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Mirror blindness: Our failure to recognize the target in search for mirror-reversed shapes

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Abstract

It is well known that visual search for a mirror target (i.e., a horizontally flipped item) is more difficult than search for other-oriented items (e.g., vertically flipped items). Previous studies have typically attributed costs of mirror search to early, attention-guiding processes but could not rule out contributions from later processes. In the present study we used eye tracking to distinguish between early, attention-guiding processes and later target identification processes. The results of four experiments revealed a marked human weakness in identifying mirror targets: Observers appear to frequently fail to classify a mirror target as a target on first fixation and to continue with search even after having directly looked at the target. Awareness measures corroborated that the location of a mirror target could not be reported above chance level after it had been fixated once. This *mirror blindness effect* explained a large proportion (45–87%) of the overall costs of mirror search, suggesting that part of the difficulties with mirror search are rooted in later, object identification processes (not attentional guidance). Mirror blindness was significantly reduced but not completely eliminated when both the target and non-targets were held constant, which shows that perfect top-down knowledge can reduce mirror blindness, without completely eliminating it. The finding that non-target certainty reduced mirror blindness suggests that object identification is not solely achieved by comparing a selected item to a target template. These results demonstrate that templates that guide search toward targets are not identical to the templates used to conclusively identify those targets.

Keywords Eye movements and visual attention · Visual search · Object recognition

Introduction

Visual search is one of the most frequent activities of everyday life; and it can be very time consuming. Among the objects that are surprisingly hard to find are mirror-reversed items that are flipped along the horizontal axis compared to the other objects. These mirror items are much harder to find than targets of other orientations (such as stimuli that are rotated or flipped vertically, relative to the non-targets; e.g., Davis et al., 2003, 2006; Gilden et al., 2010; Treisman & Souther, 1985; Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992). This is an intriguing finding, as items that differ significantly in an elementary feature such as orientation usually "pop out" from the other items in the display and are typically found quickly and efficiently (i.e., nearly independent of the number of non-targets; Buetti et al., 2016; Foster & Ward, 1991; Wolfe & Friedman-Hill, 1992; Wolfe, 1994). Mirror items seem to constitute an exception to this rule: As Gilden et al. (2010) pointed out, "visual search is parallel except in the specific case where distractors are mirror images of targets" [p. 539].

Several accounts have been proposed to explain difficult search for mirror images (e.g., Gilden et al., 2010; Treisman & Souther, 1985). However, common to all current accounts is the assumption that difficulties with mirror images arise at an early stage of attention-guiding processes, which elongates the time needed to select the target (e.g., Davis et al., 2003; Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992). However, there is an alternative. Previous studies mainly measured response times and errors in visual search. Such measures do not make it clear if difficulties with mirror images arise at an early state of guiding attention to mirror targets or if they arise at a later stage of *recognizing* a mirror object as the target (i.e., target identification) once the item is attended.

The failure to recognize or register an object has been famously reported in the Inattentional Blindness (IB) literature

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(e.g., Mack & Rock, 1998; Neisser & Becklen, 1975). Multiple experiments have shown that we can fail to notice an object even when we are directly looking at it (e.g., Koivisto et al., 2004). Could a corresponding failure to recognize the target explain difficulties in search for a mirror images? This may seem improbable, as IB studies differ significantly from typical visual search studies with mirror images: In IB tasks, the critical object is usually irrelevant to the task, unexpected (i.e., presented only once), and participants are engaged in a cognitively demanding task. By contrast, in typical visual search experiments, the mirror image is always task-relevant as it is the target, it is regularly presented, and the task of finding the target is not too cognitively demanding (e.g., Treisman & Souther, 1985; Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992).

On the other hand, difficulties in distinguishing mirror images may be hard-wired into the visual system. For instance, mirror writing is among children's most common production errors (Dehaene et al., 2010; Schott, 2007), suggesting that mirror items may be difficult to distinguish from their "normal" counterparts even when they are fully attended. In line with this possibility, neurophysiological studies have shown that object-selective neurons at multiple different levels of processing respond similarly to a stimulus and its mirror version, without differentiating between them (e.g., temporal cortex – Perrett et al., 1998; Perrett et al., 1991; posterior fusiform gyrus, posterior lateral occipital sulcus, and parahippocampal place area – Kietzman et al., 2012; visual word form area – Pegado et al., 2011). This *mirror generalization* has been thought to assist object recognition from different viewpoints (e.g., Borst et al., 2014; Dehaene et al., 2010; Rollenhagen & Olson, 2000), but would also render it difficult to identify a mirror item as the search target.

