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Testing the Egocentric Mirror-Rotation Hypothesis

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Abstract

Although observers know about the law of reflection, their intuitive understanding of spatial locations in mirrors is often erroneous. Hecht *et al.* (2005) proposed a two-stage mirror-rotation hypothesis to explain these misconceptions. The hypothesis involves an egocentric bias to the effect that observers behave as if the mirror surface were rotated by about 2° to be more orthogonal than is the case. We test four variants of the hypothesis, which differ depending on whether the virtual world, the mirror, or both are taken to be rotated. We devised an experimental setup that allowed us to distinguish between these variants. Our results confirm that the virtual world — and only the virtual world — is being rotated. Observers had to perform a localization task, using a mirror that was either fronto-parallel or rotated opposite the direction of the predicted effect. We were thus able to compensate for the effect. The positions of objects in mirrors were perceived in accordance with the erroneous conception that the virtual world behind the mirror is slightly rotated and that the reconstruction is based on the non-rotated fronto-parallel mirror. A covert rotation of the mirror by about 2° against the predicted effect was able to compensate for the placement error.

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Keywords

Mirror reflection, rotation, localization, naive optics

1. Introduction

Naive beliefs about the real-world location of objects seen in mirrors are often surprisingly inaccurate (Croucher *et al.*, 2002; Gregory, 1998; Lawson and Bertamini, 2006). For instance, when asked for the location where, upon entering a room, they would first see a given object in a wall-mounted mirror, observers misjudge the mirror image to appear much sooner than it actually does. Perceptual judgments fare better but they remain systematically biased (Bertamini *et al.*, 2003; Hecht *et al.*, 2005; Hecht and Brauer, 2007). The current paper puts to the test an explanation for this bias, which is grounded in the peculiarities of picture perception. The ex-

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planation suggests that observers misperceive the virtual world to be rotated to be more orthogonal than is actually the case, as described by Hecht *et al.* (2005) in their two-stage mirror-rotation hypothesis.

The rationale for this hypothesis is the so-called Mona Lisa effect typically found in pictures. Within limits, a portrait painting in an art gallery appears to change its orientation such that the painting remains orthogonal with respect to the observer's line of sight, no matter where the observer moves (e.g. Gibson, 1954; Goldstein, 1987). That is, the picture surface and the content of the picture have different egocentric tilts with respect to the observer. The canvas is perceived correctly whereas the portrait appears to follow the observer. If mirrors preserve some picture-like qualities, then it is conceivable that the Mona Lisa rotation effect carries over to mirrors.

We have examined this egocentric mirror-rotation hypothesis by way of a task to locate objects in the real world entirely on the basis of their mirror images. To do so, we followed a localization method used by Hecht *et al.* (2005). It involves the perceptual examination of reflected objects in a mirror. Then the mirror and objects are removed and the observer is asked to take the real-world objects he had just seen and put them in their original locations. The present study derives and tests the predictions and implications of the possible variants of the mirror-rotation hypothesis.

1.1. Rotation of the Virtual World, the Mirror, or Both?

The Mona Lisa effect cannot be directly transposed to mirror perception. The situation is more complex. A test of the seemingly simple mirror-rotation hypothesis turns out to require several sub-hypotheses. Depending on the mirror tilt with respect to the observer, objects to the left of the observer's line of sight might behave differently than objects to the right. Hecht *et al.* (2005) found a systematic tendency to place the reconstructed object too far to the outside and too close to the mirror. However, this result may have come about in several ways. It could be caused by a perceptual bias or by a reconstructive bias. That is, the virtual world could appear rotated when observers perceive it in the mirror, or the mirror's tilt could be misjudged during the reconstruction of the object. These two cases lead to different predictions. Four different cases are imaginable depending on whether we assume a mental rotation of the virtual world, of the mirror, of both, or no rotation at all. Table 1 summarizes the complete set of interpretations.

Note that for each of these cases, the mirror-rotation hypothesis always involves a two-stage process (see Hecht *et al.*, 2005). In the perception stage (1), the virtual object is perceived and located behind the mirror. In the reconstruction stage (2) the object is being located in the world on the basis of the remembered virtual object. Depending on whether or not the observer introduces a bias in stage 1 and/or in stage 2, the following scenarios are possible.

