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On what people know about images on mirrors

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Abstract

As observed by Gombrich [Gombrich, E. H. (1960). *Art and illusion*. Oxford: Phaidon Press], we confirm that most people are unaware of the size of their own image on mirrors. Specifically we have documented the knowledge that people have of the size of their own head and of the size of the mirror image of their own head. In addition we have explored naive beliefs about how the size of mirror images changes with distance. The main pattern of findings is consistent with a focus on target distance and a difficulty in factoring the observer's vantage point correctly when people reason about the problem. The issue of information about vantage point is discussed in relation to other literatures.

Keywords: Mirror; Naive physics; Imagery; Viewpoint; Spatial updating

> *I'm more like the monkey who firmly believed that he saw another monkey in the mirror…and discovered his error only after running behind the glass several times*. Galileo

1. Gombrich's bathroom mirror

There is a famous passage in Gombrich's (1960, p. 5) classic book *Art and illusion* about the perception of our own head in mirrors. Gombrich points out that we see

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ourselves in mirrors without any conscious awareness of the size of the image on the mirror surface. He suggests a little demonstration on the fogged up mirror of our bathroom. If we circle the outline of our own head we will be amazed to discover that it is much smaller than our head. Indeed, it is exactly half independently of distance. To Gombrich, this is an example of an illusion in the sense that we are only aware of seeing ourselves *face to face* and we stubbornly refuse to see the size on the mirror surface.

This important demonstration has been referred to by other authors (e.g. Gregory, 1997, 1999; Mackavey, 1980). Surprisingly, we could not find any empirical study based on this demonstration after more than 40 years from the publication of the book. In this paper we confirm the widespread lack of awareness about the size of the image on the surface of the mirror. However, establishing what people *do not* know is only a first step. We also tested what people *do believe* about the size of images on mirrors, similarly to other work in *naive optics* (i.e. work which tested what people know about what a mirror makes visible: Bertamini, Spooner, & Hecht, 2003; Croucher, Bertamini, & Hecht, 2002; or the belief about extramission: Winer, Cottrell, Fournier, & Bica, 2002).

Both the fact that our image is half the physical size, and the fact that this relationship is independent of how far we are from the mirror are counterintuitive. However, they become clearer as soon as we realise that a mirror is always located halfway between oneself and our virtual self, as shown in Fig. 1. But Gombrich's case is special in that it is concerned with our own image. When we judge the size of our face, we judge an object placed at the vantage point from which the mirror is viewed. It would be a mistake to think that what is true here, namely that the image of the face has constant size independently of distance, should be true in general. Therefore one difficulty that people encounter may be that of appreciating the differences between different viewing conditions. Fig. 2 illustrates three qualitatively different conditions in terms of image change. As the observer or target moves away from the mirror, the visual angle subtended by the image on the mirror decreases, as shown. However, the image on the mirror seen by the observer, as it would be outlined by a felt-tip pen on the glass or measured by a ruler taped to the glass and read out by the observer, stays constant when the target is also the observer, but gets smaller when the target moves away from the mirror, and increases when the target stays at a fixed distance from the mirror while the observer moves.

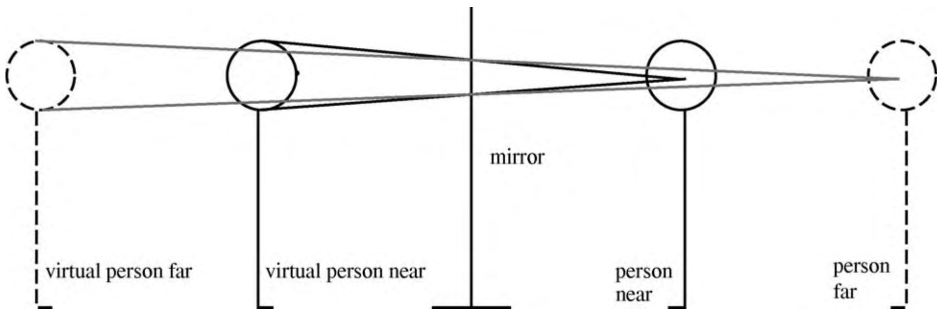


Fig. 1. Our own image size on a mirror stays constant, and is half the physical size. Consider the location of the mirror relative to the observer and the virtual observer in two cases, when the observer is near (solid line) or far (dashed line). The image on the mirror does not change.

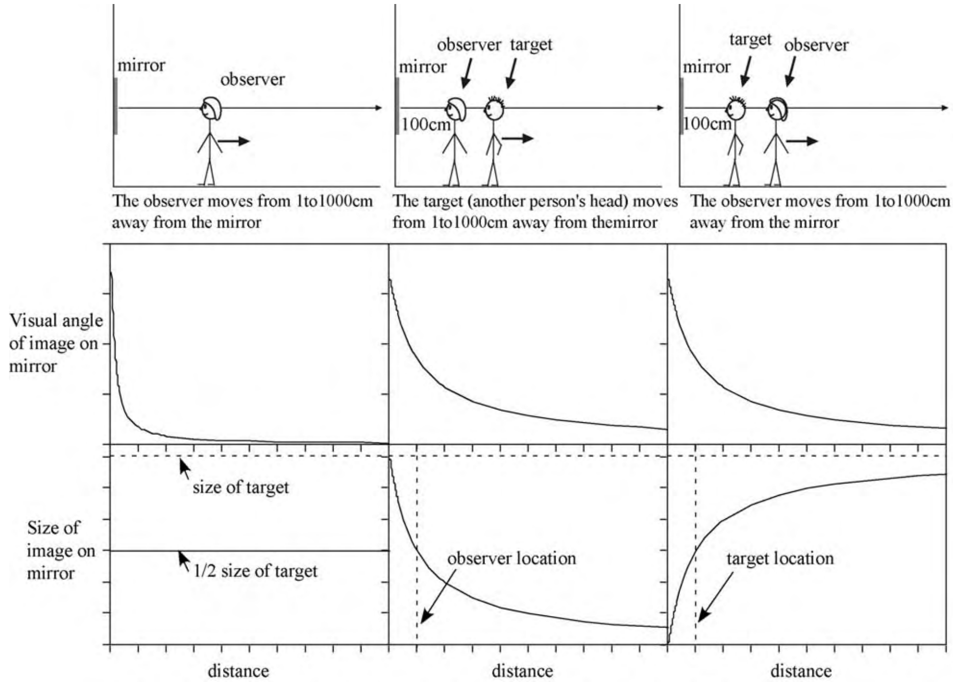


Fig. 2. The first column shows the relationship between own image size on a mirror and distance from the mirror, in terms of visual angle and physical size. The second and third columns show the case when the target is not at the same location as the vantage point. Size on the mirror decreases and increases, respectively. The target is 30 cm tall, and in the second column the observer is at 100 cm from the mirror and the target moves away from 1 to 1000 cm from the mirror. In the third column the target is at 100 cm and the observer moves. In the graphs numbers have been removed to focus on the pattern of change. When size increases, it will asymptotically equal the size of the target as observer distance becomes large compared to the distance of the target from the mirror.

