The eyes have it:
Naïve beliefs about reflections

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Abstract

Using a paper-and-pencil task, undergraduate students predicted when a character would be able to see her reflection in a planar mirror. Experiment 1 showed that participants expected the character to be able to see her reflection earlier than she actually would when moving horizontally, but not when moving vertically, confirming previous findings (Croucher, Bertamini & Hecht, 2002; Bertamini, Hecht, Spooner, 2003), but unlike previous studies the vantage-point from which the character was depicted was identical for both conditions. In Experiment 2 and 3 we tested for the role of body orientation, and relation between the eyes and the mirror surface in explaining these results. We conclude that the early error can be avoided only when the eyes define an axis parallel to the near edge of the mirror. We call this the eye-plane heuristics. Experiment 4 did not reveal a significant increase in the early error with distance from the mirror, and Experiment 5 demonstrated a weak effect of vantage-point when participants estimated the amount of background visible in a mirror from three different vantage-points.
The eyes have it

Light as such is never directly the object of experience, but human behaviour often depends indirectly on the laws of optics. For instance, what is made visible by a mirror depends on the laws of reflection, i.e., the way light travels and bounces before reaching our eyes. This report is a continuation of previous work conducted on people’s naïve beliefs about mirrors and what is visible in them (Croucher, Bertamini & Hecht, 2002; Bertamini, Spooner & Hecht, 2003). In this paper we show that a systematic error previously documented is eliminated by the use of a specific heuristic, possibly by means of the imagined axis defined by the horizontal alignment of the eyes. Therefore the early error remains as the rule and the correct performance as the exception when such a heuristic is available.

What is the early error?

Croucher et al. (2002) used a paper-and-pencil task in which an observer was described as moving with respect to a mirror. There were four types of drawings: (a) a plan drawing of a room in which an observer was walking across, with a mirror positioned on the wall. Participants indicated when the observer would be able to see her reflection in the mirror; (b) same as (a), but with a cat positioned on one side of the mirror, again the observer moved across the room, and the participants indicated when they would be able to see the cat in the mirror; (c) identical to (b) but with the observer and cat roles reversed; (d) a side-view of a room with a mirror and with the observer climbing a rope, as in (a) participants indicated the point at which the observers would be able to see themselves in the mirror. Participants predicted that the observers would see their own reflection when still some distance before the mirror (early error) for (a), (b) and (c). This error did not exist for drawing type (d) where the movement of the observer was vertical. Participants who held correct knowledge about the fact that the angle of incidence is equal to the angle of reflection were no less likely to show the early error. Physics students also produced the early error.

These findings are consistent with the naïve physics literature in that specific knowledge of the laws of physics exerts little effect on naïve beliefs about the physical world (Caramazza, McCloskey & Green, 1981; Champagne, Klopfer & Anderson, 1980; Clement, 1982;
McCloskey, Washburn, Felch, 1983; Proffitt, Kaiser & Whelan, 1990). Most people have a clear understanding that the angle of incidence is equal to the angle of reflectance, and indeed this scientific fact has been known since the time of Euclid. It appears that to make correct judgments about mirrors something more than physical knowledge of the laws of reflectance is necessary. Croucher et al. (2002) also found the early error when participants were in a real room (similar to that depicted in the paper-and-pencil tasks) and asked from where they could see their own reflection in a pretend (non-reflective) mirror. This finding is intriguing, because people have a wealth of experience walking over to mirrors to view their reflections. This pattern of results was specific to the participants’ conception of mirrors; when Croucher et al. (2002) replaced the mirror in the horizontal drawing tasks with an aperture (a window) the early error was replaced by a late error.

Four explanations for the early error

Four possible explanations were put forward by Croucher et al. to account for the presence of the early error in the horizontal conditions:

(a) Egocentric mirror rotation hypothesis: Participants may have failed to take the orientation of the mirror surface into account and treated the mirror as a surface approximately orthogonal to their line of sight.

(b) Capture hypothesis: Mirrors may be conceived as pictures that capture images for further inspection, so that the location of the observer is irrelevant.

(c) Boundary extension hypothesis: People may perceive (and remember) a larger amount of the virtual space than is actually visible in mirrors. There is evidence that something similar happens for photographs, and this phenomenon is known as boundary extension (Intraub, 1997; Intraub & Bodamer, 1993).

(d) Left-right reversal hypothesis: People have some understanding that there is a kind of left-right reversal in mirrors, and may extrapolate from this to expect complete reversal of the imagined visual space around a vertical axis (Gregory, 1997). People would then predict an observer’s reflection to appear from the left as the observer approaches from the right. Support
was given to the left-right reversal hypothesis when participants were asked where in the mirror the image would first appear (Bertamini, Spooner & Hecht, 2003). A large proportion of respondents choose the far side of the mirror, and these tended to be the same people who produced the early error.

Bertamini, Spooner and Hecht (2003) also employed 3D computer models that included simulated mirror reflections. Participants were shown images of a room that contained a mirror, but the view contained in the mirror was either accurate or altered in some way. Distortions in mirror reflections were tolerated to a large degree when people were asked to judge whether the image was correct. This was especially true for mirrors that showed too much or too little of the scene. Unlike the paper-and-pencil task there was no evidence that people perceived as correct a mirror reflection in which positions are reversed, so that an object on the left in the room was seen on the right in the virtual room; this was inconsistent with the left-right reversal hypothesis. The paper-and-pencil task and the perceived naturalness of a reflection seen in its context have therefore led to different results. This has been interpreted in the light of other findings of dissociation between conceptual and perceptual knowledge (Bertamini, Spooner & Hecht, 2003). For example, people are inaccurate regarding their predictions of the trajectories of objects that exit a curved tube, predicting (incorrectly) that the curved path will continue on exit (McCloskey, Caramazza, & Green, 1980). However, when people are presented with animations of their false predictions they report them as appearing unnatural, and instead choose the animations based on the correct physics (Kaiser, Proffitt & Anderson, 1986; Kaiser, Proffitt, Whelan & Hecht, 1992; Proffitt, Kaiser & Whelan, 1990).