(a) *Dual rotation*. This version states that in the perception stage the virtual world is misperceived as being rotated counterclockwise (for objects located on

Table 1.
Four variants of the mirror rotation hypothesis

Rotation of the mirror (stage 2)	Rotation of the virtual world (stage 1)	
	Yes	No
Yes	Dual rotation	Mirror rotation
No	Virtual world rotation	Veridical perception (no rotation)

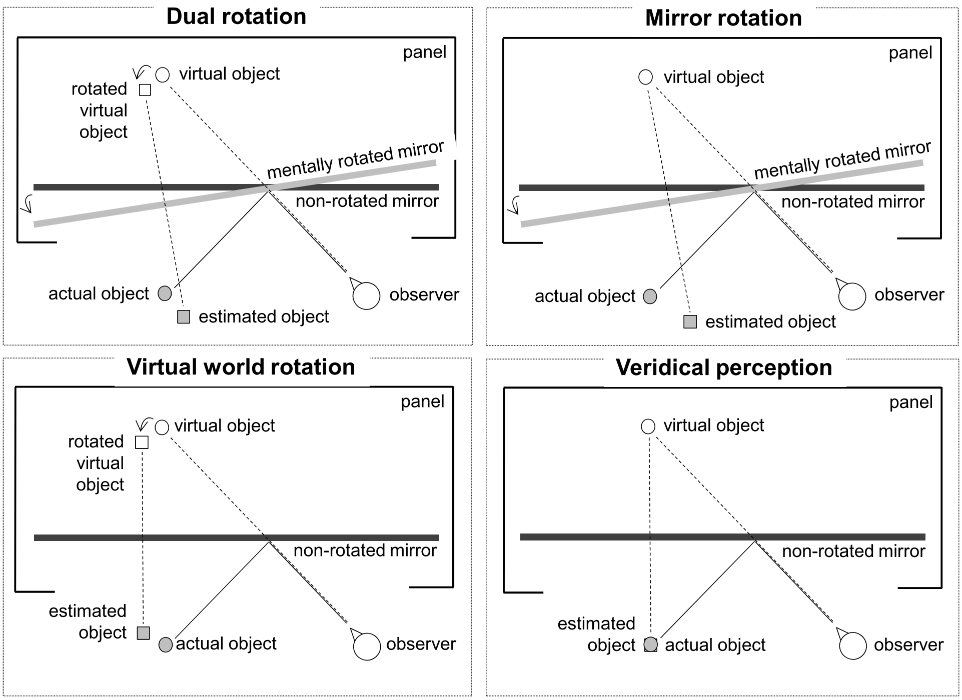

Figure 1. Illustration of the four versions of the mirror rotation hypothesis, each showing the mirror, the object and the observer. 'Dual rotation' involves the perceived rotation of both the virtual world and the mirror, 'mirror rotation' involves a rotation of the mirror only. 'Virtual world rotation' assumes a rotation of the virtual world only, and 'veridical perception' means that neither the virtual world nor the mirror is rotated. In each panel the actual object is represented by the grey circle, the virtual object by the hollow circle, the virtual rotated object by the hollow square, and the estimated object by the grey square. Note that for illustrative purposes the distances shown here are not drawn to scale.

the observer's left). This is illustrated in the upper, left panel of Fig. 1. That is, the virtual object (hollow circle) moves to the outside and closer to the mirror (hollow square). In stage 2 the observer reconstructs the object in the real world based on the rotated virtual object (hollow square). To do so, the observer uses the mirror which is mistaken to be rotated toward a position more orthogonal with respect to the observer's line of sight. Consequently, the object is being located too close to the observer and too far away from the mirror (grey square). Note that these predictions would contradict earlier findings by Bertamini *et al.* (2003), Hecht and Brauer (2007) and Hecht *et al.* (2005).

(b) *Mirror rotation*. This version of the hypothesis states that only the surface of the mirror but not the virtual world is misperceived. The simple mirror-rotation hypothesis maintains that this is in fact the case and that the would-be mirror rotation causes a reconstruction bias on the order of a few degrees of visual angle. In this version of the hypothesis the virtual object does not rotate but it is reconstructed on the basis of a rotated mirror. The prediction is that the object will be placed too close to the observer and too far away from the mirror (grey square). This version is illustrated in the upper right panel of Fig. 1.