Thus, the fact that the image of a face on a mirror is half its physical size is not a general principle, but this is not always clearly stated in the literature. Gregory (1997) for instance, discusses Velásquez's *Rokeby Venus* (1647–1651). In this painting Venus is shown from behind and her face is seen in a looking-glass supported by a cherub. The head in the mirror is slightly smaller than the head of Venus. Gregory says, "As the mirror is further away than the face, the image is with legitimate artistic licence at least twice the size it should be. This is a problem with using mirrors for painting or photography, as the image is disappointingly small when the glass is behind the subject." (p. 21). A similar argument is made by Mackavey (1980). After discussing Gombrich's demonstration, he suggests that the images painted in Velásquez's *Rokeby Venus* (1647–1651) Titian's *Venus with a mirror* (c. 1555) and Mary Cassatt's *Mother and Child* (c. 1905) are "troublesome".

2. An interlude about paintings and photographs

For the sake of argument, and consistently with this literature, we are going to consider the information in paintings as if they were photographs (for an argument about the fact

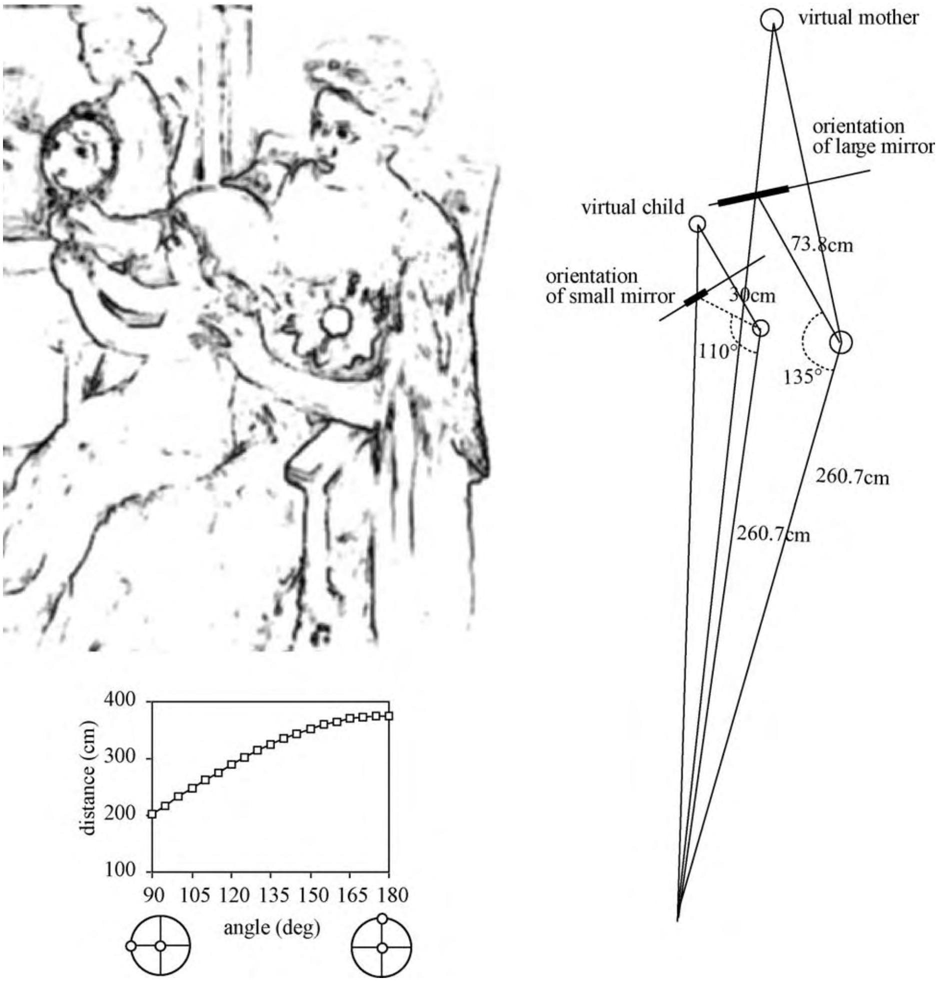


Fig. 3. Right, a line tracing of *Mother and child* by Mary Cassatt (c 1905). Left, a diagram showing the possible location of the child and the virtual child (small circles), and of the mother and virtual mother (large circles). This layout is derived from the measurement of the ratio of the images of the real and virtual heads, and on the basis of an estimate of three parameters. We used an estimate of 30 cm for the length of the child's arm, holding the mirror. We used an estimate of 110° for the arm connecting the child to the small mirror, and an estimate of 135° for the line connecting the mother to the large mirror. These values mean that the small mirror is slightly farther away in depth than the child, and the large mirror is also farther away than the mother (a value of 180° would place child and mirror on the same line). We did not estimate the distance of the mother from the mirror because we assumed that the mother is as far away from the vantage point as the child. The distance d from the child is then computed on the basis of the following formula: $d = 2k(r - \cos\vartheta)/(r^2 - 1)$ where d is the distance from the target, k is the distance between target and mirror, r is the ratio of the size of the target and the size of the virtual target as seen from the observer's vantage point, and ϑ is the angle formed by the line connecting the target and the mirror. For the child, $k = 30$, $r = 1.16$, and $\vartheta = 110$, therefore $d = 260.7$. For the mother, $d = 260.7$, $r = 1.5$, and $\vartheta = 135$, therefore $k = 73.8$. In the diagram the two systems (child and mother) are made to overlap to match the image in the painting, but the important measurements are the distances. This analysis shows how much information can be extracted from the mirror images. Moreover, although this analysis is only as accurate as its

that picture perception is not special see Cutting, 2003). In all of the examples cited above the image on the mirror is not the image of the observer, but the image that the observer sees of another person (target object, for instance Venus). This is similar to condition 3 in Fig. 2 (when the observer is farther away than the target). Under these circumstances the visual angle subtended by the head on the mirror depends on the distance of the observer. When the observer is relatively close to the mirror Gregory and Mackavey's point is well taken, but in general the relationship between the apparent heights of virtual and real targets varies vastly, from much less than half to one (asymptotically).