Taking into consideration the difference in response elicited by different experimental presentations, the left-right reversal hypothesis remains the most plausible explanation. Furthermore it is conceivable that this is the general case and in the vertical scenario something prevents this strategy, and either a simple geometric solution is grasped or a different and successful strategy is made available.

Role of familiarity
The difference in performance between the horizontal and vertical conditions is surprising given that most people have daily experience of walking in front of planar mirrors, whilst they have little experience of approaching a mirror on a rope or in a glass lift. This apparent anomaly in the value of experience was noted by Croucher et al. (2002), and two complimentary explanations were mooted.

Firstly, it was argued that the fact that people have experience of walking up to mirrors offers no benefit in answering the type of question being asked. Perhaps when attempting to predict what is visible in the mirror people assume that the problem is more complex than it actually is, so will overlook a simple geometric solution to it.

Secondly, people may be relying on some guesstimate based on their memory of what is visible in a mirror when they are in front of it. In the general (non accidental) case, when people stand in front of a mirror and look into it, they see parts of the environment that exist to either side of the mirror. They never see a tunnel in the mirror showing an image that does not extend past the mirror boundaries. Therefore, people may use this memory of the virtual world to try and answer the question, giving rise to the early error. In the vertical rope or lift conditions however, having no real life experience to draw on, participants may fall back on geometric solutions, which is what is necessary to arrive at the correct answer.

There are other examples in the naïve physics literature in which familiarity does not help people to answer conceptual questions, such as what happens to the surface of a liquid when the container is tipped at an angle. People tend to predict that the level will be tilted with the container. Surprisingly, it has been found that people who have everyday experience of tilted liquids, bartenders and waitresses, are worse at predicting that the liquid will stay horizontal than people of other professions such as bus drivers and housewives (Hecht & Proffitt, 1995; Vasta, Rosenberg, Knott, & Gaze, 1997).

The possible role of familiarity and experience of the test situation underlines a necessity to test all the differences between the vertical and horizontal conditions in the previous studies, as it is clear that people’s predictions are malleable and dependant upon context.

Summary of studies
Having explored the literature it is clear that people’s beliefs about mirrors and what is visible in them is inaccurate, with the early error proving robust across a variety of studies. Also robust is the absence of an early error when the observer is depicted moving vertically. A strategy of trying to imagine the virtual world as a copy rotated around the vertical axis of the real world is the best explanation available for the early error, in particular is the only one explaining the absence of error for vertical movement. Many questions however remain open.

In this paper we take a new approach. In Experiments 1-3 rather than trying to determine the source of the early error, we test what it is about the vertical condition that allows people to perform accurately.

We planned our experiments by taking a fresh look at the stimuli used in both the studies of Croucher et al. (2002) and Bertamini, Spooner and Hecht (2003). Apart from the difference in direction of motion, there were also other characteristics that differed between the horizontal and vertical conditions. They firstly differed in viewpoint of the room, a plan-view of the room was presented for the horizontal conditions and a side-view was presented for the vertical conditions. The stimuli also differed in the body orientation of the observer relative to the direction of motion, with the body moving perpendicular to the motion in the horizontal conditions and parallel to the motion in the vertical conditions. Finally the stimuli differed in the orientation of the axis defined by the two eyes relative to the mirror, this was always parallel to the near edge of the mirror in the vertical condition and perpendicular in the horizontal condition. We tested each of these differences in three experiments to determine their importance.

A fourth experiment was designed to explore a modified version of the capture hypotheses put forward by Croucher et al. (2002) by manipulating the distance of the observer from the mirror. Experiment 5 was designed to explore what happens when participants are asked more directly the extent of what is made visible in the mirror. This experiment can also tell us how well individuals can take the observer’s vantage-point into account when predicting what is visible in a mirror. Croucher et al. (2002) and more recently Bertamini and Parks (2004)
have suggested that people to a large extent discard the information about the location of the vantage-point.

Experiment 1: Side-view for both horizontal and vertical movement

In previous studies (Croucher et al., 2002, Bertamini, Spooner & Hecht, 2003) the test drawings always showed a plan-view for the horizontal conditions and a side-view for the vertical conditions. To control for this confound we constructed new stimuli in which the observer was always depicted from a side-view whether moving horizontally or vertically. For the vertical test drawing we chose to depict the observer travelling in a lift (as in the experiments reported by Bertamini, Spooner & Hecht, 2003), rather than climbing a rope (as in Croucher et al., 2002), as this is a more likely situation that people will have had experience of, and thus is more comparable with the realistic situation of walking across the room depicted in the horizontal conditions. If the accuracy in performance previously found in the vertical condition was due to the side-view depiction, then we expected the early error to be eliminated in the horizontal conditions when this view was used.

Method

Participants. There were 208 participants (165 female). All participants were students of psychology (or combined honours including some psychology) at the University of Liverpool or prospective students and parents visiting the departmental open day. The age range was 17 to 57 years, with a mean of 21.59 years (SD = 7.28 years).

Materials. Participants were presented with one of four schematic drawings, representing a character called Jane, who was said to move either vertically (up or down in a lift) across the page past a mirror (subsequently referred to as the lift-wall task), or horizontally across the page past a mirror that was located either on the wall (walk-wall task), the floor (walk-floor task) or ceiling (walk-ceiling task). Examples of the stimuli are shown in Figures 1 and 2. In each drawing the participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. Each participant received only one task to
complete, but received two drawings. If they received the vertical condition then they completed one drawing where Jane was moving down in the lift and another where she was moving up. Those in any of the horizontal conditions received one drawing where Jane was moving from left to right and another where she was moving right to left.

(Figures 1 and 2 about here)

**Procedure.** The test was administered in a classroom at the end of a lecture or presentation. The experimenter verbally issued a set of general instructions. The specific instructions were printed at the bottom of the test pages; these included a specific instruction making it clear that Jane was free to look in any direction she pleased. Participants were instructed to work independently and to take as much time as they required.

**Results and Discussion**

The data from Experiment 1 are displayed in Figures 3 and 4, in a format similar to that of Croucher et al. (2002). The mean response for each participant is shown to the nearest 4mm but the statistical analysis was based on a precision of 1mm. Each open circle represents the mean response for one participant (averaging top and down or left and right direction); stacked circles indicate that more than one participant made their response at that point. The dumbbell indicates the overall mean response for the particular condition illustrated.

