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Understanding 2D projections on mirrors and on windows

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Abstract—Representational art tries to capture a 3D world on a 2D surface, and artists often discuss this in relation to the projected image on window panes and mirrors. But are 2D projections on transparent surfaces useful to learn about projections in general? Most people are unaware of the 2D projected size of objects on the surface of mirrors. They also incorrectly expect that these projections always get smaller with distance of the target object from the mirror, and do not change with distance of the observer (when the target is stationary). In this paper we extend this result about surfaces of mirrors to surfaces of windows, and we confirm that the errors that people make are not specific to Western culture by replicating the study in China. In contrast to their errors about projections, people are more accurate at predicting how field of view will vary depending on distance of the observer from a mirror or window. To explain how this pattern of (false) beliefs can stem from experience we argue that people do not perceive projections on transparent surfaces.

Keywords: Mirror; naive physics; picture perception; viewpoint.

INTRODUCTION

People are fascinated by mirrors, and artists are no exception. Leonardo da Vinci famously called the mirror the master of painters ("il maestro de pittori", C. Urb., fol. 132r) and suggested that painters should aspire to match on a canvas what they see reflected in a mirror (see Note 1). Mirrors have also been used by painters as tools, the most obvious case being self-portraiture (Gregory, 1997; Melchior-Bonnet, 2001). One key fascination about mirrors may be that they present us with a visual world as rich as what we see through a window, while at the same time we are aware that they are two-dimensional surfaces. Since they are flat they must also have flat images on them, like a painting, although there is evidence that these flat projections cannot be perceived (Bertamini and Parks, 2005; Lawson *et al.*, 2007).

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If the images that result from projection of a 3D world are not available to observers, even when a frame is present as in the case of a mirror or a window, the term 'copy' or 'reproduction' in the case of drawings or paintings based on the 3D world is actually inappropriate. Artists cannot simply copy a landscape but must generate an accurate 2D projection.

It is difficult to perceive the 2D properties of a projection of the 3D world that we are looking at. Naively, one may think that having the visual information in front of us should help: after all a projection is what takes place inside our eyes (see Note 2). It may be that, on the contrary, the visual system is exclusively interested in solid shape (surfaces and media) to the detriment of any information about the projection itself. This was a central idea in Gibson's theory of direct perception (1979). A more modern, but related, concept is that of the front-end visual system as a geometry engine (e.g. Koenderink, 1990; ter Haar Romeny and Florack, 2000). This is important for visual art because it means that there is a great obstacle to overcome when the task is to produce those 2D properties, for instance on a canvas. In theory, transparent surfaces may provide artists with a useful tool. The idea of drawing on a window has been explicitly used by many artists, especially when discussing linear perspective. To take just one example, Charles Hayter wrote in his Introduction to Perspective (1813): "in every thing you draw, you are to conceive you are drawing, on a glass or transparent plane, objects which are supposed to be on other side".

In our laboratory we have conducted studies on the perception of transparent surfaces (Lawson *et al.*, 2007). However, if projective information is hard to access, an interesting question is what expectations people have about such projections. In this paper, we are interested in the errors that people make when asked about images that result from the projection of objects onto a plane defined by mirrors and windows, and in particular what people believe about projection size. Starting from previous work on mirrors, we tested what role people assign to the observer's viewpoint, whether the same beliefs extend to projections other than those on mirrors, and whether results are robust across cultures.

WHAT PEOPLE KNOW ABOUT 2D PROJECTIONS OF OBJECTS

Adding to the sense of mystery associated with mirrors is the fact that people find simple questions about planar mirrors challenging. Nevertheless, the mistakes that they make are not random. The key question is what is the origin of such mistakes and, if the origin is in the working of the visual system, what these errors can tell us about representational art. We start with a review of what is known about these mistakes.

Bertamini and colleagues have documented four types of errors. (i) *The early error*. When participants are told to imagine that they are approaching a mirror from the side, they often believe that they would see their reflection before they reach the near edge of the mirror (Bertamini *et al.*, 2003; Croucher *et al.*, 2002;

Hecht *et al.*, 2005; Lawson and Bertamini, 2006). (ii) *The Venus effect*. If people see both a person and the reflection of that person in a mirror, for instance in a painting of Venus apparently looking at herself in the mirror, they often believe that what they see in the mirror is the same as what the person sees in the mirror, i.e. they ignore viewpoint (Bertamini *et al.*, 2003). (iii) *Overestimation of projection size*. Bertamini and Parks (2005) confirmed Gombrich's observation (1960) that people estimate the reflection of their own face on the surface of a mirror to be around the same size as their face (it is, in fact, half the size; see also Lawson and Bertamini, 2006). (iv) *Projection size gets smaller with distance*. Bertamini and Parks (2005) found that most people believe that their reflection on a mirror becomes smaller as they move farther away. In reality, the size of their face projected on the surface of a mirror does not depend on their distance from the mirror (see Fig. 1).