It is hard to know exactly the distance of the mirror from the person in paintings, and even harder to know the distance of the observer (although techniques to recover affine 3D information from single views do exist, e.g. Criminisi, Reid, & Zisserman, 2000). It is also important to note that in many paintings (for instance Titian's *Venus with a mirror*) the mirror does not seem farther than Venus, it is simply displaced to the side. This layout is interesting for another reason, namely the fact that most observers will take the image in the mirror to be a view that they share with the person in the painting. We have discussed this issue in another paper and we have proposed the term *Venus effect* for it (Bertamini, Latto, & Spooner, 2003).

A different approach to a painting is to estimate the distance of the target from the mirror and from this information work out the distance of the vantage point. It turns out that the size of the object is irrelevant and the distance of the vantage point can be derived from the ratio between the two sizes. When vantage point, target object and mirror are aligned the formula is simply

$$d = \frac{2k}{r-1}$$

where d is the distance from the target, k is the distance between target and mirror, and r is the ratio of the size of the target and the size of the virtual target as seen by the observer. The basic fact on which this formula is based is that for an object to half in apparent size the distance from the observer has to double. When the image is half the size of the target, the vantage point is $2k$ from the target and $4k$ from the virtual target. In the bottom corner of Fig. 2, this happens when the target is 100 cm away from the mirror and the observer is 300 cm from the mirror, and therefore the distance between observer and target is the same as the distance between target and virtual target. For photographs, if the image in the mirror is similar in size to the image of the target, this may be an indication that a telephoto lens has been used.

Fig. 3 uses Mary Cassatt's *Mother and Child* as a test case. In this painting two mirrors are present, a small one in the hand of the child and a larger one on the wall (the painting can be seen at http://www.nga.gov/). Target and mirror are not aligned so

estimates, the images on both mirrors are broadly compatible with one another and the vantage point distance is consistent with models and painter located in the same room. Finally, the inset shows what would have happened if we had used a different estimate for ϑ in the case of the child. For ϑ between 90° (child and mirror coplanar) and 180° (child and mirror aligned) distance would vary between 200 and 350 cm. Small errors in estimates of angles are therefore not catastrophic. With respect to errors in the estimates of k the formula shows that these would be linearly related to the estimate of d.

the formula needs to include the angle between the line of sight (from observer to target) and the mirror. In the example of the child, this is the angle of her arm away from us. The new formula is below and more details are in the figure caption and Appendix:

$$d = 2k\frac{r - \cos\vartheta}{r^2 - 1}$$

If the child is holding the mirror 30 cm away from her face, given that the ratio is 1.16 we can conclude that this is consistent with a vantage point about 260.7 cm away from the child. For the image of the mother the ratio is higher, about 1.5, as it should be because this mirror is farther back. If the mother's head is at the same distance from the vantage point as the child's head (260.7 cm) and given a ratio of 1.5, the larger mirror must be approximately 73.8 cm from the mother. These measurements have a degree of imprecision because of the estimates, but the exercise should convincingly show that the mirror image is not "troublesome" (Mackavey, 1980). A distance of about 250 cm is a natural distance at which to place the models. This painting also provides an example of the Venus effect, because most observers would describe it as showing a child looking at herself in a mirror. The Venus effect is a mistake in how people interpret (or fail to interpret) the fact that the observer has a different vantage point than the child (Bertamini, Latto, & Spooner, 2003). Geometrically, this painting is simply showing a child looking at the painter (or camera) using a small mirror. An analysis of the other two paintings cited in Mackavey (1980) shows that Titian's *Venus with a mirror* ($r=1.33$, $\vartheta=80$) is also compatible with a relatively close vantage point ($d=150$) whereas Velásquez's *Rokeby Venus* ($r=1.1$, $\vartheta=110$) requires a vantage point 6 or 7 m away.

There is an inevitable risk when taking paintings as examples. Many readers will feel that painters have no obligation to reproduce size accurately, and that there may be simple practical reasons to deviate from perspective reproduction. The role of perspective in the history of art is subject of a large literature (see Edgerton, 1980; Kemp, 1990; Kubovy, 1986) and some aspects of it are still controversial (Hockney, 2001; Tyler, 2002). These issues are not central to our argument. Neither the painters' intentions nor their knowledge of catoptrics are something we want to speculate about. We have analyzed a few paintings only because they have been referred to in the literature about size and mirrors (Gregory, 1997; Mackavey, 1980), but the context in which our analysis applies is that of mirrors in general (in paintings, photographs, and real life). The point is that size in mirrors is informative, but the literature cited supports the hypothesis that humans do not find this information salient, or in other words humans are tolerant to large variability in mirror images.[1] Some of our research has indeed confirmed experimentally how tolerant participants are to distortions in mirror images (Bertamini, Spooner, & Hecht, 2003;

[1] Visual art exploits the visual system's impressive power to interpret information about space and layout. In some cases visual art may also exploit the system's tolerance, an example would be the so-called robustness of perspective (Kubovy, 1986; Rosinski & Farber, 1980; Yang & Kubovy, 1999), another example would be the Venus effect. To see what Venus sees in a mirror we do not need to be looking over her shoulder (Bertamini, Latto, & Spooner, 2003; Bertamini, Spooner, & Hecht, 2003).

Croucher et al., 2002). This paper is different from some of our previous work because we are not testing human perception directly, instead we are exploring what people believe about the size of images in mirrors.

3. What people believe

After this aside about paintings we return to people's understanding of mirrors. It is possible that size constancy makes it difficult to appreciate what happens on the surface of a mirror, because observers see the world inside the mirror. After all a mirror surface can be described as a cross section of the optic array, similarly to the glass pane of a window. The counterintuitive increase in size in Fig. 2 is also true for a target located 1 m outside a window. It is possible that the mirror surface and the windowpane are *transparent* to our perceptual experience in both senses of the word. This is particularly true of our direct experience of mirrors, as opposed to a pictorial reproduction of a mirror, such as that discussed in relation to paintings. On similar grounds, but from a semiotics standpoint, Eco (1985) has argued that images in mirrors (but not their pictorial reproductions) do not qualify as signs.