**Lift-Wall.** The mean response in the Lift-Wall condition was 0.89 mm after the mirror edge when Jane was depicted moving upwards and 3.52 mm before the mirror edge when moving downwards; there appeared to be no significant effect of direction. A paired samples t-test confirmed this suggestion \((t (81) = 1.89, p = 0.06)\). Data were therefore collapsed across direction for subsequent analysis. The mean response for the collapsed Lift-Wall condition was 1.23 mm before the mirror edge, thus there appeared to be little or no error in this condition. A one-sample t-test revealed that the mean response did not significantly differ from the correct response of zero \((t (83) = -0.58, p = 0.57)\).

**Walk-Wall.** The mean response in the Walk-Wall condition was 8.16 mm before the mirror edge when Jane was depicted moving from right to left, and 7.92 mm before the mirror edge when moving left to right; there appeared to be no effect of direction (as confirmed by a
paired samples t-test: \( t (37) = -0.11, p = 0.91 \). We therefore collapsed the data across direction for subsequent analysis. The mean response for the collapsed Walk-Wall condition was 8.04 mm before the mirror edge, thus there appeared to be an early error. A one-sample t-test revealed that the mean response was significantly different from zero \( (t (37) = -2.41, p<0.05) \), demonstrating the presence of the early error.

**Walk-Floor.** The mean response in the Walk-Floor condition was 11.13 mm before the mirror edge when Jane was depicted moving from right to left, and 11.44 mm before the mirror edge when moving from left to right; there appeared to be no effect of direction (as confirmed by a paired-samples t-test: \( t (44) = 0.13, p = 0.89 \)). We therefore collapsed the data across direction for subsequent analysis. The mean response for the collapsed Walk-Floor condition was -11.29 mm before the mirror edge, thus there appeared to be an early error. A one-sample t-test confirmed that the mean response was significantly different from zero \( (t (44) = -3.92, p < 0.01) \).

**Walk-Ceiling.** The mean response in the Walk-Ceiling condition was 9.58 mm before the mirror edge when Jane was depicted moving from right to left, and 8.37 mm before the mirror edge when moving from left to right, thus there appeared to be no effect of direction (as confirmed by a paired-samples t-test: \( t (40) = -0.64, p = 0.53 \)). Data were therefore collapsed across direction for subsequent analysis. The mean response for the collapsed Walk-Ceiling condition was 8.98 mm before the mirror edge, thus there appeared to be an early error. A one-sample t-test confirmed that the mean response was significantly different from zero \( (t (40) = -2.95, p<0.01) \), again signifying presence of the early error.

(Figures 3 and 4 about here)

Experiment 1 revealed the presence of the early error for all the horizontal conditions and its absence for the vertical condition. Thus, accurate performance in the vertical conditions of this and previous studies was not due to the side-view depiction in the drawings. Even controlling for the difference in viewpoint and familiarity between the horizontal and vertical conditions, the difference in performance remains. Two differences remain between the
horizontal and vertical conditions that might account for the findings of Experiment 1: body orientation and eye-plane. Experiment 2 was designed to examine the issue of body orientation.

Experiment 2: Body orientation

In the stimuli of Experiment 1 and in previous studies, Jane’s body is always perpendicular to the direction of motion in the horizontal conditions, and parallel in the vertical conditions. Experiment 2 was designed to address the issue of body orientation by presenting a vertical movement condition (as in the Lift-Wall task) but altering the body orientation to be perpendicular, as in the previous horizontal conditions. If body-orientation is a critical factor in previous vertical movement conditions then we should expect participants in this new vertical condition to make early errors. Note however, that Jane's head was rotated to appear exactly as in the lift drawings. This was done not to confound body orientation with eye-axis orientation, a factor tested in Experiment 3.

Method

Participants. There were 37 participants (32 females). All participants were students of psychology (or combined honours including some psychology) or prospective students and parents visiting the departmental open day. The age range was 18 to 49 years, with a mean of 23.70 years (SD = 9.00 years).

Materials. The materials were identical to Experiment 1 except for the drawing of the character (see top panel of Figure 5). In the new stimuli Jane was travelling vertically in the room (and along the page) as in the Lift-Wall condition but this time instead of being in a lift Jane was in a “Mission Impossible” style harness, we termed this new task the Harness-Wall task. This configuration allowed us to maintain the vertical direction but altering the body orientation to be perpendicular to the mirror surface. Again the participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. Each participant received only one task to complete, but received two drawings; one drawing where Jane was moving down in the harness and another where she was moving up.
Procedure. The test was administered in a classroom at the end of a lecture. The experimenter verbally issued a set of general instructions. The specific instructions were printed at the bottom of the test pages. These included a specific instruction making it clear that Jane was free to look in any direction she pleased. Participants were instructed to work independently and to take as much time as they required.

Results and Discussion

The data from Experiment 2 are displayed in the bottom panel of Figure 5, in an identical format to Experiment 1.

Harness-Wall. The mean response in the Harness-Wall condition was 0.19 mm after the mirror edge when Jane was depicted moving downwards, and 0.29 mm before the mirror edge when moving upwards, thus there appeared to be no effect of direction. A paired-samples t-test confirmed this suggestion ($t(36) = 0.14, p = 0.89$). The data were collapsed across direction. The mean response for the collapsed Harness-Wall condition was 0.05 mm before the mirror edge, thus there appeared to be little or no error. A one-sample t-test confirmed that the mean response did not differ significantly from the correct response of zero ($t(36) = 0.03, p = 0.98$).

The Harness-Wall condition showed the same pattern of results as the Lift-Wall condition in Experiment 1. Therefore we rule out body orientation as the explanation for the lack of early error in the vertical condition of Experiment 1. This leaves the factor of eye-axis to be investigated. In the vertical conditions the axis defined by the two eyes is parallel to the near mirror edge, whilst in the horizontal conditions it is perpendicular (see Figure 6).