Bertamini and Parks (2005) suggested that people generally fail to appreciate the role of the observer's viewpoint when they are reasoning about mirrors. The Venus effect can be seen as a clear illustration of this. Here, people seem to believe that a mirror provides everybody with the same information, even though observers occupy different locations. This phenomenon may relate to the need that any animal has to access visual information that is invariant of changes in fixation (saccades), head and body movements, and location in space. Although viewpoint-specific information is what is captured by a camera snapshot, and is what classical painters

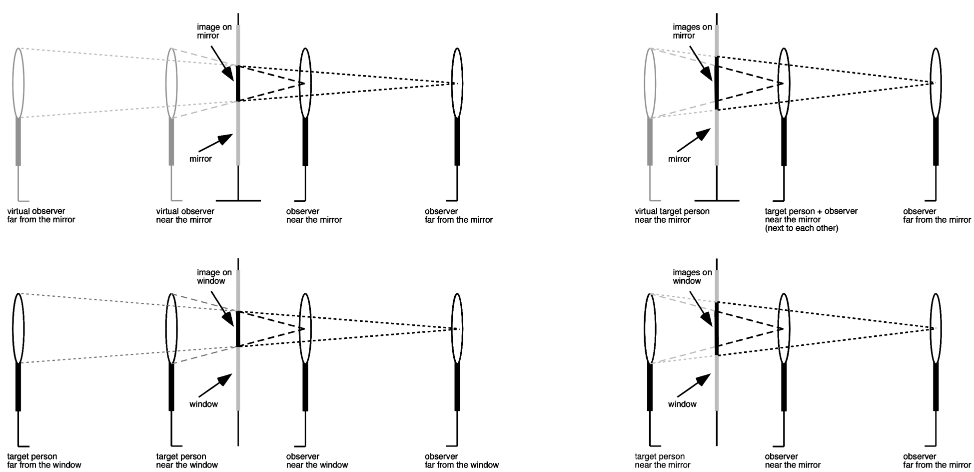


Figure 1. In the top-left diagram a mirror is in front of an observer and the virtual observer on the other side of the mirror is shown. Because observer and virtual observer are at the same distance from the surface of the mirror the projection of the person's head (labelled image) is always half its height. In the top-right diagram the observer looks at another person. Suppose this person does not move, the projection of their head will be bigger from a farther viewpoint of the observer. The bottom row shows that the same principles apply to projections on windows as long as the target object is located where the virtual target was in the case of the mirror. We have not shown what happens when the observer is stationary and the target person moves farther away from the mirror/window. This is left as an exercise for the reader (correct answer: the image gets smaller).

struggled to capture on a reproduction plane (e.g. a canvas), it is not what is made explicit to us by our visual system.

One fundamental problem for vision is that the angle subtended by a given stimulus depends both on its size and its distance from the observer (viewpoint). If observers were not able to cope with this they would experience a world of ever-changing objects. However, because of size constancy, people experience object size to be approximately constant with changes in viewing distance (for a review see Ross and Plug, 1998). Most people are also aware, at least at a conceptual level, that objects subtend smaller visual angles when farther away. With respect to size constancy, virtual objects inside mirrors are not different from other objects, and their size can be perceived accurately (Higashiyama and Shimono, 2004). However, the 2D projection of an object on the surface of the mirror is different.

As pointed out by Gombrich (1960), projection size is independent of viewpoint when the observer and the target are the same, for example when we look at ourselves in a mirror. This is counterintuitive, and most people predict projections of objects to get smaller in this situation (Bertamini and Parks, 2005). However, in the more general case of an observer looking at a target that is not the observer, viewpoint does matter. When the viewpoint is fixed and the target moves farther away, the projection of the target becomes smaller, whilst when the target is fixed and the viewpoint moves farther away the projection of the target becomes bigger.

Perhaps the most striking result in Bertamini and Parks (2005) was that most people believe that the projection of a target object on the mirror surface will remain the same size if the observer changes location (away), as long as the target object remains in the same location. This is not only incorrect, but even more surprising, this belief goes against the reasonable (albeit incorrect in the special case of projected images) belief that objects become smaller as viewing distance increases (Bertamini and Parks, 2005; Lawson and Bertamini, 2006).

In a recent study, Lawson and Bertamini (2006) found that problems with judging size on mirror surfaces persist when observers are allowed to look at a mirror. Therefore the origin of the difficulty is likely to be perceptual, and not only in reasoning about the situation. Lawson and Bertamini (2006) argued that the projection of an object on the surface of the mirror is not accessible to observers because only the virtual object inside the mirror is perceived. Lawson, Bertamini and Liu (2007) have confirmed that, even after detailed instructions, observers overestimate the projected size of objects on mirror surfaces while standing in front of a mirror. Independently of distance, people judged the projected size of the object to be closer to its actual size than its projected size. This is consistent with what people maintain when questioned: as long as the target is stationary, viewpoint does not matter and projected size remains the same from different viewpoints (Bertamini and Parks, 2005).

We believe that 2D projections are not perceived as having an existence independent of the 3D object which is projected. This may seem obvious, but it is worth remembering that, although projections do not exist as physical objects, observers understand what a projection is, projections can be described in geometrical terms, they can be pointed at accurately, and the distance from the observer of a projection is clearly specified by the frame of the mirror. A specular surface is not transparent, but it is perceived as transparent because a 3D scene is perceived on the other side of the mirror. Experiment 1 compared people's understanding about mirrors and windows. If projections on transparent surfaces are not perceived as stimuli with properties that can be described by the observer, then the same difficulties in estimating projection size should exist for projections of objects on other transparent surfaces such as the glass pane of a window.