In Experiment 1 we asked people to pretend that they are looking at a mirror and to draw the outline of their own head. The idea is that participants should rely on their experience of seeing themselves in mirrors, which for most people is probably a daily occurrence. Despite this amount of experience, we expect that participants will draw what they believe is an accurate estimate of their own head size, disregarding the fact that on the glass of the mirror the image must be smaller. On the other hand, it is possible that by imagining that they are in front of a mirror they will draw something smaller. People might rely on memory even if they are unaware of the exact behaviour of a mirror. Experiments 2 and 3 map people's beliefs about the behaviour of the image on the mirror, when they are asked to predict how it changes with distance. Even if people do not know the size of the image on the mirror, they may know the direction of change of the image with a change of viewpoint.

4. Experiment 1. Estimated head size

This experiment is closely related to Gombrich's (1960) observation, and also its discussion in Mackavey (1980). We asked two groups of naive participants to draw with a felt-tip pen on a sheet of paper. One group was asked to draw an outline of their own head as accurately as possible in terms of size. The other group was asked to pretend that the paper was a mirror, and to outline their own face as it would appear to them on the mirror. We kept everything the same for the two groups except for the instructions. Moreover, as a baseline, we also collected data using an estimation of head size. That is, we asked people to guess the size of their own head without looking at a mirror.

If Gombrich (1960) and Mackavey (1980) are correct, no significant difference between the two groups should be present. If people are unaware of what is the size on the mirror, they will respond to the pretend mirror question in exactly the same way as when asked to draw their head. However, people may not be aware of what the image size is, but if they can pretend that they are looking into a mirror, they might still be able to draw a smaller outline. If size constancy makes the head look of normal size inside the virtual space of the mirror, this is due to the location of the head at a distance. When participants pretend to look in a mirror they may pretend that the outline is farther than the paper itself. Therefore, if they were able to pretend that the outline is far away they should draw it smaller, because otherwise it would look disproportionately large.

There is another (related) reason why people may draw a small outline. Memory of mirror images may be affected by the fact that size perception compromises between the distance of the virtual person and the distance from the mirror itself. Parks (2001) has suggested that, by analogy with the moon illusion, when looking in a mirror we register two distances, one for the distal virtual head, and one for the image on the glass surface of the mirror. Given that the visual angle does not change, if distance is underestimated then size may be underestimated every time we look at ourselves in a mirror.

4.1. Method

There are three conditions: (a) drawing of head size ($N=21$, females $=11$, average age $=26.5$), (b) drawing of an outline on a pretend mirror ($N=21$, females $=11$, average age $=26$), (c) baseline estimation of head size ($N=55$, females $=30$, average age $=$ 31 years). We refer to these conditions respectively as Drawing, Pretend mirror and Baseline.

The data for the first two conditions (Drawing and Pretend mirror) were collected in the laboratory. Volunteers were placed in front a flip chart mounted on an easel on which a blank A3 sheet of paper was fixed (29.7×42 cm). They were given a felt-tip pen and asked to draw an outline of their own head (Drawing condition) or they were asked to pretend that the paper in front of them was a mirror and outline their own head how it would appear to them on the mirror (Pretend mirror condition). Volunteers were assigned randomly to either the Drawing condition or the Pretend mirror condition. Importantly, everything was the same in these two conditions except for the instructions. From the drawings, a horizontal and a vertical extent were measured and taken as the estimate of height and width.

The data for the Baseline condition were collected by means of a web form. In the form volunteers were asked to report their sex and age, they were asked to use a ruler and familiarize themselves with either centimeters or inches. Next, they were asked to estimate their head size without using the ruler. A diagram showed exactly what was meant by head height, namely the distance from chin to the top of the head. Finally they were asked to use the ruler and enter in the web form the actual height. Although specific issues exist for web-based experimentation, the existing literature suggests that the data collected in this way are reliable (for a collection of contributions on this topic see Reips & Bosnjak, 2001).

4.2. Results

Boxplots and medians are shown in Fig. 4. These values are deviations from the dimensions of the participants' heads. For the Pretend mirror condition these are *not* deviations from the correct answer. Because the correct answer is that the dimension on