Experiment 3: Eye-plane
To test the role played by the plane defined by Jane's eyes relative to the mirror we constructed a new set of paper-and-pencil tasks. Jane is always moving horizontally, with the mirror placed on either the wall, floor or ceiling as in Experiment 1, however, this time the alignment of Jane's eyes always define an axis parallel to the near edge of the mirror (by eyeplane we mean the plane defined by these two axes). To do this we placed Jane on a trolley such as might be found in a hospital. If having an axis (defined by the two eyes) parallel to the near edge of the mirror eliminates the early error then we should find that the early error present in the horizontal conditions of Experiment 1 should disappear. It would also show that there was nothing special about vertical movement in the room.

Method

Participants. There were 59 participants (45 females). All participants were students of psychology (or combined honours including some psychology) or prospective students and parents visiting the departmental open day. The age range was 17 to 55 years, with a mean of 26.86 years (SD = 13.50 years).

Materials. Stimuli were similar to those in Experiment 1 (see Figure 7). The new stimuli repeated the horizontal stimuli of Experiment 1 but placed Jane on a trolley so Jane's eyes always defined an axis parallel to the near edge of the mirror. The mirror was placed either on the wall (Trolley-Wall task), ceiling (Trolley-Ceiling task) or floor (Trolley-Floor task). Participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. Each participant received only one task to complete, but received two drawings, one drawing where Jane was moving from left to right and another where she was moving right to left.

(Figure 7 about here)

Procedure. The test was administered in a classroom at the end of a lecture. The experimenter verbally issued a set of general instructions. Specific instructions were printed at the bottom of the test pages that made it clear that Jane was free to look in any direction she
pleased. Participants were instructed to work independently and to take as much time as they required.

**Results and Discussion**

The data from Experiment 3 are displayed in Figure 8, in an identical format to Experiment 1.

*Trolley-Wall.* The mean response in the *Trolley-Wall* condition was 3.09 mm before the mirror edge when Jane was depicted moving from right to left, and 4.22 mm before the mirror edge when moving left to right, thus there appeared to be no effect of direction. A paired-samples t-test confirmed this suggestion ($t (21) = 1.84, p = 0.08$). The data were therefore collapsed across direction. The mean response for the collapsed *Trolley-Wall* condition was 3.66 mm before the mirror edge, thus there appeared to be little or no error. A one-sample t-test confirmed that the mean response did not differ significantly from the correct response of zero ($t (21) = -0.82, p = 0.42$).

*Trolley-Ceiling.* The mean response in the *Trolley-Ceiling* condition was 11.3 mm after the mirror edge when Jane was depicted moving from right to left, and 6.33 mm after the mirror edge when moving left to right, thus there appeared that there might be a significant effect of direction. A paired-samples t-test refuted this suggestion ($t (17) = 1.97, p = 0.07$); the data were therefore collapsed across direction. The mean response for the collapsed *Trolley-Ceiling* condition was 8.81 mm after the mirror edge, thus there appeared to be little or no error. A one-sample t-test confirmed that the mean response did not differ significantly from the correct response of zero ($t (17) = 1.71, p=0.11$).

*Trolley-Floor.* The mean response in the *Trolley-Floor* condition was 0.16 mm after the mirror edge when Jane was depicted moving from right to left, and 1.63 mm before the mirror edge when moving left to right, thus there appeared to be no effect of direction. A paired-samples t-test confirmed this suggestion ($t (18) = 1.30, p = 0.21$). The data were therefore collapsed across direction. The mean response for the collapsed *Trolley-Floor* condition was 0.74 mm before the mirror edge, thus there appeared to be little or no error, a one-sample t-test
confirmed that the mean response did not significantly differ from the correct response of zero 
\( t (18) = -0.27, p = 0.79 \).

The results of Experiment 3 demonstrate that the axis defined by the eyes of the observer is the critical variable that allows people to avoid the early error. The stimuli for Experiment 3 were identical to the horizontal stimuli of Experiment 1, but with the axis relative to the mirror changed from being parallel to the top edge of the mirror to being parallel to the near edge.

(Figure 8 about here)

Eye-Plane

Experiment 3 clearly shows that eyes’ position relative to the mirror has an effect on the participants’ ability to answer correctly about what is visible in a mirror. Changing the orientation of the observer’s eyes relative to the mirror in the horizontal condition is the only manipulation that we have devised or come across that leads to accurate performance for horizontal movement. What is it that is special about the axis defined by the eyes? Clearly two points in space are necessary to define an axis, and in this case the two eyes provide these points. It follows that it is not possible for the eyes to define a vertical axis, unless the body (or the head) of the observer is rotated, such as in the trolley horizontal conditions of Experiment 3\(^1\). But Experiment 3 has demonstrated that what is important is not whether the axis is horizontal or vertical, but its relationship with the mirror. When the eye-axis can be imagined as moving towards the near edge of the mirror, the eye-axis and the near edge together define a

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\(^1\) Presumably the trolley condition with the mirror placed on the floor (ceiling) is equivalent to a condition in which Jane walks as in Experiment 1 but with her head titled 90° forward (backward). That would make the walking condition similar to the harness of Experiment 2. However, people do not naturally imagine this situation even though they are informed that Jane can look in any direction.
The eyes have it
plane. Participants seem understand that only when this plane has become orthogonal to the
plane of the mirror will the observers be able to see themselves in the mirror. This strategy has
intuitive appeal if one relate the situation to that of looking beyond an obstacle, for instance a
wall. People are well aware that what is visible depends directly on the relationship between the
eye-plane and the top of the wall. In addition, when the eye-plane becomes orthogonal to the top
of the wall this is a special turning point after which more and more becomes visible.

This use of the eye-plane can be described as a heuristic. This heuristic is available only
when the eyes axis is parallel to the near edge of the mirror. When using this heuristic
participants do not make the early error, but when this heuristic is not available participants may
imagine the virtual world as left-right reversed (and therefore make the early error).

