncovered or by showing them all five mirrors uncovered immediately before they did the task. The latter group saw the reflections that they would have to draw just before responding.

6.1. Method

Two groups of 41 students were tested with the same configuration of mirrors as shown in Fig. 6. These comprised five 45 cm wide × 30 cm high mirrors each separated by a 15 cm gap. One group was only shown the middle mirror uncovered prior to doing the task whilst the other group was shown all five mirrors uncovered. As a pretext to ensure that they looked at the uncovered mirrors before doing the task, at the start of the study participants were asked to adjust the height and position of their chair so that the reflection of their face appeared in the centre of the middle mirror. This also ensured that people's heads were at the same location. The mirrors were then covered and people were given the same response sheet and instructions as in Experiment 4.

6.2. Results and discussion

Responses were scored as in Experiment 4. For the group only shown the middle mirror uncovered prior to doing the task there were 41% correct responses. Unlike Experiment 4, nobody scored less than 1, see Fig. 8. This was presumably because the pre-task chair adjustment and seeing the middle mirror reflection before doing the task meant that they knew they could see all of their face in the middle mirror – indeed, everybody drew a full face in the middle mirror. Everybody else (58%) scored over 1 and made multiple reflection errors. Thus removing the need to perspective-take and to interpret the spatial layout of the scene from a photograph did not reduce the number of multiple reflection errors compared to Experiment 4 (37% multiple reflection errors). Indeed any trend was in the opposite direction.

There were overestimation errors in all four directions but again there was a horizontal bias. The mean left and right total score (0.77) was greater than the mean top and bottom total score (0.26; this difference was significant with a related samples matched pairs Wilcoxon signed rank test, $Z = 3.440$, $p < 0.001$). Most faces were drawn in the middle mirror (49% of the total face score of 83) with similar numbers in the left (18%) and right (20%) mirrors and fewer in the bottom (8%) and top (7%) mirrors, see Fig. 9.

For the group shown all five mirrors uncovered prior to doing the task there were 76% correct responses. Nobody scored less than 1 and all but two people correctly drew a full head in the middle mirror. Only 24% scored over 1 and made multiple reflection errors. Again, there was a horizontal bias in errors. Removing the two participants who did not draw a full head in the middle mirror, the combined left and right mirror face scores (0.26) were greater than the combined top and bottom mirror scores (0.08; though this difference was only marginally significant with a related samples matched pairs Wilcoxon signed rank test, $Z = 1.919$, $p < 0.06$). Most faces were drawn in the middle mirror (73% of the total face score of 55) with similar numbers in the left (10%) and right (10%) mirrors and very few in the bottom (2%) and top (5%) mirrors, see Fig. 9.

People had lower scores, so were more accurate, in the five mirrors uncovered condition (mean five mirror total score = 1.34) than the middle mirror only uncovered condition (2.02; significantly different in a two-tailed Mann–Whitney test, $Z = -3.290$, $p < 0.001$). Thus providing task-relevant information by showing people all five mirrors uncovered just before doing the task did reduce multiple reflection errors substantially. Nevertheless, even in this condition a quarter of people made multiple reflection errors so the overestimation belief is not easily overturned by disconfirmatory evidence. This finding is consistent with the results of Experiments 1–4 which showed that the multiple reflection error is common in adults although we never see our face reflected multiple times on the same mirror or reflected simultaneously on coplanar mirrors. If we gradually learnt from our interactions with mirrors then multiple reflection errors should be rare, but they are not.

7. General discussion

The five studies reported here explored a striking and unexpected error in people's understanding of mirrors. Many people believe that the reflection of their face can be seen in two or more coplanar mirrors. This multiple reflection error is particularly surprising because it directly contradicts our everyday experience that mirrors reflect a single, coherent scene. In Experiments 1–3 people looked at real mirror reflections in the task and in Experiment 5 they responded after seeing their own reflection in the mirrors. However, many people did not use this helpful information or test the accuracy of their assumptions. Reflections from adjacent mirrors in Experiments 1–3 showed different, non-overlapping areas of the scene so people could have deduced that Janine could only see herself in one mirror at a time. Still more compellingly, a quarter of participants made multiple reflection errors in Experiment 5 despite being shown the correct answer immediately before responding.