(c) *Virtual world rotation*. Here only the virtual world is being mentally rotated. As in the first version (a), the virtual world — including the virtual object — is assumed to be mentally rotated counterclockwise in stage 1. Then the rotated virtual object is used to reconstruct the object in the real world based on the non-rotated, fronto-parallel mirror in stage 2. The difference between this version of the mirror-rotation hypothesis and the other ones becomes apparent in Fig. 1 (lower, left panel). It is able to explain the consistent outward bias as well as the misjudgment of objects to be too close to the mirror, which have been observed in earlier experiments. Therefore this version of the hypothesis is put to a test in the present study.

(d) *Veridical perception (no rotation)*. For completeness sake, it is possible that (a)–(c) are mistaken. In theory neither the mirror nor the virtual world could be misperceived. The observer perceives the virtual object and reconstructs it on the basis of the non-rotated, fronto-parallel mirror and accordingly should estimate the location of the actual object correctly (see lower, right panel of Fig. 1). Such perfect performance has never been found in the earlier experiments.

The virtual world rotation version (c) of the hypothesis seems to be the best alternative to explain all or most of the earlier findings. Let us take a closer look at the two-stage process that is involved. First the observer sees the reflection of the real object in the mirror according to the laws of optics. In stage 1 (perception phase), the observer mistakes the virtual world in the mirror to be rotated. If the observer is seated on the right side in front of the mirror, he/she would perform a counter-clockwise mental rotation of the virtual world. And accordingly, if the observer is placed on the left side of the mirror, he/she would perform a clockwise mental rotation. The virtual position of the object in the mirror — which is to be remembered — changes as a function of this mental rotation: for an observer sitting on the right side of the mirror the object is displaced to her left. For an observer sitting on the left side of the mirror the object is displaced to the right. In other words, the object appears to be farther to the outside than is the case.

In stage 2 (reconstruction phase) the observer now uses this shifted, remembered image for the localization task, while at the same time assuming that the now concealed mirror-surface is planar and non-rotated. Thus, if the mirror has not changed, but the reflection has moved away from the observer, an outward-bias in the subsequent localization task should occur. That is, for the observer sitting on the mirror's right side the object should be placed too far to the left in real space. When sitting on the mirror's left side, the object should respectively be placed too far to the right. We call this an outward displacement. Note, that this virtual world rotation hypothesis (in opposition to the other variants) consistently predicts an outward bias independent of the relative positions of the mirror, the observer, and the object!

In summary, this version of the rotation hypothesis describes how an object is seen in a mirror following a mental rotation of the virtual world seen in it (including the object). The mental rotation makes the virtual object shift to the outside and closer to the mirror. Finally, this shifted virtual object is reconstructed assuming the mirror to be in its fronto-parallel orientation, resulting in a displacement error too far to the outside and too close to the mirror.

Based on the virtual world rotation hypothesis, the process can also be tracked in reverse order. That is, the horizontal and vertical coordinates of the observers' judged localization can be used to calculate the exact would-be rotation of the virtual world, which would move the reflections of the original objects in such a manner as to coincide with the judged positions. We applied this reconstruction of the would-be virtual world rotation (according to hypothesis (c)) to the data obtained in the fourth experiment by Hecht *et al.* (2005) and found an average angle of mental rotation of about 2°. Their data can be explained by a mental rotation of 2° followed by a reconstruction as described by the virtual-world rotation version of the egocentric mirror-rotation hypothesis. Most importantly, the mental rotation appears to be rather robust across situations. This allowed us to make predictions about the expected placement errors in our experiment.

Previous studies could not distinguish between these four versions of the hypothesis and did not describe the process in detail. In a nutshell, the 'mirror rotation' and the 'dual rotation' versions predict that objects on the contra-lateral side of the mirror should produce an inward error of reconstruction (Fig. 1, grey squares in the upper panels), whereas the 'virtual world rotation' version predicts an outward bias in the above cases. Finally the 'veridical perception' version predicts unbiased performance.

1.2. Sagittal and Lateral Parameters in Localization Tasks

Higashiyama (2004) found that observers are able to perform simple localization tasks with mirrors when it comes to the sagittal plane. For instance, their observers had no trouble in realizing that an object placed 20 m behind them was much farther away than an object placed only 10 m behind them, both merely viewed through a mirror. Note that such distances in front of or behind the observer are largely affected by perspective. The lateral placement is less affected by perspective. We aimed to investigate the ability of localizing objects seen in a mirror including both the sagittal and the lateral plane. The latter has often been neglected in research probably because a decisive role of perspective has been presupposed. The great advantage of assessing sagittal and lateral data is the possibility of computing the angles of virtual lines of sight.