Distance from the Mirror

Experiment 1 and 2 have shown that the orientation of the axis defined by the eyes is a
critical variable in the way in which participants think about what is visible in a mirror, however,
Croucher et al. (2002) also proposed two other hypotheses to explain the early error: the
boundary extension and the capture hypotheses. Our approach thus far has been to test the
differences between the horizontal and vertical conditions in relation to the early error. Our
rationale for Experiments 4 and 5 is to provide some scrutiny of the other hypotheses put
forward by Croucher et al. (2002) for the presence of the early error (when the eye-plane
heuristic is not available).

The boundary extension hypothesis and the capture hypotheses are not mutually
exclusive and some aspects of the problem are captured by each of these explanations. The
capture hypothesis has previously been sketchily defined, and simply argues that the reason
people make the early error is that they envisage the mirror as an invariant photograph of the
reflected room, so as soon as the mirror is visible then so too is this photograph. Perhaps a
more definitive and arguably more likely scenario is that people's judgements are based on their
memory of the visible-cone apparent when stood in front of a mirror. As discussed earlier,
when you stand in a generic position in front of a mirror you do not see a tunnel-like view, i.e.
with depth but no width extending further than the mirror frame. What is visible in a mirror fans-out to the left and right. It may be the case that participants infer that this image remains in the mirror even when they are not stood in front of it, and in order for them to be visible they simple need to enter this visibility cone. As this cone extends sideways, participants may suppose that the further they are placed from the mirror, the earlier they will become visible in it.

In addition, we suggest that one of the reasons we do not get an early error in the vertical condition is that when people stand in front of a mirror they are not as aware of the fact that the mirror shows them parts of the environment that are below and above the frame of the mirror. This is because there are typically a floor and a ceiling that block the view, and they tend to be mono-textured and of little salient interest. We may be accustomed to people approaching from the side or behind us when we look in a mirror, and thus we have experience and realize that the mirror shows us this extended view in the sideways and depth direction. Conversely, we have little or no experience of things moving in the vertical plane from below or above us.

We decided to investigate the effect of altering the distance of the observer from the mirror in order to test our visibility cone hypothesis. Because of the possible disassociation of this effect on the horizontal and vertical conditions we decided to investigate its effect under both conditions. Experiments 4a and 4b test the effect of the observer’s distance from the mirror in the vertical and horizontal conditions respectively.

Experiment 4a: Exploring Distance from Mirror on Vertical Condition

Experiment 4a was designed to assess the effect on prediction of the observers’ distance from the mirror in the vertical condition. This was simply achieved by doubling the distance at which the observer and the lift were plotted from the mirror/wall.

Method

Participants. There were 47 participants (30 females, 10 males and 7 people who neglected to give their details). All participants were students of psychology (or combined honours including some psychology) or prospective students and parents visiting a
departmental open day. The age range was 17 to 55 years, with a mean of 27.15 years (SD = 13.92 years).

Materials. Essentially identical in form to the Lift-Wall condition of Experiment 1 but with Jane and the lift depicted further from the mirror (see top panel of Figure 10 for illustration). We termed this new task the Lift-Wall-Far task. Again the participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. Each participant received only one task to complete, but received two drawings, one drawing where Jane was moving upwards and another where she was moving downwards.

(Figure 9 about here)

Procedure. The test was administered in a classroom at the end of a lecture. The experimenter verbally issued a set of general instructions. The specific instructions were printed at the bottom of the pages, these included a specific instruction making it clear that Jane was free to look in any direction. Participants were instructed to work independently and to take as much time as they required.

Results and Discussion

The data from Experiment 4a are displayed in the bottom panel of Figure 9, in identical format to Experiment 1.

Lift-Wall-Far. The mean response in the Lift-Wall-Far condition was 1.81 mm after the mirror edge when Jane was depicted moving upwards and 2.51 mm after the mirror edge when downwards, thus there appeared to be no effect of direction. A paired-samples t-test confirmed this suggestion ($t(46) = -0.37, p = 0.712$). The data were therefore collapsed across direction. The mean response for the collapsed Lift-Wall-Far condition was 2.16 mm after the mirror edge, thus there appeared to be little or no error. A one-sample t-test confirmed that the mean response did not significantly differ from zero ($t(46) = 0.65, p = 0.52$).

We also compared the collapsed responses to the Lift-Wall-Far experiment with the collapsed response to that of the Lift-Wall condition of Experiment 1. An independent t-test
revealed no significant difference between the responses to the two experiments ($t(129) = -0.89$, $p = 0.37$).

Discussion

The results of Experiment 4a show no effect of distance from mirror on judgements of what is visible in the mirror. Increasing the distance of Jane from the mirror when moving vertically in front of it, did not increase decrease accuracy of performance: A lack of an early error remained, and when compared to Experiment 1 there was no effect of distance on judgement of when Jane was able to see herself in the mirror.

Having found no effect of increased distance on the accurate performance in the vertical condition it was logical to test whether an increase in distance may increase the size of the early error in the horizontal condition. Experiment 4b was designed and conducted for this purpose.

Experiment 4b: Exploring Distance from Mirror on Horizontal Condition

Method

Participants. There were 32 participants (25 female). All participants were students of psychology (or combined honours including some psychology) or prospective students and parents visiting a departmental open day. The age range was 18 to 40 years, with a mean of 22.41 years (SD = 5.51 years).

Materials. Essentially identical in form to the Top-Jane-Jane condition of Experiment 1a of Croucher et al. (2002). We used these stimuli as they were more realistic and suitable for increasing the distance between Jane's path and the mirror. For our Horizontal-Near condition the stimuli were identical to Top-Jane-Jane (from Croucher et al., 2002) for our Horizontal-Far condition we used the same stimuli as in the Horizontal-Near condition but with distance of Jane's path from the mirror doubled (see top panels of Figure 10). Again the participants were asked to indicate where Jane would be positioned when she could first see herself in the mirror. Each participant responded to either the Horizontal-Near or Horizontal-Far condition.
Procedure. The test was administered in a classroom at the end of a lecture. The experimenter verbally issued a set of general instructions. The specific instructions were printed at the bottom of the pages. These included a specific instruction making it clear that Jane was free to look in any direction she pleased. Participants were instructed to work independently and to take as much time as they required.

Results and Discussion

The data from Experiment 4b are displayed in the bottom panels of Figure 10, in an identical format to Experiment 1.