The same principles of perspective specify the properties of projections on the surface of a mirror as on any other projection plane. The difficulty that participants in our studies face, therefore, relate to the difficulty that artists have in understanding perspective. Historically, it was only during the Renaissance that perspective was rigorously described. Brunelleschi is usually credited, and later Leonardo da Vinci, and Alberti wrote formally about it (Kubovy, 1986). Thus, for centuries, artists had no clear understanding of how to produce a picture in perspective although around them there were accurate 2D projections of 3D scenes on the surface of mirrors and windows. It is interesting that one of the so-called 'perspective apparatuses' described by Dürer in his 'Painter's manual' was a type of movable window with strings that could be used to work out the projection of a given object onto the window surface. This trick was necessary because the projection of an object is not accessible perceptually, even to skilled artists.

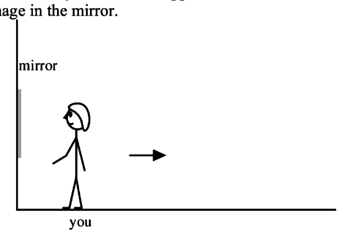
EXPERIMENT 1: EFFECT OF DISTANCE FOR MIRRORS AND WINDOWS

Experiment 1 is a direct comparison between what people believe about images on mirrors and on windows. Participants were shown simple diagrams and provided three forced-choice answers about mirrors (Fig. 2) or about windows (Fig. 3). For mirrors, the three dynamic scenarios described were similar to those used by Bertamini and Parks (2005): (1) The observer moved away from the mirror. The question is what happens to the projection of the observer's head on the surface of the mirror; (2) A target (Jane) moves away from the mirror and the observer remains stationary. The question is what happens to the projection of Jane's head on the surface of the mirror; (3) The observer moves away from the mirror and Jane remains stationary. The question is again what happens to the projection of Jane's head on the surface of the mirror. All three scenarios were presented to each individual because Bertamini and Parks (2005) found no differences between data collected using a within or a between design.

A second group of participants (window group) saw diagrams that were modified to describe the observer standing in front of a window, and the target (Jane) standing on the other side of the window (see Fig. 3). The window group may have had an advantage because the target object was drawn on the opposite side of the window in the diagram, whilst the virtual target on the other side of a mirror was only implied

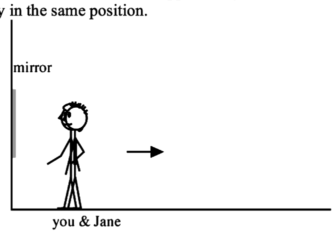
Please answer the following three questions:

1. Imagine you are facing a mirror on a wall, looking at the image of yourself in the mirror. Imagine drawing on the mirror with a felt-tip pen an outline that is the size of your face as it appears on the mirror. Now imagine you move back (away from the mirror) and again look at your image in the mirror.



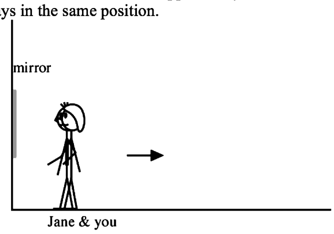
Please think carefully about what happens to your image - does it:
A. stay the **same size** - the size of the image of your face is the same size as the felt-tip outline
B. get **smaller** - the size of the image of your face is smaller than the felt-tip outline
C. get **bigger** - the size of the image of your face is larger than the felt-tip outline

2. Imagine you are facing a mirror on a wall, looking at the image of Jane in the mirror. Imagine drawing on the mirror with a felt-tip pen an outline that is the same size as Jane's face as it appears to you on the mirror. Now imagine she moves back (away from the mirror) while you stay in the same position.



Please think carefully about what happens to Jane's image as you see it now. Does it:
A. stay the **same size** - the size of the image of Jane is the same size as the felt-tip outline
B. get **smaller** - the size of the image of Jane is smaller than the felt-tip outline
C. get **bigger** - the size of the image of Jane is larger than the felt-tip outline

3. Imagine you are facing a mirror on a wall, looking at the image of Jane in the mirror. Imagine drawing on the mirror with a felt-tip pen an outline that is the same size as Jane's face as it appears to you on the mirror. Now imagine you move back (away from the mirror) while Jane stays in the same position.



Please think carefully about what happens to Jane's image as you see it now. Does it:
A. stay the **same size** - the size of the image of Jane is the same size as the felt-tip outline
B. get **smaller** - the size of the image of Jane is smaller than the felt-tip outline
C. get **bigger** - the size of the image of Jane is larger than the felt-tip outline

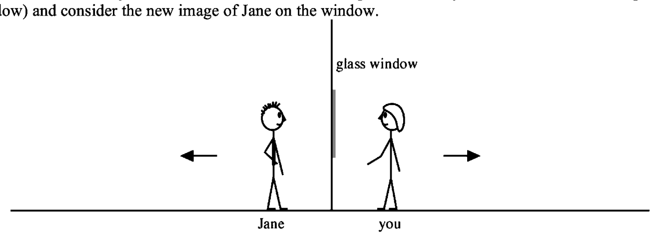
Figure 2. Mirror version of the questionnaire used in Experiment 1.

in the diagrams. Nevertheless, we expected a similar pattern of responses for the two groups.

The questionnaire was completed by 194 participants aged between 12 and 67 (mean age 31). They were prospective students and their parents who were attending a lecture as part of an open day at the University of Liverpool, UK. There were 95 participants (65 females) in the mirror group and 99 participants (74 females) in the window group.