1.3. Aim of the Current Experiment

Which version of the mirror-rotation hypothesis can explain the findings? A setting with a fronto-parallel mirror should allow us to decide between the four versions. Can a rotation of a mirror around its vertical axis improve the ability to locate objects in the world on the basis of their mirror images? If the 'virtual world rotation' version of the mirror-rotation hypothesis is correct, then a real clockwise rotation of the virtual world of 2° should compensate the mental rotation as long as the observer assumes the mirror to be fronto-parallel. A clockwise mirror rotation of 2° would cause such a rotation of the virtual world and thus cancel the placement errors found with a perfectly fronto-parallel mirror (Hecht *et al.*, 2005).

Thus, a rotated mirror causes the reflection (or virtual world) to be shifted: a clockwise real rotation of the mirror makes the reflection shift horizontally to the observer's right side, whereas a counter-clockwise real rotation makes it move to the left side. If, for example, the mirror is placed at the left side of the observer and the target is placed behind her on the left side, the following will happen during a clockwise real mirror rotation: the reflection moves to the right side, which is to the centre of the mirror and laterally in the observer's direction. Now assume that the observer is unaware of the manipulated real rotation because the rotated mirror is placed behind a frame or window. The observer is then likely to perceive the mirror-surface as parallel to the unrotated frame. In this case we would expect the following: with the mirror not having changed — from the observer's point of view — and with the reflection appearing closer to the observer, her assessment of localization should be shifted laterally in her direction, towards the right compensating outward errors. The current experiment tested whether this is in fact the case. For economic reasons, we investigated only real mirror rotations to one side assuming that the results would hold symmetrically for the other side. Hecht *et al.* (2005) found that errors in localization tasks appeared similarly on both sides.

2. Method

2.1. Observers

Eleven university students and one working adult (5 women, 7 men, age ranging from 19 to 35) volunteered to participate. All had normal or corrected vision.

2.2. Apparatus, Stimuli and Design

We used a $3 \times 2 \times 2$ repeated measures design with the factors lateral location (3 levels: 21.4°, 24.0°, 26.6°), sagittal location (2 levels: 200 cm, 300 cm) and real mirror rotation (2 levels: fronto-parallel, rotated by 2° clockwise), which resulted in a total number of 12 trials per observer.

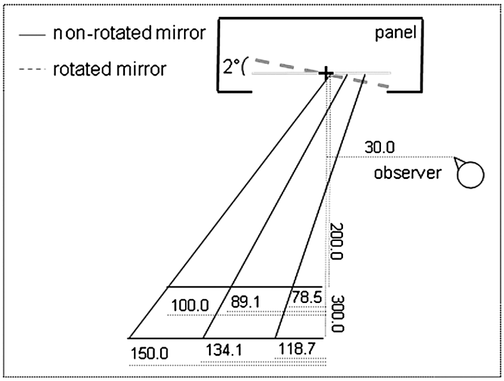

Figure 2. Schematic illustration of the experimental setup showing the observer (to the mirror's right side) and the six locations of the object (to the mirror's left side) as a combination of two sagittal distances and three lateral distances. Dotted lines indicate distance values in cm. Note that the distances are not drawn to scale.

A planar mirror was installed on a tripod. The mirror could be smoothly rotated around its vertical axis and was fully concealed by a black wooden panel. The panel was placed at a distance of 2 cm from the mirror. A round aperture (23 cm in diameter) was cut out of the wooden panel, centered at a height of 82 cm above the floor. The observer was asked to sit in a position 30 cm to the right side of the centre of the mirror and 60 cm in front of it. The observer's chin was held by a chin-rest at a height of 109 cm above the floor, such that she was looking slightly downwards into the mirror. The target was a small yellow plastic-pin, 1 cm in length, which was positioned in 6 different places on the left side of the observer. In the sagittal line, the pin was placed either 2 m away from the mirror or 3 m away from it. The visual angles were the same for both sagittal distances. That is, the visual angles for positions at 200 cm and 300 cm were identical (see Fig. 2). The target was placed once in each position for each inclination of the mirror.