Horizontal-Near. The mean response in the Horizontal-Near condition was 19.12 mm before the mirror edge, thus there appeared to be an early error. A one-sample t-test confirmed that the mean response was significantly different from zero ($t(15) = -2.30, p < 0.05$).

Horizontal-Far. The mean response in the Horizontal-Far condition was 21.50 mm before the mirror edge, thus there appeared to be an early error. A one-sample t-test confirmed that the mean response was significantly different from zero ($t(15) = -3.05, p < 0.01$).

To assess the effect of Jane’s distance on the mean judgement of when she would become visible, an independent-measures t-test was performed to compare the mean response from the Horizontal-Near condition to that from the Horizontal-Far condition. The t-test revealed no significant difference between the two means ($t(30) = 0.22, p = 0.83$).

Effect of Distance

The results from Experiments 4a and 4b show no effect of distance of the observer from the mirror on judgements of what is visible in the mirror, for both the horizontal and vertical conditions. For the horizontal condition this result goes against the idea that people form an idea of what is visible in a mirror based on the memory of what is visible from a canonical default distance from a mirror. If this was the case then they should expect a mirror to have a visibility cone that opens up with distance, and thus the size of the early error should have been greater in the horizontal-far condition than in the horizontal-near condition. In other words they would
expect the observers to see themselves as soon as they entered this *visibility cone*, as such this hypothesis is not supported. A more static version of the capture hypothesis is still defensible, in which the mirror is like a photograph, but this hypothesis still requires further assumptions to know what should be present in the photograph to begin with.

The fact that the same insensitivity to distance from the mirror exists for the vertical condition is inconclusive with regard either the *visibility cone* hypothesis or the capture hypothesis as there is typically no early error in the normal vertical condition and increasing distance from the mirror did not elicit one.

**Experiment 5: Quantifying perceived boundaries of visibility:**

**Examining the Capture Hypothesis**

The idea behind the capture hypothesis is that the mirror is conceived of as a photograph, and as such the location of the observer is irrelevant, therefore people will assume that if the observer can see the mirror then they can see what is in the mirror. The strong form of the capture hypothesis predicts that people would forecast that the observer could see their reflection in the mirror as soon as they enter the room (at the earliest or starting point in the test). We know from the size of the early error in the horizontal conditions of Experiment 1 (and from Croucher et al., 2002) that this strong prediction does not hold, although there were a few participants who placed their predictions at or close to the start point. However, as discussed earlier it is possible that people's responses are based on a blend between the capture hypothesis and the boundary extension hypothesis, and that this blended strategy is attenuated by people’s memory of what is visible in a mirror when they are stood in front of one.

Related to the capture hypothesis is the question of how well individuals take the vantage-point into account. The Venus effect (Bertamini, Latto & Spooner, 2003) and more recent work on judgments about image size in mirrors (Bertamini & Parks, 2004) suggest that the vantage-point is almost completely disregarded or at least its role not appreciated properly by most people.
Experiment 5 was designed to quantify the extent of people’s belief about the boundaries of what a mirror shows to an observer stood in front of it. We designed a paper-and-pencil task, in which there was again a horizontal and vertical condition. We placed Jane in a stationary position in front of a mirror and asked how much of the space in the room Jane would be able to see in the mirror. We did that by asking participants to circle all the nails in the back wall that Jane could see in the mirror.

The observer was depicted as either standing to the right of one end of the mirror, the centre of the mirror or to the left of the other end of the mirror (see Figure 11). A strong capture hypothesis would predict that the location of the observer’s eye position in relation to the mirror should make no difference to the participants’ pattern of responses concerning the extent and number of nails that are visible in the mirror.

Method

Participants. There were 66 participants (40 females, 22 males, and 4 people who neglected to give their details). All participants were students of the university of Liverpool, most were enrolled on a psychology course, but some were recruited from other departments. The age range was 18 to 34 years, with a mean of 19.95 years (SD = 2.84 years).

Materials and Procedure. Example illustrations of both the horizontal and vertical stimuli can be found in Figure 11. Participants received either the horizontal or vertical paper-and-pencil tasks. In the horizontal condition participants were shown three side-on diagrams of Jane walking into a room a room, in which there is a large mirror on one wall. We termed this condition Walk-Nail. The three images differed in the position of Jane in front of the mirror, she was shown standing either toward the left to the mirror, toward the right of the mirror, or directly in front of the centre of the mirror. On the wall behind Jane were nine numbered nails (numbered 1 at left-hand side of room to 9 on right). Participants were asked in each position to indicate which nails Jane could see in the mirror.

In the vertical condition participants were again shown three diagrams of Jane travelling vertically through a room in a lift, the room having a large mirror on one wall. We termed this condition Lift-Nail. In the three images Jane was shown standing either above the mirror, below
The eyes have it

either in front of the centre of the mirror. On the wall behind Jane were nine numbered nails (numbered 1 at top-side of room to 9 at the floor side). Participants were asked in each position to indicate which nails Jane could see in the mirror.

The test was administered in a classroom at the end of a lecture. The experimenter verbally issued a set of general instructions. The specific instructions were printed at the bottom of the test pages, including a specific instruction making it clear that Jane was free to look in any direction she pleased. Participants were instructed to work independently and to take as much time as they required.

(Figure 11 about here)

Results and Discussion

The data from the Walking and Lift conditions are shown in Figure 12. A repeated-measures ANOVA was conducted, using Condition (Walking versus Lift) as a between-participants factor and Position (Left/top, Middle, and Bottom), and Nail (numbered 1 to 9) as within-participant factors. There was a significant effect of Condition ($F(1,64) = 9.74, p<0.001$), with significantly more nails circled in the walking condition (51.1%) than in the Lift condition (36.3%). There was no significant effect of Position ($F(2,128) = 0.68, p=0.51$), indicating that the location of Jane in relation to the mirror had no effect on mean number of nails circled. There was a significant effect of Nail ($F(8, 512)= 59.02, p<0.001$) indicating that participants were sensitive to nail position. There was no significant Condition by Nail interaction ($F(8,512) = 0.595, p = 0.66$), indicating that the pattern of responding was not significantly different between the walking and lift conditions. There was also no significant Condition by Position interaction ($F(2,128) = 0.10, p = 0.91$). There was a significant Position by Nail interaction ($F(16,1024) = 4.68, p<0.001$) indicating a significant difference in the pattern of responding between the left/top, middle and bottom/right conditions. There was no significant Position by Condition by Nail interaction ($F(16,1024) = 0.83, p = 0.66$).