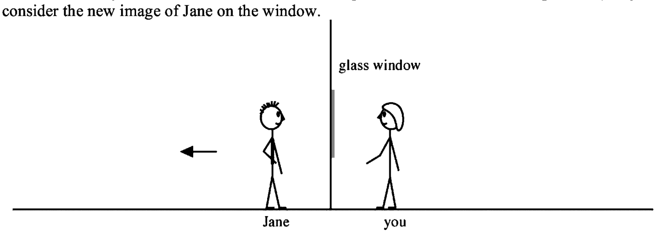
Please answer the following three questions:

1. Imagine you are facing a window, looking at the image of Jane. Imagine drawing on the glass with a felt-tip pen an outline that is the size of Jane's face as you see it on the window. Now imagine that both you and Jane move two steps back (away from the window) and consider the new image of Jane on the window.



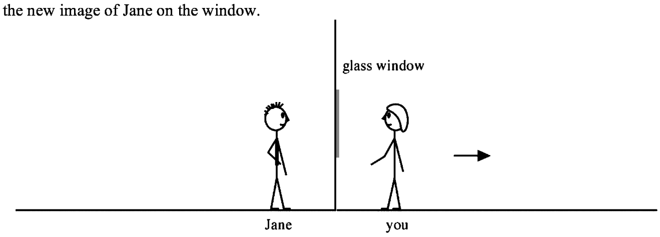
Please think carefully about what happens to the image - does it:
A. stay the **same size** - the size of the image of Jane is the same size as the felt-tip outline
B. get **smaller** - the size of the image of Jane is smaller than the felt-tip outline
C. get **bigger** - the size of the image of Jane is larger than the felt-tip outline

2. Imagine you are facing a window, looking at the image of Jane. Imagine drawing on the glass with a felt-tip pen an outline that is the size of Jane face as you see it on the window. Now imagine that Jane moves two steps back (away from the window) and consider the new image of Jane on the window.



Please think carefully about what happens to Jane's image as you see it now. Does it:
A. stay the **same size** - the size of the image of Jane is the same size as the felt-tip outline
B. get **smaller** - the size of the image of Jane is smaller than the felt-tip outline
C. get **bigger** - the size of the image of Jane is larger than the felt-tip outline

3. Imagine you are facing a window, looking at the image of Jane. Imagine drawing on the glass with a felt-tip pen an outline that is the size of Jane face as you see it on the window. Now imagine that you move two steps back (away from the window) and consider the new image of Jane on the window.



Please think carefully about what happens to Jane's image as you see it now. Does it:
A. stay the **same size** - the size of the image of Jane is the same size as the felt-tip outline
B. get **smaller** - the size of the image of Jane is smaller than the felt-tip outline
C. get **bigger** - the size of the image of Jane is larger than the felt-tip outline

Figure 3. Window version of the questionnaire used in Experiment 1.

Results and discussion

Figure 4 presents the results from the mirror and window groups. In the mirror group, 87% of participants believed that the projection of the observer on the mirror surface becomes smaller as the observer moves away. A similar proportion (79%) believed that the same happens when the target is another person. Note that this is the correct answer to the second, but not to the first, question. Only 14% reported

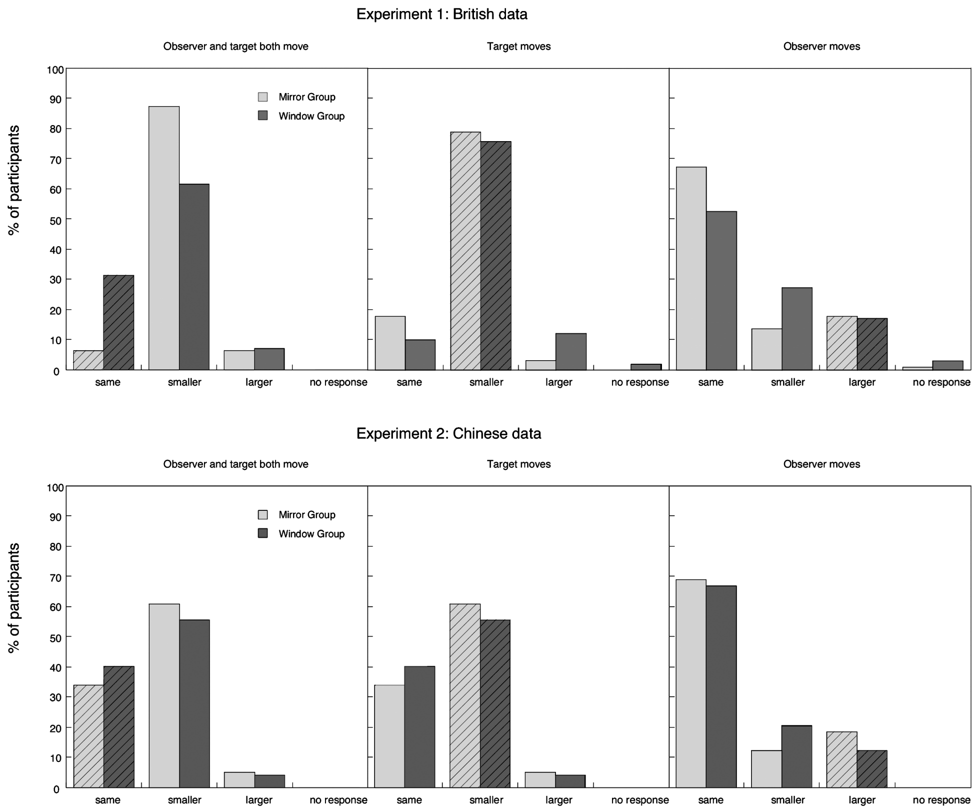


Figure 4. Results from Experiments 1 and 2. The correct response is shown with hatched bars.

that the projection gets smaller to the third question, whereas 64% believed that it remains the same. Therefore, the three modal responses were the same as those found by Bertamini and Parks (2005), with the majority responding ‘smaller’, ‘smaller’ and ‘same’. The percentages were also similar in the new data (87%, 79% and 64%) and in the old data (86%, 89% and 66%).