The experiment was performed in a windowless and fully sound-proofed room which had a dark-brown and even floor. The parts of the walls which were visible in the mirror were concealed by black cloth.

2.3. Procedure

Real mirror rotation was blocked and counterbalanced. Within each of the two blocks, the object positions were randomized. A few practice trials with different object positions were used to acquaint observers with the task. At the beginning of each trial the observer saw the target in the mirror for 5 s. The mirror was then concealed and the target was removed. Now the observer was asked to turn round and indicate with a laser-pointer where the real object had been placed in their own opinion. The object was then placed in this position by the experimenter, and when the observer was pleased with the result, the lateral and sagittal deviations from the original position were assessed.

In addition to these measures, the angles of deviation were calculated for each of the observer's estimates. They were defined by the difference between the angle of the original position and the angle of the estimated position. In other words, they were defined by the (imaginary) line between the real object and the reflection in the mirror on the one hand and the line between the estimated position and the reflection in the mirror on the other.

After the experiment, all observers were asked whether they had noticed the differential rotation of the mirror in both experimental blocks. No one reported awareness of this experimental manipulation.

3. Results

Two 3 × 2 × 2 repeated measures ANOVAs with the factors lateral location (three levels: 21.4°, 24.0°, 26.6°), sagittal location (two levels: 200 cm and 300 cm) and real mirror rotation (two levels: fronto-parallel, rotated by 2° clockwise) were conducted on placement errors for lateral (x) and sagittal (y) placement errors separately. For lateral placement errors we obtained a significant main effect of real mirror rotation, $F(1, 11) = 7.10$, $p < 0.05$, Cohen's $f = 0.30$, indicating smaller x-errors, $M = 3.11$ cm, SD = 13.74 cm, for a real mirror rotation of two degrees away from the observer than without rotation, $M = 14.55$ cm, SD = 11.85 cm (Fig. 3). Mean x-errors away from the observer for the fronto-parallel mirror contradict the 'dual rotation' and 'mirror rotation' version and support the 'virtual world rotation' version. The main effect of the real mirror rotation also confirms the 'virtual world rotation' version, because an unnoticed real mirror-rotation away from the observer should compensate the mental rotation. No other statistically significant main or interaction effects were observed.

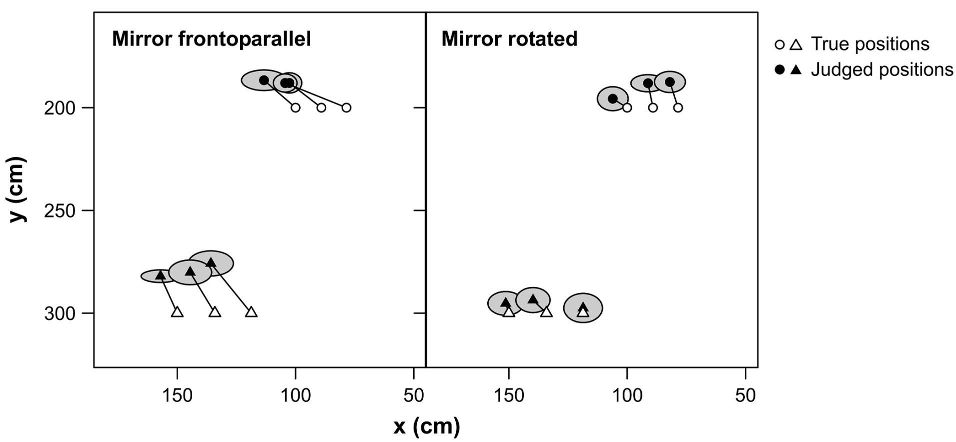

Figure 3. Actual and judged positions of the target objects as a function of mirror rotation. The horizontal and vertical radii of the ellipse around the estimated target positions represent the standard error of the respective lateral and sagittal placements.