(Figure 12 about here)
Overall these results are inconsistent with the capture hypothesis (at least in its strong form) because it was found that the location of the observer (Jane) had a significant effect on the pattern of responding both in the walking and in the lift conditions. Examination of the summary panels in Figure 12, shows that the effect of changing the position of Jane was to increase the number of responses at the nail positions furthest from Jane. For example in the horizontal condition, when Jane was depicted on to the left of the mirror there were more responses (nails circled) to the right, and the converse was also true. This pattern of responding is consistent with the actual differences in what is visible in the mirror when observer position is altered. The other finding evident from the graphs is that although there is a significant effect of position on what subjects believe is visible in the mirror, there is still a high tolerance to include nails that would not be visible from the vantage-point of the observer in all three locations. Thus the participants demonstrate some sensitivity to the vantage-point of the observer, but when they lack the accurate "cut-off point" afforded by the eye plane then they make the early error.

The trend is for observers to correctly say that when the observers are located on one side of the mirror, they would see more nails on the opposite side. This is not consistent with the left-right reversal hypothesis because if the virtual world is rotated around the vertical axis more nails should become visible on the same side. There are two possible explanations for this apparent contradiction. First of all the early error is not universal, presumably if we could correlate the performance on the nail task with the performance on the early error we would found a correlation (similar to that found by Bertamini, Spooner & Hecht, 2003). Bertamini, Spooner & Hecht (2003) found that it was not a majority of people who expected Jane to appear at the far end of the mirror, rather it was the same subgroup who exhibited the early error. The second explanation is that there may be subtle differences or even a dissociation between the performance when the question is about the virtual world, and its relationship with the mirror surface, as is the case in the typical early error task, and the performance when the question is about real objects on this side of the mirror. All of this speculation is beyond what we can answer with the available data. However, in broad agreement with the idea that the role of the vantage-point location is not properly appreciated one can look at the data in Figure 12 and
notice the high level of similarity between the responses in the three conditions (three locations of the vantage-point).

General Discussion

Eliminating the Early Error

The rationale for the first part of our study was to test the differences between the horizontal and vertical conditions to identify the key difference that leads to accurate performance in the vertical condition. We conclude that we can eliminate the early error in the horizontal conditions by changing the orientation of the eye-axis (i.e., the axis defined by the two eyes) relative to the near edge of the mirror (Experiment 2). Other differences between the horizontal and vertical conditions were tested in Experiments 1 and 2.

As the early error is ubiquitous, it seems plausible that when the observer’s eye-axis is parallel to the near edge of the mirror it cues participants to use a specific heuristic not otherwise available; but this heuristic is the exception and not the rule.

Exploring The Early Error

The second half of our investigation explores the alternative hypotheses that have been put forward in relation to the early error in the horizontal conditions when the observers’ eye-plane does not elicit the heuristics discussed above.

The manipulation of distance from the mirror in Experiment 4 had no significant effect on the early error in the horizontal condition or the accurate performance in the vertical condition. This finding is incompatible with our modified visibility cone version of the capture hypothesis, i.e. if participants imagine that what is depicted in the mirror is an image that is identical to what is visible in a mirror when they are stood in a generic position in front of one, then they should predict that Jane would see herself as soon as she enters the cone: This occurs earlier as the distance from the mirror is increased. It should be noted that this is an elaborated definition of the capture hypothesis from that given by Croucher et al., (2002). Their definition implies that the view on the mirror surface is like a photograph that captures the entire contents
of the room, and therefore subjects should predict that the observers see themselves in the mirror as soon as the mirror is visible, i.e. as soon as Jane enters the room. Very few subjects gave this response, therefore the capture hypothesis is conceptualized by Croucher et al., (2002) as a bias. Our visibility cone hypothesis supposes an invariant image, but one that captures only what is visible of the room when one is in a generic (central) location in front of a mirror, at a generic distance, thus defining a capture cone.

The lack of support for the capture hypothesis in the results of Experiment 4 was strengthened by our findings in Experiment 5. When we manipulated the location of the observer in front of a mirror and then asked the extent to which the environment around the observer was visible in the mirror, participants showed some sensitivity to the location of the observer. Furthermore this sensitivity was in an accurate/correct direction, participants judged that more of the scene would be visible on the opposite side to the location of the observer. This suggests three things. Firstly, it suggests that they are not using a static capture schema of the mirror. Secondly, the accurate trend of the sensitivity is consistent with a memory of what is visible in a mirror when one is in front of one. Thirdly, this result seems inconsistent with the left-right reversal hypothesis suggested by Croucher et al. (2002). However, this may only be because we could not correlate responses with the early error in this study. It should be stressed that the data only suggest that participants take the vantage-point into account significantly, but not fully. Figure 12 indeed shows a great overlap between the data for the three vantage-points, and such tolerance can be seen as consistent with the limited ability of people to appreciate the role of the vantage point as found by Bertamini, Latto and Spooner (2003) and Bertamini and Parks (2004).

**Conclusion**

The results from five experiments yield two clear findings. Firstly, the early error that has previously been found when the movement relative to the mirror is horizontal can be eliminated when the eyes of the observer define an axis parallel to the near edge of the mirror. We believe that under these conditions a strategy based on the eye-axis is elicited which leads to
accurate judgement. In short, this strategy is similar to imagining that the observer needs to look over an obstacle, and the eye-plane makes clear what is visible over such obstacle.

Secondly, the results from Experiments 4 and 5 gave no support for a strong capture hypothesis and no new support for the left-right reversal hypothesis. As for the egocentric mirror rotation hypothesis and the boundary extension hypothesis, they are problematic for other reasons. Principally these two hypotheses predict the presence of the early error for the horizontal and vertical conditions, so *prima facie* seem to be inconsistent with the evidence. However, as we have argued, if the early error in the vertical condition is eliminated by the eye-plane heuristics, these hypotheses may regain some plausibility because the fact that they do not explain the difference between horizontal and vertical conditions is less of a problem.