Most people believed that size remains equal in question three, even though the viewpoint was farther away. Bertamini and Parks (2005) suggested that people may think of the mirror as a device, like a camera, that captures an image. The observer simply witnesses the product of the interaction between the mirror and the target. However, this suggests that mirrors are special. Therefore, let us consider people’s understanding of the projections of objects on windows.

The proportion of participants who believed, incorrectly, that the projection of an object on the window grows smaller as the observer moves away was large (62%) although smaller than for the mirror. A large proportion correctly believed that the same happens when the target is another person (76%). Only 27% reported that the projection gets smaller to the third question, whereas 53% believed that it remains the same. We compared responses to each question across the mirror and window groups, adjusting the α level for multiple tests ($\alpha = 0.016$). There was a significant difference between the two groups on question one ($\chi^2 = 20.25, df = 2, p < 0.01$) but not on the other two questions. Figure 4 shows a greater number of correct responses ('same') for the mirror group on question one. However, the modal answer was the same in both groups and was incorrect ('smaller'), therefore the difference is quantitative. Most importantly, the overall pattern of results was the same for the mirror and the window group.

EXPERIMENT 2: CROSS-CULTURAL COMPARISON OF BRITISH AND CHINESE RESPONSES

We believe that the problem that people have in understanding what happens to the size of projected objects is rooted in perception, namely that, unlike both 3D physical objects and 3D virtual objects, these 2D projections cannot be perceived. Lawson and Bertamini (2006) and Lawson, Bertamini and Liu (2007) have found support for the strong claim that there is a perceptual cause of people's errors. In their studies, observers failed to judge projection size accurately while standing in front of mirrors. If there is a perceptual cause of people's errors then the phenomenon should be universal.

However, an alternative view is that the origin of the problem is an analytic focus on salient objects and the use of categorisation rules to organise the environment that is characteristic of Western cultures (Nisbett and Miyamoto, 2005). This cultural difference has empirical support from a number of studies (e.g. Kitayama *et al.*, 2003). One explanation of the responses of most of our Western participants in Experiment 1 is that they did not appreciate the context described in our questions: they focussed on the target instead of, or more so than, the location of the observer's viewpoint. Context information may be precisely what Western cultures are less sensitive to (e.g. Masuda and Nisbett, 2001).

To test this possibility, we translated the questionnaire used in Experiment 1 into Chinese, and administered it to undergraduate students in Xi'an, the capital of the Shaanxi province (Northwest China). The only modification to the diagrams in Figs 2 and 3 was that the observer's hair was darker and the second individual had a short plait. The questionnaire was completed during a lecture by 194 undergraduate students at Shaanxi Normal University. They were aged between 18 and 24 (mean age 20), and spoke Mandarin as their first language. There were 97 participants (79 females) in the mirror group and 97 participants (79 females) in the window group.

Results and discussion

Figure 4 presents the results from the mirror and window groups. In the mirror group, most participants believed that the projection on the mirror becomes smaller as the observer moves away (61%). A similar proportion believed that the same happens when the target is another person (65%). Only 12% reported that the projection gets smaller to the third question, whereas 69% believed that it remains the same. In the window group, 56% of participants believed that the projection on the window grows smaller as the observer moves away, and 75% believed that the same happens when the target is another person. Only 21% reported that the projection gets smaller for the third question, whereas 67% believed that it remains the same.

We compared responses to each question across mirror and window groups, adjusting the α level for multiple tests. There were no significant differences between the two groups. Following similar steps, we compared the Chinese data to the Western data from Experiment 1. For mirrors, Chinese participants performed better on question one ($\chi^2 = 22.82$, $df = 2$, $p < 0.01$), but not on the other two questions. However, although the Chinese correctly chose 'same' more often than Westerners, for both groups the modal answer was 'smaller' (Fig. 4). Furthermore, for the window condition there were no significant differences between the Western and Chinese groups.

It appears that the Chinese group responded similarly to mirrors and windows. Westerners had more difficulty with the first mirror question to which they responded 'smaller' more than either the Chinese group or to the equivalent window question. However, caution should be taken in drawing strong conclusions from the difference between the results from Experiments 1 and 2. The significant difference occurred on a single question and, more importantly, even on this question the modal answer was the same for Chinese and Western participants.

In summary, Bertamini and Parks (2005) found that most participants responded 'smaller', 'smaller' and 'same' to the three questions illustrated in Fig. 2. Experiments 1 and 2 demonstrated that this pattern is robust and generalises to projections of objects on windows as well as mirrors, and to Chinese as well as British participants.

EXPERIMENT 3: FIELD OF VIEW

There is no doubt that it is hard to respond to questions about projections of objects on transparent surfaces. It may be easier, however, to appreciate what the correct answer is to some of our questions by thinking about the situation differently. The projection of an object takes up a certain proportion of the surface of a mirror, and the size of the mirror is clearly specified by its outside frame. Therefore, observers standing in front of a mirror could try to estimate the proportion of the surface of the mirror occupied by an image. For instance, if the projection of an object is near the outside edge, then its size is similar to the size of the mirror itself. Obviously this strategy may only be available when a mirror is present in front of the observer. However, even in this situation Lawson *et al.* (2007) found little evidence that observers spontaneously use such a strategy.