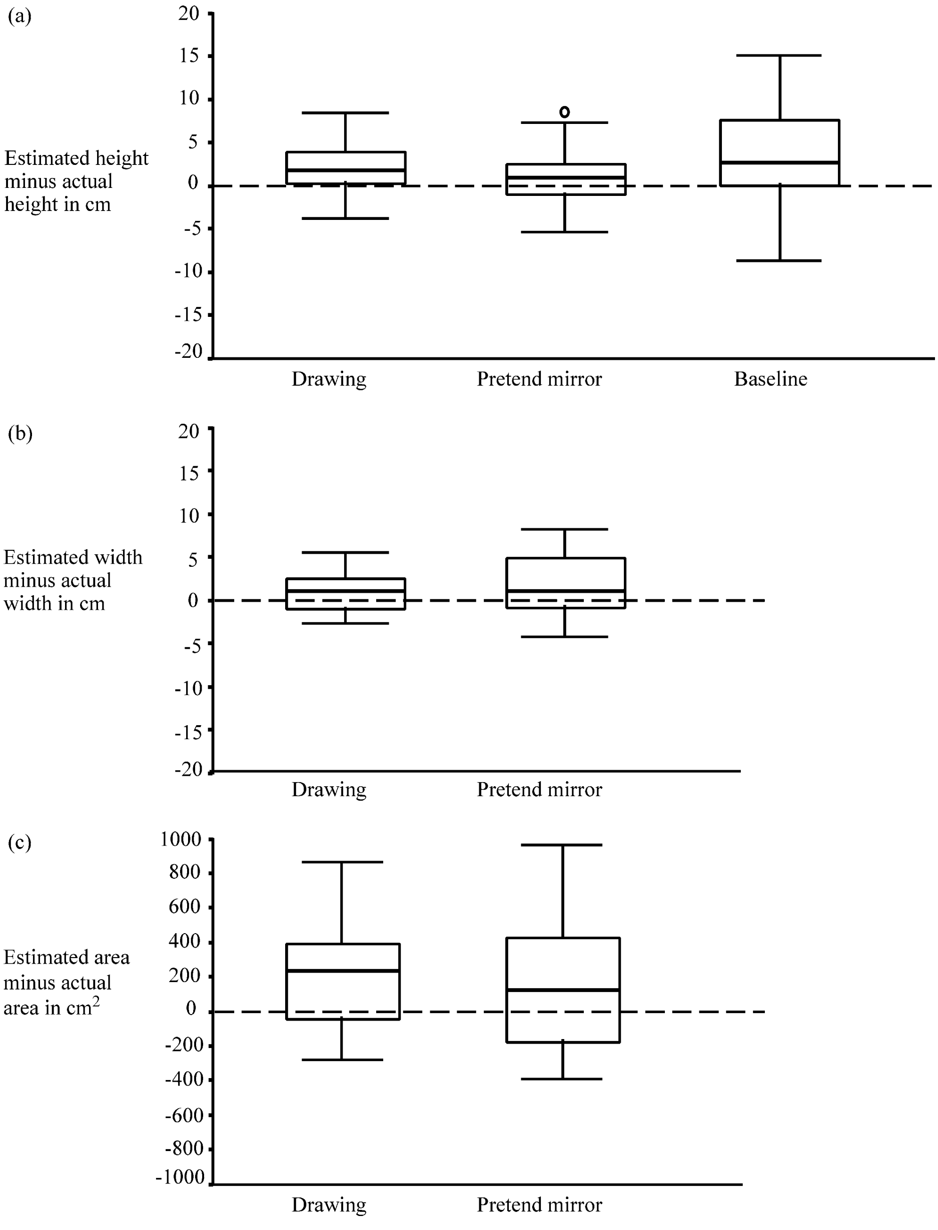


Fig. 4. Data from Experiment 1. (a) Deviations from head height in the responses when participants were asked to draw the outline of their own head, to draw the outline on a pretend mirror, or to estimate height in centimeters or inches (boxes are bound by the 25th and the 75th percentiles). (b) Deviations from head width when participants were asked to draw the outline of their own head, or to draw the outline on a pretend mirror. (c) Deviations from head area. Height and width were combined to compute the area of an elliptical outline.

the mirror is half the physical dimension of the head, the typical answer was far from accurate. However, it is interesting to compare the responses in the Pretend mirror and in the Drawing conditions, and therefore Fig. 4 shows deviations from physical size. Independent sample t-tests confirmed that there was no significant difference between the Drawing and Pretend mirror conditions for height ($t(40)=0.98$) width ($t(40)=0.42$) or area ($t(40)=0.33$). It seems that people have no access to the knowledge that their own head on the mirror is half its physical size. There was also no difference between the Baseline estimate of height and the Drawing ($t(74)=1.00$) and Pretend mirror ($t(74)=1.65$) conditions.

There was a tendency to overestimate head size. For height the mean overestimation was 2.08, 1.10 and 3.57 cm, respectively, for Drawing, Pretend mirror and Baseline. For both height and width, the mean deviation was significantly different from zero ($t(41)=3.20$, $P<0.01$ and $t(41)=2.95$, $P<0.01$). Although the overestimation was slightly larger for males, the difference between males and females was not significant. This overestimation of head size is consistent with the known overestimation of size in the literature on body size estimation (e.g. Shafran & Fairburn, 2002; Smeets, Smit, Panhuysen, & Ingleby, 1998; Werner, Wapner, & Comalli, 1957).

Experiment 1 confirmed Gombrich's observation. Although we mentioned reasons why people might be able to draw a smaller outline in the pretend mirror condition, this did not happen. In the introduction we said that both the fact that the image of our head is half its physical size and the fact that it does not change with distance are counterintuitive. In the next two experiments we turn to this second aspect. What do people believe about the behaviour of image size on mirrors as the vantage point moves closer or farther from the mirror?

5. Experiment 2. Separation of target and vantage point

In Experiment 1 we have found that people are unable to outline their own head on a pretend mirror. The second study used a different methodology. We explicitly asked people what happens to the size of the image on the surface of the mirror. Even though people are unaware that the size of their heads is half the physical size, it is possible that they are aware that size does not change with distance. The participants in the Pretend mirror condition did not volunteer the observation that the outline they were asked to draw would be different depending of the distance from the flip chart. However, they were simply asked to find the best distance from which to draw and they were not interviewed at length. As explained in the introduction, the independence from distance only applies to the situation where observers look at their own image. Therefore, we asked people to say whether the image on the mirror surface would stay the same, get smaller, or get bigger, in three different situations.

5.1. Method

A questionnaire was handed out in a classroom, students were asked to take part and told to answer three questions. To make the questions as clear as possible they were presented together with simple diagrams of the situation, similar to those at the top of

Fig. 6. For a first group of people ($N=139$, females$=110$, average age$=20.5$) the three questions and diagrams were presented on the same sheet of paper. For a second group ($N=49$, females$=32$, average age$=31.5$) the questions were separated so that each person would only be presented with one situation.

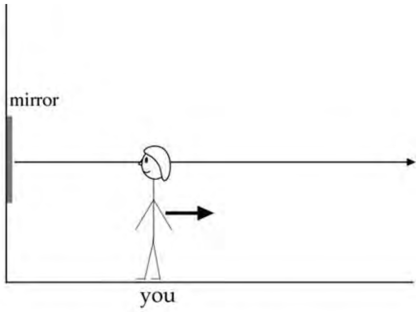
We will refer to the two groups as Experiment 2a and 2b. Experiment 2b was a control for a possible effect of the within-subjects design. Moreover, for this second group the question was written in detail to ensure that no ambiguity was present about the fact that the question was about the image on the mirror. The full wording of the questions and the diagrams used in Experiment 2b can be seen in Fig. 5. The question specifically mentioned the image that could be outlined with a felt-tip pen on the glass surface. Finally, in Experiment 2b participants were explicitly asked to use the space left on the page to write down an explanation of how they came to their answer.

5.2. Results

Results can be seen in Fig. 6. The data from the two groups are presented side-by-side in the same bar graph. A large proportion of participants believe that the image on the mirror grows smaller as the observer moves away (85.6 and 87.5% in Experiments 2a and 2b). A similar proportion of participants believes that the same happens when the target is another person (89.2 and 86.4%). As this is correct, this may be the source of the incorrect answer to the first question. Responses were more spread out to the third question, with 66.2 and 80% of the participants claiming that the size of the image will stay the same. This is interesting for at least two reasons. (a) It is reasonable to suspect that when faced with a difficult question people resort to the piece of knowledge about the fact that things appear smaller at larger distances. In other words perhaps our participants are mistakenly responding to the behaviour of the visual angle (see Fig. 2). Because of this possibility it is interesting that most people said that the size remains equal in condition three, even though the vantage point clearly moves away from both the mirror and the target. (b) It is possible that the mirror is thought of as a device that captures an image of the target on the basis of the location of the target, but independently of the location of the observer, as if the mirror acts as a camera. What the observer does is simply to view the product of the interaction between the mirror and the target.