The efficiency of a search can be influenced at, at least, two points. The selection of items can be more or less 'guided' by feature information (Egeth et al., 1984; Wolfe et al., 1989). That is, candidate targets can be distinguished from obvious non-targets because, perhaps, the possible targets are red and the other items are not, then search will be more efficient because the items that are not red do not need to be selected. Once items are selected, search efficiency is influenced by the speed with which each item can be identified. For instance, a search for one letter among others will be less efficient if the letters are upside-down, because it will take longer to identify each upside-down letter.

Models do not always distinguish between effects at the selection and post-selection stage. For instance, Bayesian Ideal Observer models or other Signal Detection Models often characterize visual search as a signal detection task in which attention can be modelled as a set of probabilities or weights that the target is present at a given location (e.g., Najemnik & Geisler, 2005; see also Palmer et al., 2000; Schimozaki et al., 2012). Drift Diffusion models often regard visual search as a perceptual decision-making task in which attention can feature as a choice bias or bias that drives evidence accumulation (e.g., Smith & Corbett, 2019). The biased competition model describes how stimuli compete for attention and the mechanisms that ultimately lead to selection (e.g., Desimone, 1996; Desimone & Duncan, 1995; Duncan, 1998). Even models that have more clearly defined pre-attentive, attentive, and post-selective stages often do not clearly distinguish between pre-selective and post-selective stages, because, in broad terms, the same factors can influence both stages (e.g., Treisman & Sato, 1990; Wolfe, 1994; but see Wolfe, 2021). For instance, target-distractor similarity influences both the speed of selection and post-selective target identification processes (Becker, 2011; Duncan & Humphreys, 1989; Navalpakkam & Itti, 2007; Wolfe, 1994). If targets differ from distractors in their orientation, for example, it will be harder to select candidate targets if the target-distractor difference in orientation becomes smaller. It will also be harder to determine if the orientation of a selected item is, in fact, the target orientation (as reflected, for instance, in elongated dwell times on the target once it is found; e.g., Becker, 2011).

In other tasks, it is quite easy to see a distinction between attention-guiding and post-selectional processes. For example, imagine a search for green oak leaves among green and brown maple leaves. Pre-selective color processing would get you to the green leaves. Post-selective shape processing would be required to identify oak leaves among the green. This can be thought of as evidence for two types of "template": a relatively coarse, "guiding template" and a more precise "target template" (e.g., Becker, Martin, & Hamblin-Frohman, 2020b; Hamblin-Frohman & Becker, 2021; Martin & Becker, 2018; Wolfe, 2021; Yu et al., 2022). This distinction can be seen within a single basic feature like color. Attention can be guided by a relative property, selecting all "bluer" items, whereas later target identification processes require a more precise feature-specific target template (e.g., to select a specifically turquoise item as the target; Martin & Becker, 2018; Hamblin-Frohman & Becker, 2021; York et al., 2020; Yu et al., 2022).

Thinking in these terms, we can ask if the difficulties in search for mirror targets arise from a problem in selection or subsequent identification. Zhaoping and Frith (2011) reported that difficulties with a specific version of mirror search (N among reversed-N) were mainly due to later, perceptual or decisional processes that commence after the target has been found (i.e., after the eyes were fixating on the target; see also Zhaoping & Guyader, 2007). While this study compares a reverse-N search task with a different mirror search task, the results do indicate that difficulties with mirror search tasks can arise at later, post-selectional levels of processing.

Another important question is also whether difficulties with mirror search are due to hard-wired limitations of the visual system. Is there a fundamental predisposition to see mirrored items as the same as their unmirrored version? Or are difficulties in mirror search due to other, more malleable factors? Previous studies often randomly varied the target or non-target orientation across trials (e.g., Davis et al., 2003, Exp. 1; Treisman & Souther, 1985; Wolfe & Friedman-Hill, 1992; but see Davis et al., 2003, Exp. 2; Van Zoest et al., 2006). Hence, mirror costs could be a by-product of target/non-target uncertainty. Uncertainty may have prevented observers from forming a precise target template, or a precise mental representation of how the target differed from the non-targets. Difficulties in mirror search can only be safely attributed to hard-wired limitations if we can rule out target and non-target uncertainty as the source of the difficulties.