A similar logic can be applied to the change in the field of view as the observer moves. Let us consider a window and a scene visible outside the window (the same reasoning applies to a mirror). As the observer moves farther back from the window, less of the scene is visible through the window. If there were several objects, say myrtle bushes, visible from the original viewpoint, only a single bush may be visible from the farther viewpoint. The size of the window itself has not changed, so if only one bush is visible it means that the projection of this single bush on the window must now be larger. This reasoning helps to answer correctly the third question of Experiments 1 and 2 about changes in the projected size of an object when the observer moves whilst the target object is static. We expect that reasoning about the field of view (how much is visible) is easier than reasoning about the projected size of a single object (how big is that image) because the field of view can be understood concretely in terms of a changing scene, whereas the size of the projection of an object cannot be directly perceived but, instead, must be inferred. This is true despite the fact that similar geometric principles apply to both, as explained above. To test this idea we asked people what happens to the amount of the scene visible inside a mirror or through a window with a change of viewpoint. We compared these questions to matched questions about the size of the projections of objects (images) on the surface of a mirror or a window: these questions were similar to those asked in Experiments 1 and 2.

A website questionnaire was completed by 241 participants aged between 16 and 66 (mean age 31). There were 55 participants (40 females) in the mirror image group, 68 participants (44 females) in the window image group, 56 participants (34 females) in the mirror scene group, and 62 participants (35 females) in the window scene group.

The mirror image and window image conditions were included to try to replicate the results of Experiment 1 with a web-based study. The mirror scene and window scene conditions were new and the questionnaires are shown in Fig. 5. As the landscape in a scene cannot move, the scene groups were given just one scenario in which only the observer moved. This scenario is similar to that described in question 3 for the mirror and window conditions in Experiments 1 and 2. However, the question is different.

Results and discussion

Figure 6 presents the results for the image and scene groups. The image groups can be compared to the groups in Experiments 1 and 2 (Fig. 4). Even with a smaller dataset the basic finding was replicated: the modal answer was 'smaller' for question 1, 'smaller' for question 2 and 'same' for question 3. In the mirror group the percentages were 85% ('smaller'), 89% ('smaller') and 65% ('same'). In the window group the percentages were 71% ('smaller'), 82% ('smaller') and 44% ('same'). We compared responses to each question across the mirror and window groups, adjusting the α level for multiple tests ($\alpha = 0.016$). There were no significant differences between the groups on any of the three questions.

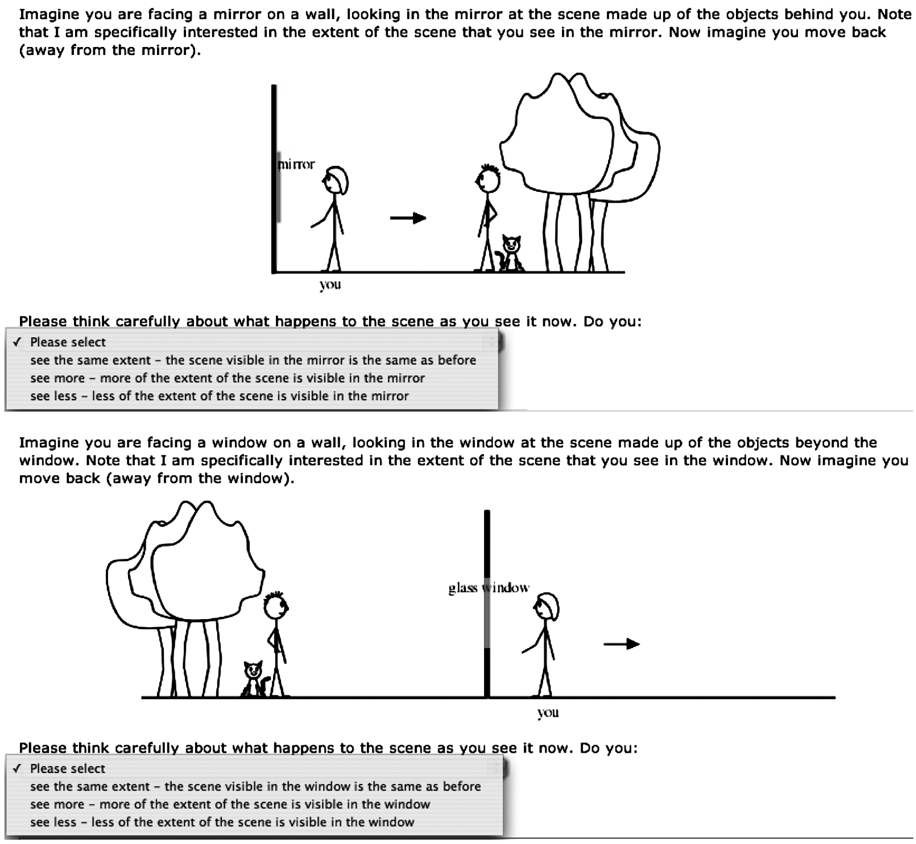


Figure 5. The scene diagrams used in Experiment 3. Different groups were shown the mirror and the window versions.