The multiple reflection error seems to be caused by people grossly overestimating the extent of a scene that is visible reflected in a mirror. This overestimation occurred horizontally and, to a lesser extent, vertically and in both perspective-taking tasks (Experiments 1–4) and when people just had to imagine what the mirrors in front of them would show if they were uncovered (Experiment 5). Multiple reflection errors were found using both implicit (Experiments 1–3) and explicit (Experiments 4–5) measures, and were sensitive to the scene context, rarely occurring when the observer was far away from the mirrors (Experiments 1–3).

Converging evidence for this overestimation belief comes from the early error in which people believe that they can see themselves in a mirror when they are standing to the side of it (Croucher et al., 2002; Lawson & Bertamini, 2006). However, Croucher et al. found that the early error only occurred horizontally, not vertically, whereas here people overestimated vertically as well. This discrepancy may have arisen because in Croucher et al's scenarios the observer themselves moved vertically. In contrast, in Experiment 3 here Janine moved horizontally with only the mirrors being arranged vertically, whilst in Experiments 4 and 5 the observer did not move at all. If the observer moves vertically this may more effectively draw people's attention to the observer's position relative to the mirror. Supporting this explanation, Bertamini, Lawson, Jones, and Winters (2010) found that people made a similar pattern of vertical and horizontal errors when predicting what would be visible in a mirror for a static observer.

One important question arising from this research is whether people would make an analogous error with windows as the multiple reflection error with mirrors. Much the same optics governs windows and mirrors and people sometimes seem to treat them similarly when asked to predict their behaviour. For example, people produce large overestimations of the size of projections on the glass surface of both windows and mirrors (Lawson et al., 2007). Looking at a mirror reflection is akin to looking through a window in that a greater area is visible than that of the surface occupied by the window. This may be a major reason for people's overestimation belief, since the area of the virtual world reflected is always larger (and often very much larger, for instance when looking at a landscape) than the surface of the mirror so people may remember that mirrors show lots of information. However, people only need to consider direct lines of sight with windows which may make the task easier. In particular, they may realise that, given that lines of sight must be straight, this means that the same thing cannot be seen through multiple coplanar windows simultaneously.

There is probably no single, simple explanation for the multiple reflection error. People's overestimation of what is reflected in a mirror is probably related to other findings in visual perception. For example, children do not know that lines of sight need to be straight until about 5 years old so they overestimate what would be visible when looking down a curved tube (Flavell, Green, Herrera, & Flavell, 1991). Also people often overestimate what was visible in a view of the real world framed by an aperture in boundary extension tasks (Gottesman & Intraub, 2002, 2003). This is similar to the case of remembering what was visible when you looked at a reflection in a mirror. Introspective reports in the present studies also indicated that people often mistakenly thought that if you turn your head or your eyes towards a mirror you will see yourself reflected in it. One participant said that "mirrors look back at you". Furthermore, people may be particularly prone to overestimating when they are asked if they could see themselves (rather than other objects) reflected in a mirror. Almost nobody will have a clear, thought-through and self-consistent theory of optics which they use to guide their predictions. Most people probably use a set of underspecified beliefs and heuristics, some of which are incompatible, leading them to make unsophisticated, noisy and inaccurate predictions. People rarely think explicitly about optics and what determines what they can see in a mirror or a window – or, indeed, what they can see directly. If they ever need to know about this they can usually find out the answer directly. For example, if you wanted to know where you have to stand to see yourself in a mirror you would usually be near to a mirror and you could move about in front of it to work out the answer. Interestingly, the present results suggest that people rarely undertake such explicit hypothesis-testing, even when the situation strongly encourages them to do so. This lack of learning from our environment is presumably why our naive theories of optics are so poor.

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