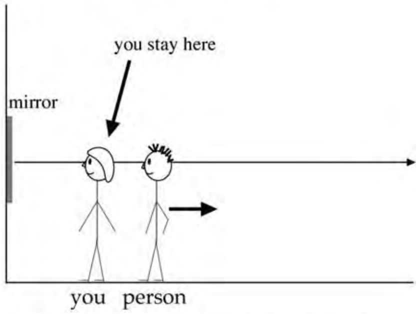
To understand better the line of reasoning adopted by our participants, in Experiment 2b participants were asked to take time to write on paper how they reached their conclusion. The large majority of people who were presented with question one and two, simply reported that things get smaller with distance (87.5% for question 1 and 86.4% for question 2). Interestingly one person who claimed that the image would remain the same in question two, stated that what matters is the observer, and as the observer stays stationary so the image must not change size. However, as can be seen in Fig. 6, this answer was the exception and not the rule. The more interesting condition was question three. Twelve people out of 15 (80%) claimed that, as the target does not move, so the size of the image will stay the same. This confirms the hypothesis that people tend to disregard the location of the observer. This is also consistent with what was found by Croucher et al. (2002) and Bertamini, Spooner, and Hecht (2003). Their findings relate to the ability of people to predict when something becomes visible in a mirror. In those studies there was

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 on the mirror. Please think carefully about what happens to your image. Does it:



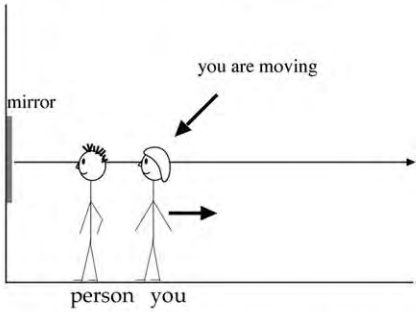
A. stay the **same size** - the size of the image of your face is the same size as the felt-tip outline
B. get **smaller** - the size of the image of your face is smaller than the felt-tip outline
C. get **bigger** - the size of the image of your face is larger than the felt-tip outline

Imagine you are facing a mirror on a wall, looking at the image of another person in the mirror. Imagine drawing on the mirror with a felt-tip pen an outline that is the same size as the other person's face as it appears to you on the mirror. Now imagine he moves back (away from the mirror) while you stay in the same position. Please think carefully about what happens to that person's image as you see it now. Does it:



A. stay the **same size** - the size of the image of the other person's face is the same size as the felt -tip outline
B. get **smaller** - the size of the image of the other person's is smaller than the felt-tip outline
C. get **bigger** - the size of the image of the other person's is larger than the felt-tip outline

Imagine you are facing a mirror on a wall, looking at the image of another person in the mirror. Imagine drawing on the mirror with a felt-tip pen an outline that is the same size as the other person's face as it appears to you on the mirror. Now imagine you move back (away from the mirror) while the other person stays in the same position. Please think carefully about what happens to that person's image as you see it now. Does it:



A. stay the **same size** - the size of the image of the other person's face is the same size as the felt -tip outline
B. get **smaller** - the size of the image of the other person's face is smaller than the felt-tip outline
C. get **bigger** - the size of the image of the other person's face is larger than the felt-tip outline

Fig. 5. Extended wording for the questions used in Experiment 2b, with diagrams. Each question was presented on a separate page, and participants were asked to use the blank space at the bottom to explain in words the line of reasoning that they had followed.

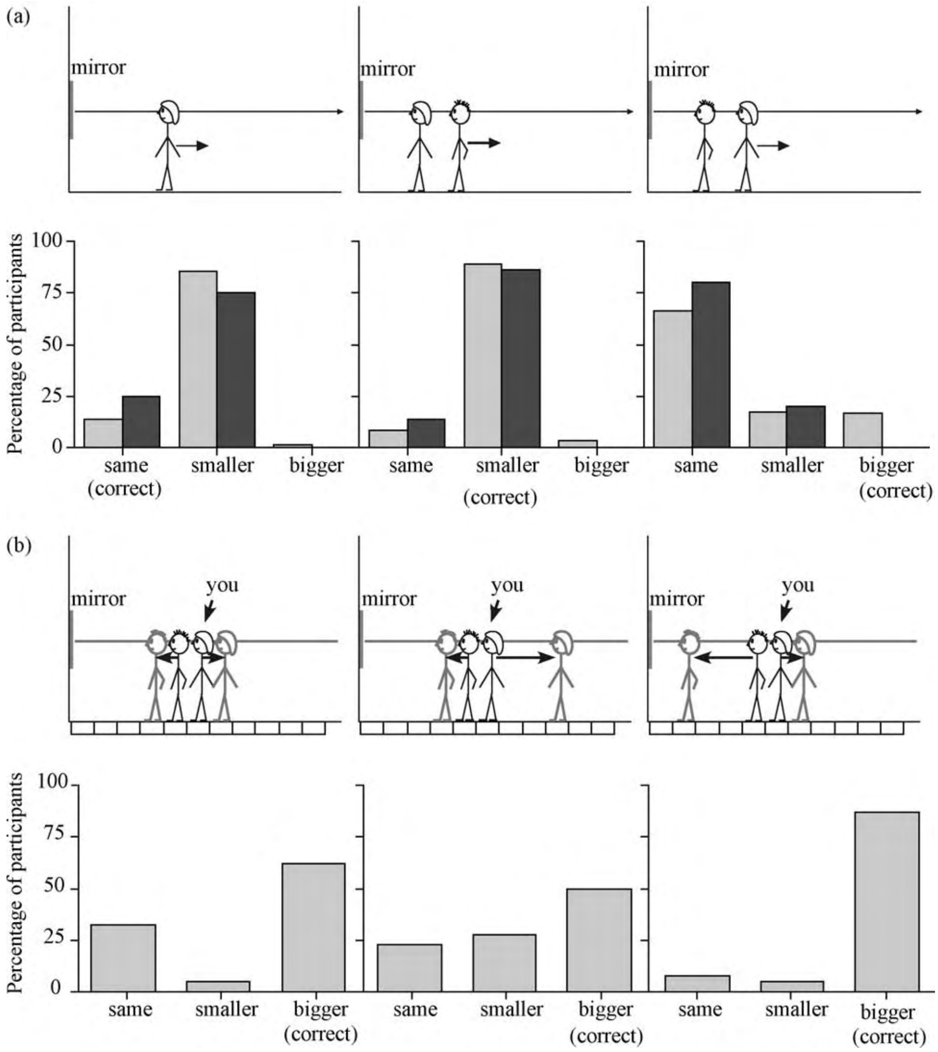


Fig. 6. (a) Frequency breakdown of responses for Experiment 2. Lighter bars show data from 139 participants who answered all three questions. Darker bars show data from 49 participants who were asked to answer question 1 ($N=12$), question 2 ($N=22$) or question 3 ($N=15$). All 49 participants were also asked to comment on how they came to their answer, see text for details. (b) Frequency breakdown of responses for Experiment 3. See text for an analysis of the trend within participants.

a tendency to overestimate what is visible but also a failure to factor in the location of the observer.