In the window scene group most participants believed that 'less' of the scene is visible from farther away (69%). Here, 'less' corresponds logically to 'larger' object projections and is the correct answer because the scene does not move. Next we tested the difference between the window scene and question 3 in the window image condition, shown one above the other in Fig. 6. A χ^2 test confirmed that the window scene group were more accurate ($\chi^2 = 28.66$, $df = 2$, $p < 0.001$).

In the mirror scene group 45% of participants correctly believed that 'less' of the scene becomes visible from farther away whilst 41% answered 'more'. We tested the difference between the mirror scene and question 3 in the mirror image condition (see Fig. 6). A χ^2 test confirmed that the mirror scene group were more accurate ($\chi^2 = 31.56$, $df = 2$, $p < 0.001$). In addition, the window scene group were more accurate than the mirror scene group ($\chi^2 = 8.01$, $df = 2$, $p = 0.018$).

In summary, when asked about the extent of the scene visible when only the observer moves away, the modal answer was the correct response of 'less' for both mirrors and windows. People were more accurate than when asked about the projection of a single target object, particularly for the window scene group.

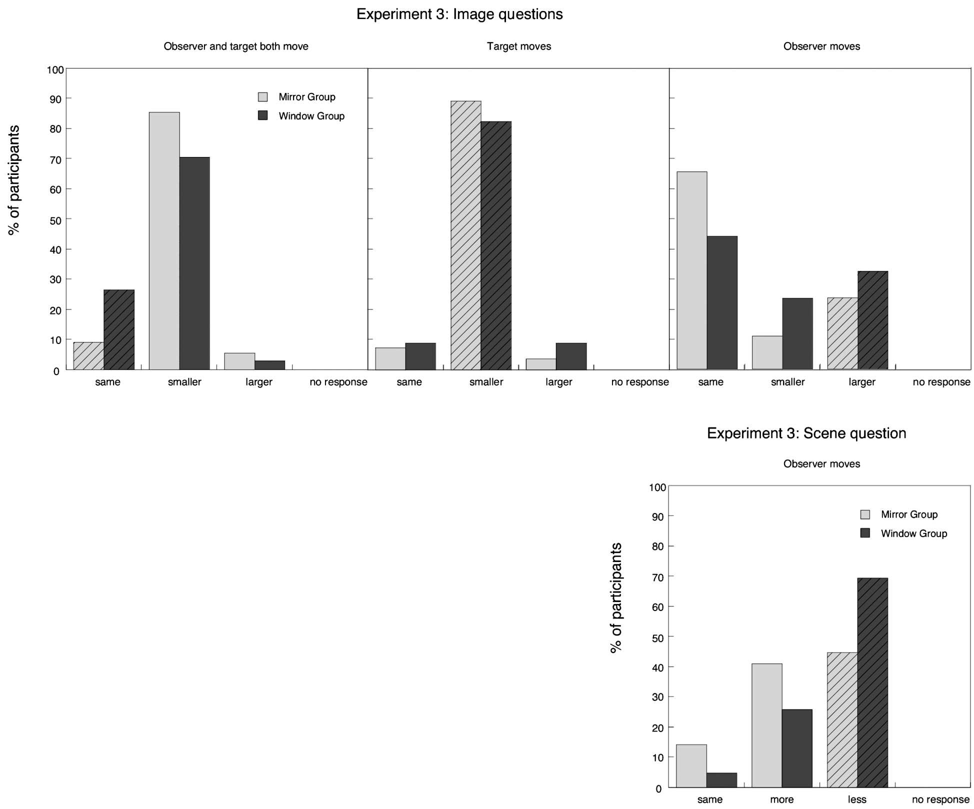


Figure 6. Results from Experiment 3 for the image groups (top) and the scene groups (bottom). The correct response is shown with hatched bars. The term image is used to refer to the projection of the object on the surface of the mirror or window.

This confirms our hypothesis that people may understand that the extent of what is visible can change with a change of viewpoint, while at the same time not realise that the projection on the transparent surface also must change with a change of viewpoint. We believe that the advantage for the question about field of view is due to the fact that field of view is not something that happens on the surface of the transparent surface, as it can be described as amount of scene visible through an aperture. People are likely to recall their everyday experiences with observing scenes through windows (and less, frequently, mirrors) and the need to move closer to windows to see more of a scene beyond.

GENERAL DISCUSSION

There are some inconsistencies in how people think about projections on the surface of mirrors. When questioned explicitly, most people make a distance error: they believe that the projection of a target (e.g. their own face) on a mirror becomes smaller as they and the target move farther away from the mirror. In fact, the projection remains the same size if the target is always the same distance from the mirror as the observer. Furthermore, if the target object is stationary and only the observer moves back, people expect the projection of the target to stay the same size (Bertamini and Parks, 2005). In fact in this case the projection becomes larger. These errors may be based on how we perceive reflected objects since we know that people overestimate projection size even when they are standing in front of a mirror (Lawson and Bertamini, 2006). The belief about projections getting smaller originate from perception in a more indirect way, as observers tend to produce similar estimates for projections of a target seen from different viewing distances (Lawson *et al.*, 2007). People may think of the projection of an object on a transparent surface as an interaction between the target object and the surface which does not involve the observer, so they ignore viewpoint. This may derive from their difficulty in perceiving changes that are viewpoint-specific, that is, how the visible world changes as viewpoint changes whilst the physical world is constant.