Sagittal placement errors also produced a significant main effect of real mirror rotation $F(1, 11) = 8.67$, $p < 0.05$, Cohen's $f = 0.19$. That is, a real mirror rotation of two degrees away from the observer produced smaller y-errors, $M = 7.06$ cm, SD $= 14.48$ cm, than the fronto-parallel mirror, $M = 16.57$ cm, SD $= 14.66$ cm (Fig. 3). It is the same effect that we found in lateral placement errors; the real mirror rotation compensates the mental one. This finding equally confirms the 'virtual world rotation' version of the hypothesis and we did not observe any other statistically significant main or interaction effects in this analysis. The average sagittal errors across all locations differed significantly from zero when the mirror was fronto-parallel, $t(11) = 3.92$, $p < 0.01$, but no such difference was observed for the rotated mirror, $t(11) = 1.69$, $p = 0.12$. Comparable results were obtained for the lateral placement errors where a significant difference from 0 was only obtained for the fronto-parallel mirror, $t(11) = 4.25$, $p < 0.01$, but not for the rotated one, $t(11) < 1$. Thus, when the mirror was fronto-parallel, observers estimated the objects too far to the left and too close to the mirror (Fig. 3). The 'virtual world rotation' version of the mirror-rotation hypothesis is compatible with this result as a mental rotation causes the virtual picture to move away from the observer and closer to the mirror.

The estimates for both mirrors, expressed in angles, showed smaller errors for the rotated mirror ($M = -1.25°$, SD $= 3.20°$) than for the fronto-parallel one ($M = -4.16°$, SD $= 2.06°$) with a significant difference of 2.91°, $t(11) = 3.38$, $p < 0.01$. The mean angles across all locations differed significantly from 0 for the fronto-parallel mirror, $t(11) = 6.98$, $p < 0.001$, whereas no such difference was observed for the rotated mirror, $t(11) = 1.36$, $p = 0.20$. Thus, a constant outward-bias that is compatible with the results of Hecht *et al.* (2005) was only observed for the fronto-parallel mirror.

To summarize, a hidden real rotation of a planar mirror by 2° away from the observer minimized the localization errors by about 70% compared to a usual fronto-parallel mirror, when the errors are expressed in degrees of angle.

4. Discussion

We have put to a test the 'virtual world rotation' version of the mirror-rotation hypothesis, which posits that observers behave as if the virtual world was rotated but not the mirror. Based on previous studies, we predicted lateral positioning errors for objects that had to be placed in the world on the basis of a mirror image. We rotated the actual mirror behind a frame such that it would compensate for the hypothesized mental virtual world rotation. The results support the hypothesis. First, we were able to refute 'dual rotation', 'mirror rotation' and 'veridical perception' in favor of 'virtual world rotation'. Second, the unnoticed actual mirror rotation by 2° in the direction opposite to the mental rotation did indeed compensate the error. The real rotation of the mirror significantly decreased the positioning errors both in the lateral and in the sagittal direction. When expressed in degrees of angle, the rotated mirror reduced estimation errors from $w_{0^\circ} = 4.16^\circ$ to $w_{2^\circ} = 1.25^\circ$, amounting to an impressive improvement of 70%.

In conclusion, we were able to confirm the 'virtual world rotation' version of the '2 stage-egocentric mirror-rotation hypothesis' and its predictions. Currently, nothing more can be inferred about the underlying processes. However, the hypothesis was able to explain the results of all experiments using the localization task.

One might argue that instead of the mental counter-clockwise rotation of the virtual world followed by a reconstruction based on the actual mirror, the same placement error would ensue if the mirror was mentally rotated in a clockwise fashion followed by a reconstruction based on the mentally rotated mirror. This can indeed explain the results we obtained with the fronto-parallel mirror. However, it contradicts the findings with the mirror that was deliberately rotated by 2°. In this latter case the deliberate rotation of the mirror in the clockwise direction would be added to the clockwise mental rotation. Thus, the error should double or at least increase and not decrease as was the case for our observers.

We are aware that the mirror rotation hypothesis finds its limits when it comes to more blatant qualitative errors, for which a confusion of geometry might be the cause (Savardi *et al.*, 2010). The mirror rotation hypothesis provides an explanation for and makes precise predictions for quantitative localization errors.

Another interesting issue is the deeper nature of the bias we observed. It could either be a mere processing bias or a more fundamental perceptual bias. Note that strictly speaking, we cannot distinguish between the perceived image of the mirror and the processing based on the mirror object alone. As our data were collected in terms of object placements, they cannot clarify this difference.

We can conclude, however, that the errors which arise when we reproduce the location of an object seen in a mirror can be explained by an egocentric bias assuming that the virtual world behind the mirror is rotated. This interpretation is supported by the fact that a compensation of the bias is possible by a covert rotation of the mirror making it less orthogonal to the observer's line of sight. More research is needed to better understand this process.

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