Future research needs to test the egocentric mirror rotation and boundary extension hypotheses, and also examine people’s memories of what is visible in a mirror when they are stood in front of it, because the evidence is consistent with people's judgements being influenced by this factor. In other words, when we stand in front of a mirror the extension to left and right is clearly evident, but extension in the vertical direction is not as salient due to occlusion and blandness of ceiling and floor.

As in all investigations under the umbrella of naïve physics our study has highlighted the need to resolve the interaction of experience, familiarity and conceptual knowledge on performance. We believe this report provides some valuable insights regarding the way these factors may affect people’s naïve notions regarding mirror reflections.
References


Author Note

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Figure Captions

*Figure 1.* Example of stimuli for Experiment 1: Top Panel: the *Walk-Wall* condition; Middle Panel: the *Walk-Floor* condition; Bottom Panel: the *Walk-Ceiling* condition. An observer (Jane) is depicted walking along the dashed line and instructions were shown at the bottom of the page. Participants also saw stimuli in which Jane walked into the room from the right.

*Figure 2.* Example of stimuli for Experiment 1: the *Lift-Wall* condition. The lift moves along the dashed line vertically. Instructions were shown on the page. Participants also saw stimuli in which the lift started from the top.

*Figure 3.* Data for Experiment 1, open circles indicate individual means, stacked when necessary, and black dumbbell indicates overall mean. Top Panel: *Walk-Wall* Data Plot; Middle Panel: *Walk-Floor* Data Plot; Bottom Panel: *Walk-Ceiling* Data Plot.

*Figure 4.* Data for *Lift-Wall* condition of Experiment 1, open circles indicate individual means, stacked when necessary, and black dumbbell indicates overall mean.

*Figure 5.* Top Panel: Example of stimuli for Experiment 2: *Harness-Wall* condition. The harness moves along the vertical dashed line. Participants also saw stimuli in which Jane descended from the top. Bottom Panel: Open circles indicate individual means, stacked when necessary, and black dumbbell indicates overall mean.

*Figure 6.* Illustration of eye-plane position relative to top edge and near edge of mirror. When the eye-plane is parallel to the near edge one can imagine this plane as rotating as the observer moves around the near edge, which provides a hinge. Only when this plane becomes orthogonal to the mirror surface one has the impression that it is possible to see above the obstacle provided by the wall.
Figure 7. Examples of stimuli for Experiment 3: Top Panel: *Trolley-Wall* Stimuli; Middle Panel: *Trolley-Floor* Stimuli; Bottom Panel: *Trolley-Ceiling* Stimuli. Participants also saw stimuli in which the trolley started from the right.

Figure 8. Data for Experiment 3, open circles indicate individual means, stacked when necessary, and black dumbbell indicates overall mean. Top Panel: *Trolley-Wall*; Middle Panel: *Trolley-Floor*; Bottom Panel: *Trolley-Ceiling* Data Plot.

Figure 9. Top Panel: Example stimuli for Experiment 4a: *Lift-Wall-Far* condition. Bottom Panel: Data for Experiment 4a.

Figure 10. Examples of stimuli for Experiment 5: Top Panel: *Plan-Walk-Wall-Near* and *Plan-Walk-Wall-Far* conditions. Bottom Panel: Data for Experiment 5.

Figure 11. Examples of stimuli for Experiment 5: Top Panels: *Walk-Nail* Stimuli (from left to right; Left, Centre and Right sub conditions). Bottom Panels: *Lift-Nail* Stimuli (from left to right, Top, Middle and Bottom sub-conditions).

Figure 12. Data for Experiment 5. Top Panels: *Walk-Nail Condition*, Frequency plotted against Nail Number. Bottom Panels: *Lift-Nail condition*, Frequency plotted against Nail Number.
Jane walks into a room and straight across. There is a flat mirror on the wall on her left. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane walks into a room and straight across. There is a flat mirror on the floor. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane walks into a room and straight across. There is a flat mirror on the ceiling. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)
Jane is in a glass-lift which ascends through a room.

There is a mirror flat on the wall.

Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror.

(Jane is free to look around as much as she likes).
Jane walks into a room and straight across. There is a flat mirror on the wall on her left. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane walks into a room and straight across. There is a flat mirror on the floor. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane walks into a room and straight across. There is a flat mirror on the ceiling. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)
Jane is in a glass-lift which ascends through a room.

There is a mirror flat on the wall.

Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror.

(Jane is free to look around as much as she likes).
Jane is in a Mission Impossible style harness, which pulls her up through a room. There is a mirror flat on the wall. Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes).
Jane is wheeled into a room on a hospital trolley. There is a flat mirror on the wall. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane is wheeled face-down into a room on a hospital trolley. There is a flat mirror in the floor. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane is wheeled into a room on a hospital trolley. There is a flat mirror in the ceiling. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)
Jane is wheeled into a room on a hospital trolley. There is a flat mirror on the wall. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane is wheeled face-down into a room on a hospital trolley. There is a flat mirror in the floor. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)

Jane is wheeled into a room on a hospital trolley. There is a flat mirror in the ceiling. Please mark where on the dotted line Jane's eyes will be when she first sees her face in the mirror. (Jane is free to look around as much as she likes.)
Jane is in a glass-lift which ascends through a room.

There is a mirror flat on the wall.

Please mark where on the dotted line Jane’s eyes will be when she first sees her face in the mirror.

(Jane is free to look around as much as she likes).
Jane walks through the door and across the room. There is a mirror flat on the wall. Please mark with a cross where she will be standing when she can first see her own reflection in the mirror. (Jane is free to look around the room as much as she likes.)
Jane is in a room and is looking at the mirror on the wall.

On the back wall of the room are some spots as numbered in the diagram.
Please circle all the spots (numbers) that Jane can see in the mirror from where she is standing (Jane is free to look around as much as she likes).