Aims of the study

The main aim of the present study was to assess whether difficulties with mirror images are exclusively or primarily due to early, attention-guiding processes, or to later, target identification processes. For that purpose, we monitored the observers' eye movements during visual search. Eye tracking makes it possible to distinguish early, attention-guiding processes from later processes concerned with target identification, based on the assumption that eye movements to a location are almost always preceded by a covert attention shift to that location (Deubel & Schneider, 1996). We inspected the *number of fixations prior to selecting the target* and *time to target* (latency of selecting the target for the first time, from the onset of the trial) to index attentional and attention-guiding processes (e.g., Zhaoping & Frith, 2011; see also Becker, 2010, 2011). Failure to recognize the target would be reflected in observers continuing the search even after they already selected the target, and was measured by inspecting the *number of fixations after the first target selection*, and the *time after target* – namely, the time elapsed from the first target selection to the manual response (e.g., Hout & Goldinger, 2015; Zhaoping & Frith, 2011).

To gauge difficulties that are uniquely associated with mirror images, we used items of several other different orientations (e.g., 90^0 and 180^0 rotations), which served as control stimuli. Thus, if difficulties in search for mirror images are mainly due to early, attention-guiding processes, selection of mirror targets should require a larger number of fixations and a longer "time to target," compared to other oriented targets. By contrast, if mirror images create difficulties in later, target identification processes, mirror search should show an increase in fixations *after* the target is selected (compared to other oriented targets) and a longer time after target selection to the response. In addition, we compared the number of fixations prior to target selection versus after target selection to assess the relative contributions of early versus late processes to the mirror effect on visual search.

Deviating from previous studies, we tested the effects of mirror items under conditions of *target certainty versus uncertainty* (Experiment 1), and *non-target certainty versus uncertainty* (Experiment 2), by keeping the orientation of target/non-targets constant across trials or randomly varying the target/non-target items. Thus, in the most certain cases, observers knew the orientation of both the target and the non-targets in advance, which allowed search to be guided by a very specific target template. In the least certain cases, observers did not know the orientation of either the targets or the non-targets, which might be expected to hamper any "guided search" (e.g., Wolfe, 1994, 2021). Difficulties with mirror search can only be attributed to hard-wired limitations if difficulties with mirror items persist even under maximum certainty.

In Experiment 3, we additionally implemented an *awareness measure* to test if participants were indeed unaware of the target after they had already fixated on the target and continued with the search.

The search stimuli for Experiments 1–3 were composed of multiple geometrical shapes (disk, triangle, etc.), designed to mimic the complexity and inter-item symmetry of objects in the normal environment (e.g., Roggeveen et al., 2004; Troje & Bülthoff, 1998). As in previous studies, the stimuli were all easily distinguishable at different orientations, and did not resemble any known natural objects or artefacts (see Fig. 1a).

The design of the study allowed us to address several questions: (1) if difficulties with mirror items are due to early, attention-guiding, or later, target identification processes; (2) if early and late processes indeed rely on the same target template and processes (e.g., Duncan & Humphreys, 1989), or if they operate on different principles (e.g., Hamblin-Frohman & Becker, 2021; Wolfe, 2021), and (3) if difficulties with mirror search are due to target or non-target uncertainty, or whether they may reflect hard-wired limitations.

Experiment 1

In Experiment 1, observers were asked to search for a target with a pre-defined, constant orientation (0°) that was presented among five non-target items that were all identical to each other. They either had different orientations from the target or were the target's mirror image (see Fig. 1a). The observer's task was to locate the target as quickly and precisely as possible, and to identify the item inside the target (x/o) with a button press. The x and o characters inside the search items were kept small to encourage eye movements to the center of the items and prevent saccadic undershoot (e.g., McSorley & Findlay, 2003; see Becker, 2010, for a similar method).