The fact that some participants in both Experiments 2a and 2b responded “smaller” to the viewer-moving scenario does suggest that, for them at least, viewer motion was important, particularly since that response cannot be attributed to a momentum effect from prior responses to the other conditions (in which “smaller” was a popular response) in the case of Experiment 2b. The effect of viewer motion may be, in turn, attributed to an increase in viewer-to-mirror distance or to an increase in the total distance (viewer-to-mirror-to-target). In addition, we note that some “bigger” responses were given to the viewer-moving scenario, but such responses were not found in participants who were only given this scenario. Of the 23 participants who did respond “bigger”, 16 had responded “smaller” to both of the two prior conditions, suggesting a compensation effect.

6. Experiment 3. Observer, target and total distance

To further verify the importance of target-to-mirror and total (viewer-to-mirror-to-target) distance, three new scenarios were presented to a new set of participants. In all scenarios both viewer and target were said to move: (1) the viewer moved back and at the same time the target moved forward an equal amount, (2) the viewer moved back a greater distance than the target moved forward and (3) the viewer moved back but the target moved forward a greater distance (see Fig. 5). Under the assumption that amongst participants both target and total distance are believed to be important it is predicted that more than a random chance of participants would show one of two specific patterns of responses across the three scenarios. That is, participants whose decisions were influenced by target distance alone, would respond “bigger” to all three scenarios. Participants who were influenced by total distance alone, would respond “same, smaller, bigger” to the three scenarios, respectively.

Apart from these two patterns, it is also interesting to consider whether participants are influenced by both beliefs equally. In this case they would produce the pattern “bigger, (same), bigger”. However, the “same” prediction with this pattern must be parenthesised because it is a weak one, “bigger” and “smaller” are possibilities depending on the relative weights given to the two aspects of the situations. We also note that if participants were influenced by observer distance alone, they would respond “smaller” to all three scenarios, but based on the results from Experiment 2 we do expect this pattern to be infrequent.

6.1. Method

A questionnaire was handed out to participants, who were either students or staff at the University ($N=40$, females $=26$, average age $=31$). None of the participants had taken part on the previous experiments, and there was no time pressure on answering the questions.

6.2. Results

Overall percentages (not the patterns across individuals) can be seen in Fig. 6. Of the two predicted patterns, 15 (37.5%) participants showed the pattern expected if only target distance was important, and 8 (20%) the pattern expected if only total distance was important. By contrast, no subject behaved as though only the observer's distance was important ("smaller", "smaller", "smaller"), and only 3 (7.5%) responded as though both factors were important and equally weighted. Thus, although not all participants' responses fit one of the two patterns, a satisfactory 57.5% of them did, which is higher than it would be expected by chance (binomial test, $P<0.001$). Moreover, the two larger groups based their responses on target distance or on total distance, showing that people have a degree of self-consistency, even though different conclusions are reached by different people.

7. Discussion

In this paper we have analysed the issue of how images change in size on the surface of a mirror. The canonical situation in which we observe our own image is known to be interesting because of image size if half the physical size of our body and independent of distance. However, in other situations image size varies (Fig. 2). In the Appendix we demonstrate that the ratio between apparent size of a target and apparent size of a virtual target is informative about the distance of the vantage point. Moreover, when two targets are present in front of the same mirror information is also available about relative distance of the targets and therefore relative size. Work is ongoing in our laboratory to see whether human observers can use this type of information, but in this paper we focus on people's understanding of the behaviour of the image on the mirror.[2]

We have found limits to people's knowledge of mirrors with respect to image size. We can summarise our findings in three points. (a) As Gombrich (1960) pointed out, we are unaware that the image of our head on a mirror is half its physical size, and when asked people draw on a pretend mirror the estimated physical size (Experiment 1).

(b) Most people believe that images on mirrors become smaller when the target moves away, and that they remain the same when the target remains still while the observer moves away (Experiment 2). It seems plausible to suggest that participants hold to a general belief that things appear smaller at larger distances of the viewpoint. This would explain the mistaken belief that our own image on mirrors gets smaller as we move away. However, this belief implies that when the target is stationary and the observer moves away the response would again be that the image gets smaller. This was not the case as a clear majority believes that in this case the image stays constant, suggesting that the critical factor was the location of the target.

(c) The distance of the target object is an important factor in determining the change in image size. A large proportion of people (37.5%) consistently relied on this principle when presented with a set of difficult questions in which both target and observer moved (Experiment 3). The fact that people may focus on a single factor is consistent with what Proffitt and Gilden (1989) have suggested with respect to understanding motion. They pointed out that people reason fairly well about particle motion but not about extended-body motion and the difference is the dimensionality of the problem. In addition, it appears

[2] There is a superficial similarity between the information that can be gathered from reflections and that gathered from cast shadows (Casati, 2003; Kersten, Knill, Mamassian, & Bülthoff, 1996). However, serious differences also exist: unlike reflections in mirrors the shape and size of shadows depends on location and distance of the source of illumination.

that for the motion of objects as well as for images on mirrors the high degree of familiarity with these phenomena does not lead to an understanding of the underlying principles.

There is no doubt that our questions were difficult. One way to summarise our results is to say that participants have difficulty when they need to understand what changes with a change in vantage point. We mentioned in the introduction that it is well known that observers are highly tolerant to looking at pictures from an incorrect vantage point, both in the case of static snapshots and movies on television and at the cinema (Pirenne, 1970; Rosinski & Farber, 1980). However, there was a systematic pattern in the responses here that cannot be explained simply by tolerance or lack of knowledge. As mentioned before, one might have expected that people always resort to a belief that size gets smaller as the observer moves away, but this was not the case. The main variable that people seem to focus on is the relationship between target and mirror. This is entirely consistent with other findings in naive optics. For instance, Croucher et al. (2002) used a paper-and-pencil task in which participants had to predict when a character would first be able to see herself in a mirror while walking into a room. They found no difference between the condition in which the character was walking into a room and a condition in which the character was stationary inside the room while a target (a cat) walked into the room. What was critical was the relationship between the target and the mirror.