Our first aim in this paper was to investigate whether the clear difficulty in understanding projections on mirrors is specific to mirrors or if it extends to other transparent surfaces. In Experiment 1 we found a close similarity between beliefs about projections on mirrors and on windows. In both cases most people believed that projections get smaller when both the observer and the target object are moved back from the mirror or window. People also believed that projections of objects remain the same size if the target object is stationary and only the observer moves away from the mirror or window. There was one minor difference between mirrors and windows: when observer and target move by the same amount away from the window more participants correctly responded that the projection size was the "same" than for the equivalent mirror question. Note, however, that even in the window group the majority responded "smaller". The difference in relation to the mirror condition was, therefore, only quantitative. It could have originated from the fact that in the window diagram the target person was visible, whilst in the mirror diagram the virtual person was only implicit. Experiments 2 and 3 confirmed the same pattern of responses to the three questions ('smaller', 'smaller' and 'same') across both mirror and window groups. These results, together with the data reported in Bertamini and Parks (2005), document a robust phenomenon that generalises to other transparent surfaces such as windows.

The second aim of this paper was to test whether these effects are specific to Western culture. In Experiment 2 we replicated the basic pattern of results with a Chinese population, but with a significant difference on question one. As in the case of windows, this difference was not a change in the modal answer ('smaller'), but only in the strength of the effect (more 'same' responses). The possibility of a small difference between cultures may need further investigation. However, because the modal answers were the same in Experiments 1 and 2, we conclude that a tendency of Westerners to focus on the salient target object (Nisbett and Miyamoto, 2005) is not enough to explain the errors that people make in understanding projection size.

The final goal of this paper was to test whether the difficulty documented in Experiments 1 and 2 is specific to reasoning about projections of individual target objects. Experiment 3 introduced a variant on the third question (in which only the observer moves). This time, instead of asking what happens to the image, that is the projection of an object, we asked what happens to the amount of scene visible. We expected that people could better deal with a question about what is visible through an aperture because in that case they do not need to think about what happens on the transparent surface. We confirmed that people understand that the amount of scene visible through a window and, to a lesser degree, inside a mirror, reduces as the observer moves farther from the window or mirror. This suggests that people fail to apply their knowledge about what happens to scenes as the observer moves away from an aperture to reason about projections of objects on the surface framed by that aperture. In the case of mirrors, similar proportions responded 'more' (41%) and 'less' (45%). Mirrors may be more closely associated with looking at a specific object, i.e. ourselves, than with looking at a scene. Hence, reframing the question in terms of a scene may not benefit people so much as for windows. In addition, although mirrors are very common, windows are ubiquitous in our environment.

In the introduction we motivated our investigation of projections of objects, in part, because these studies are relevant to the aim of an artist to capture a 2D projection in a picture. Hagen (1986) has argued that all representational pictures obey natural perspective, because they are based on 3D projective geometry (but other authors do not agree, e.g. Willats, 2003). It is often an explicit goal of an artist to capture an accurate projection of the world on a flat surface, although we must stress that art cannot be reduced to depiction. There is a difference between pictures and transparent surfaces: we can look through windows and mirrors, they are apertures onto a physical and a virtual 3D world, respectively. In this sense, it is perhaps not surprising that projections of objects on the plane defined by the glass of a window or a mirror are not perceived by people or, consequently, learnt about. However, the goal of pictorial representation is for us to look into a picture and ignore its 2D surface. Although a picture is not an aperture, our visual system perceives it as an aperture through which we see a static 3D world. Wollheim (1980) coined the term 'seeing-in' for the special perceptual state associated with viewing pictures, and a recent edited book on picture perception carries the title *Looking into Pictures* (Hecht *et al.*, 2003). Many questions about what it means to look into a picture remain controversial. Perhaps the best known is the question of whether a compensation process is necessary to explain why observers usually do not perceive distortions in pictures even though they are often viewed from the incorrect vantage point for the perspective shown in the picture (Kubovy, 1986; Pirenne, 1970). The results here and those reported by Lawson *et al.* (2007) may be relevant to understanding why pictures are so effective at representing reality. Even when, at a conceptual level, people know that there is no 3D world, as is the case for the virtual world in a mirror, they are unable to perceive the projected image on the transparent 2D surface.

In this paper, we have studied what people know about 2D projections on transparent surfaces. We found that people believe that projections of objects get smaller if the target moves farther away from the surface and, conversely, people believe that projections remain the same size if the target is static. We have demonstrated that both of these beliefs lead to systematic errors because they ignore the importance of the observer's viewpoint. We offer the speculation that this is a by-product of people's ability to abstract away from the *hic et nunc* of information that is tied to a specific viewpoint. In turn, this ability may go some way to explain how people can gather information from a painting depicting a 3D world without being overly disturbed by the fact that the picture is necessarily shown from a single, static viewpoint which usually differs from that of the viewer.

A final word should be said about the value of empirical data. Our questions were simple in that they were reasonably short and referred to situations not unlike what we experience in everyday life. Yet, results showed large and systematic mistakes about people's knowledge of how projections behave; in particular, viewpoint was treated as unimportant. We had not originally predicted this pattern of results. Empirical investigation of what people perceive as well as what they believe about projections is therefore invaluable for understanding the relationship between vision and visual art.

NOTES

1. For someone painting on a canvas this is almost impossible, but Leonardo's interests spanned art, science and technology, and he might have found modern virtual reality a step in the right direction, though such digital technology still cannot match the quality of what we see in a mirror.
2. We are not making a point specifically about the retinal image; there are other examples of projections that describe the visual information surrounding an observer, for instance Helmholtz's 'celestial sphere' (1867/1925).

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