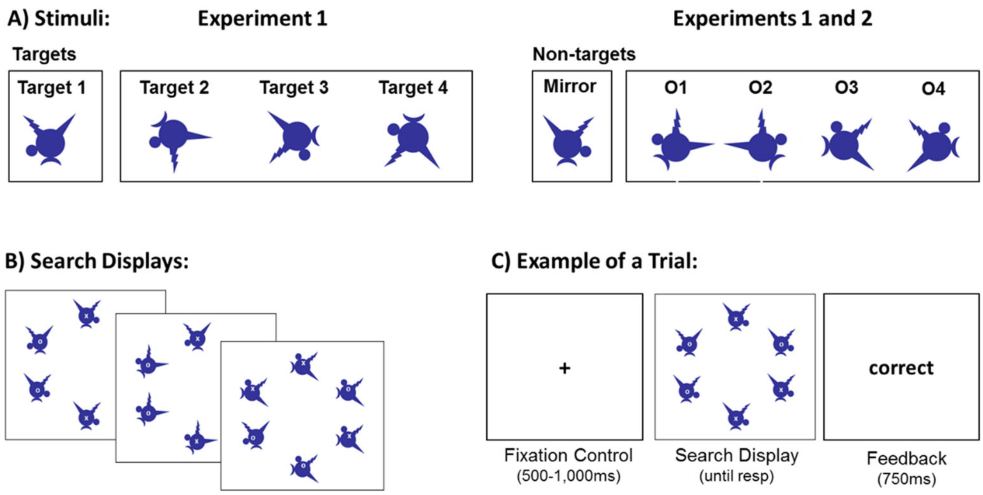

Fig. 1 **a** Overview of stimuli: In the variable target condition of Experiment 1 (target uncertainty), every target on the left (1–4) could be displayed with any of the five non-target stimuli displayed on the right. In the fixed target condition of Experiment 1 and in Experiment 2 (target certainty), only Target 1 was used. In Experiment 2, Target 1 was either displayed randomly among any of the five non-target stimuli (non-target uncertainty), or the non-targets were held constant across a mini-block of trials; non-target certainty). **b** Search displays and **c** the sequence of displays used in Experiments 1 and 2. The observer's task was to search for the pre-defined target and respond to the small x or o inside the target. We centrally measured the mean response time, separated into the time until the first fixation on the target vs. afterwards, and the number of fixations during a trial, before vs. after the target had been selected for the first time

Target and non-target uncertainty was varied in Experiments 1 and 2 by implementing two blocked conditions in which the target/non-targets were either constant or varied randomly. In Experiment 1, the non-targets always varied between five possible orientations (implementing non-target uncertainty), and we manipulated target uncertainty in two conditions (see Fig. 1a, left).

In the *Variable Targets* condition, the target varied between four possible orientations, creating target uncertainty, whereas in the *Fixed Target* condition, only a single target was presented (Target 1, see Fig. 1a), providing certainty about the target. To ensure that differences between the conditions were due to target certainty versus uncertainty and not differences between the target stimuli, we focused the data analysis on the target that was the same in both conditions (i.e., Target 1).

To assess whether mirror items cause particular difficulties in visual search, we compared performance when the target was presented among mirror non-targets versus when it was presented among non-targets of other orientations (O1, O2, O3, O4; see Fig. 1a).

If difficulties in search for mirror targets are indeed due to early attentional processes, mirror search should differ from other-oriented searches only in the number of fixations prior to target selection and the time to target, while the number of fixations after target selection and the time after target selection should not differ. On the other hand, if difficulties in search for mirror items are due to later processes of object identification, the number of fixations after target selection and the time after target selection (to the response) should be markedly higher in the mirror condition than with other-oriented non-targets.

Method

Participants To determine the required sample size for the study, we used the effect size for mirror search effects from the study of Van Zoest et al. (2006; $\eta^2 = .89$ for the difference between rotated (mirror search) vs. upright (vertically flipped search) in Exp. 1). An a priori computation for the required sample size in G*Power showed that we would require four participants to detect a corresponding effect with a repeated-measures ANOVA at an alpha level of .05 and a power of .95. As our study aimed to detect this effect in two logically independent measures, we tripled the minimum required sample size and aimed to collect data from 12 participants. All participants were naïve as to the purpose of the experiment and were reimbursed with $10/h.

Apparatus Stimuli were generated with Presentation (Neurobehavioural Systems) and presented on a 17-in. LED monitor with a resolution of 1,280 × 1,024. Eye movements were monitored with an Eyelink 1000 eye tracker (SR Research, Ontario, Canada).

Stimuli, design, and procedure The target and non-targets all consisted of an abstract shape at different orientations (size: 3.2°× 3.2°). The target was always present, and presented among five non-targets that all had the same orientation within a trial. Search items were presented equidistantly 7.9° from the center, and observers were instructed to report the identity of a small letter that was inside the target ("o" or "x"; 0.27°×

0.27°), by pressing one of two response buttons (see Fig. 1b and c). The target position, letter identity, and orientation of the non-targets varied randomly, with the limitations that all displays contained an equal number of x and o stimuli and that all non-target orientations were presented equally often.

Experiments 1 and 2 each contained two blocked conditions, the order of which was counterbalanced across observers. In Experiment 1, the non-targets always varied (O1 – O4). Within a trial, all distractors were of the same orientation. In the variable target condition, we presented targets of four possible orientations across trials. In the fixed target condition, we presented only Target 1 on all trials. Observers always searched for the odd item among identical distractors. Only the results for Target 1 were analyzed, while all other trials were considered to be fillers. Participants completed 675 trials in Experiment 1.