In the area of spatial reasoning it has long been recognised that we need to separate changes due to movement of the observer and changes due to rotation of the object or scene. Imagining changes due to self-motion is generally easier than imagining changes due to object rotation (Amorin & Stucchi, 1997; Creem, Wraga, & Proffitt, 2001; Huttenlocher & Presson, 1973). Similarly, work on scene recognition has found that viewpoint changes have little effect on detection of layout changes compared to equivalent orientation changes (Simons & Wang, 1998; Wang & Simons, 1999, but things may be different with implicit measures of performance, see Chua & Chun, 2003). Prima facie it seems that these results are at odds with our findings because they show good performance in imagining or taking into account viewpoint changes. But there is a possible reconciliation. When observers have to notice what has changed in the scene ignoring the changed vantage point they are behaving as if viewpoint information has been discarded (or updated).[3] Viewpoint specific information is accidental in that it is not information about the objects or the scene itself. If discarding this information and building a viewer independent representation is an process that the visual system engages in (Kersten, Mamassian, & Yuille, 2004) then perhaps people find it difficult when the question is not about what has changed in the scene, but what has changed with a change of viewpoint. These are exactly the type of questions we asked.

In conclusion, work on naive optics has documented limits on people's understanding of the behaviour of mirrors. In particular, people tend to overestimate what is made visible

[3] We mentioned already the situation where observers watch a photograph or a film screen from a vantage point different from that of the camera. Although distortions should be introduced by such mismatch, by and large observers never report them. It has been suggested that this is the result of a compensation process (Goldstein, 1987; Kubovy, 1986; Rosinski & Farber, 1980; Yang & Kubovy, 1999, but see Cutting, 1987). Similarly, an automatic updating has been suggested as the reason why memory for layout is good after viewpoint changes (Simons & Wang, 1998). However, the degree to which this spatial updating is truly automatic is still controversial (Waller, Montello, Richardson, & Hegarty, 2002).

by a mirror and they may also misjudge the left–right location of objects in mirrors (Bertamini, Spooner, & Hecht, 2003; Croucher et al., 2002). People also misjudge what other people might see in a mirror (Bertamini, Latto, & Spooner, 2003). Here we have also shown that people use an incorrect principle in predicting changes in image size. It appears that mirrors are treated as devices that capture an image and therefore the size of the image depends mainly on the distance of the target, whilst the location of the observer (vantage point) is to a large extent disregarded.

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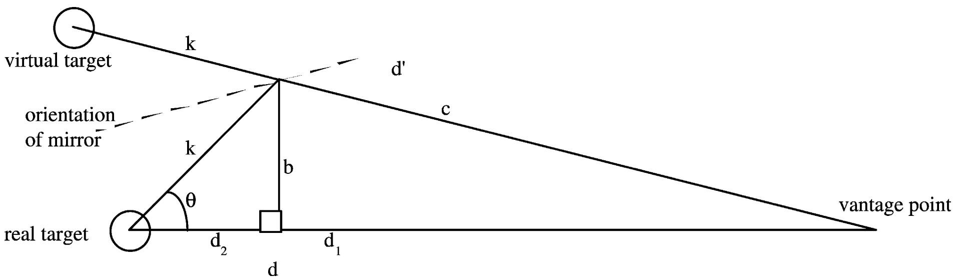
Appendix

The starting point in the analysis is that a real target and a virtual target inside a mirror are objects of exactly the same physical size. Therefore the ratio between the height of their two images (r=image/image$'$) is inversely related to the ratio between their two distances from the same vantage point ($r = d'/d$). We also know that $d' = d + 2k$, where k is the distance between target and mirror. This is because the virtual target is at the same distance inside the mirror as the real target is from the mirror. From this the first formula is derived (from left to right)

$$r = \frac{d + 2k}{d} \quad r = \frac{2k}{d} + 1 \quad d = \frac{2k}{r - 1}$$

When the mirror is not aligned with the target we need to know the angle θ, as well as k. The diagram below shows that d can be decomposed into d_1 and d_2, and $d' = c + k$ is the distance to the virtual target inside the mirror. Note that $d' = d + 2k$ is not true any longer. We start by expressing c in terms of d and k



$$c^2 = b^2 + (d - d_2)^2$$

Since $b = k \sin\theta$ and $d_2 = k \cos\theta$ we can write

$$c^2 = k^2 \sin\theta^2 + (d - k\cos\theta)^2 \qquad c^2 = k^2 + d^2 - 2dk\cos\theta$$

$$c = \sqrt{k^2 + d^2 - 2dk\cos\theta} \qquad d' = k + \sqrt{k^2 + d^2 - 2dk\cos\theta}$$

Next we express r (as before) as the ratio between the distances from the vantage point to the virtual and the real target

$$r = \frac{k + \sqrt{k^2 + d^2 - 2dk\cos\theta}}{d}$$

$$(rd - k)^2 = k^2 + d^2 - 2dk\cos\theta \qquad r^2d^2 + k^2 - 2rdk - k^2 - d^2 + 2dk\cos\theta = 0$$

$$(r^2 - 1)d^2 + 2dk(\cos\theta - r) = 0 \qquad d^2 = \frac{-2dk(\cos\theta - r)}{r^2 - 1}$$

$$d = 2k\frac{r - \cos\vartheta}{r^2 - 1}$$

This formula is more general, and when $\vartheta = 180°$ the simper version can be derived

$$d = \frac{2k(r+1)}{(r-1)(r+1)} \qquad d = \frac{2k}{r-1}$$

Another interesting aspect of this situation is that some relative information may be available even without any estimation of k. Consider the case of two objects (A and B) at unknown distances (d_A and d_B) in front of a mirror. Let us assume that the mirror is in the fronto-parallel plane. Therefore

$$d_A + k_A = d_B + k_B \qquad d_A - d_B = k_B - k_A$$

From what we have seen before, we can write k as a function of r and d (for both object A and object B)

$$k_A = \frac{r_A - 1}{2}d_A \qquad k_B = \frac{r_B - 1}{2}d_B$$

We can then replace and have a formula in which k does not appear

$$d_A - d_B = \frac{r_B - 1}{2}d_B - \frac{r_A - 1}{2}d_A \quad d_A = \frac{r_B + 1}{2}\,\frac{2}{r_A + 1}d_B \quad d_A = \frac{r_B + 1}{r_A + 1}d_B$$

This means that if two values of r are available for two objects, then the ratio of their physical heights and the ratio of their distances from the same vantage point are available without the need to estimate neither k_A nor k_B.

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