To ensure stable eye tracking, we implemented a fixation control: Observers had to fixate on a small black fixation cross (0.27°× 0.27°) prior to each trial, and the search display was presented only when observers fixated on the cross for 500 ms (within a time-window of 2,000 ms); otherwise, they were calibrated anew. The search display was presented until the manual response, and was immediately succeeded by a feedback display containing the words “Correct!” or “Wrong!” which provided observers with feedback about their button press response (see Fig. 1c).

Results

Data As we expected to find large costs in mirror search, we chose a liberal outlier criterion, only excluding trials with response times (RTs) longer than 10,000 ms and shorter than 200 ms, which accounted for a loss of just 0.03% of the data. Moreover, we excluded trials in which the target had not been fixated, which led to an additional loss of 3.78% of the data.

Mean RT As shown in Fig. 2, it is clear that there are large RT costs in the mirror condition and that they can be attributed to increases in the time spent *after* the observer fixates the target. As shown in the figure, the result patterns were quite similar for the fixed and variable target conditions, with mirror search showing large RT costs in both conditions. Indeed, a 2 × 5 ANOVA with the variables target variability (variable vs. fixed) and non-target type (mirror, O1, O2, O3, O4) showed no main effect of target variability, $F<1$, but a significant main effect of the non-target type, $F(4,44) = 16.29$, $p < .001$, $\eta^2 = .60$, and a significant interaction between the variables, $F(4,44) = 3.04$, $p = .027$.

Pairwise, two-tailed *t*-tests revealed that mirror search produced large and significant RT costs compared to each of the four other-oriented control stimuli, both in the variable target condition, all ts > 4.4, ps = .001, η^2s > .67 (O1: $t(11) = 4.52$, $p = .001$; O2: $t(11) = 4.74$, $p = .001$, O3: $t(11) = 4.40$, $p = .001$; O4: $t(11) = 4.47$, $p = .001$), and in the fixed target condition, all ts > 3.3, ps ≤ .007, η^2>.60 (O1: $t(11) = 4.09$, $p = .002$; O2: $t(11) = 4.04$, $p = .002$, O3: $t(11) = 3.31$, $p = .007$; O4: $t(11) = 3.47$, $p = .005$). The costs of mirror search (RT in mirror condition minus average RT of O1–O4 conditions) were larger in the variable target condition (1,476 ms) than the fixed target condition (1,333 ms), but this difference just failed to reach significance, $t(11) = 1.95$, $p = .077$.

More importantly, the RT costs could not be fully explained by the time needed to select the target: In the variable target condition, the time required to find a mirror target (from the onset of the search display until the eyes were first fixating on the target) was slightly elevated compared to the O1 and O2 conditions, $t(11) = 2.87$; $p = .015$, $\eta^2 = .43$, and $t(11) = 2.98$, $p = .013$, $\eta^2 = .43$, but did not differ significantly from search among O3 and O4 non-targets, ts < 1, ps > .53. In the fixed target condition, it took longer to find the target among mirror images than among O1 non-targets, $t(11) = 3.21$, $p = .008$, $\eta^2 = .48$, but mirror search did not differ from any of the other conditions, all ts < 1.6, ps > .14. The costs of finding a mirror target also did not differ between the variable target condition (193 ms) and the fixed target condition (201 ms), $t < 1$.

By contrast, time elapsed *after* the target had been selected was significantly increased in the mirror condition compared to all other orientation conditions (O1–O4), both in the variable target condition, all ts > 4.2, ps = .001, η^2s > .62 (O1: $t(11) = 4.28$, $p = .001$; O2: $t(11) = 4.46$, $p = .001$, O3: $t(11) = 4.41$, $p = .001$; O4: $t(11) = 4.34$, $p = .001$), and in the fixed target condition, all ts > 3.4, ps ≤ .005, η^2s > .52 (O1: $t(11) = 3.99$, $p = .002$; O2: $t(11) = 4.16$, $p = .002$, O3: $t(11) = 3.44$, $p = .005$; O4: $t(11) = 3.74$, $p = .003$). The costs of responding to the mirror target were also significantly larger in the variable target condition (1,282 ms) than in the fixed target condition (1,133 ms), $t(11) = 2.64$, $p = .023$, $\eta^2 = .39$.

These results show that the large costs of mirror search cannot be fully attributed to early, attention-guiding processes that guide attention to the target, but are mainly due to later processes that commence after the target has been selected. In line with this interpretation, comparing mirror costs between the time needed to select the target (pre) versus the time after target selection (post) revealed that mirror costs (mirror – average of O1, O2, O3, O4) were significantly larger post selection than prior to selection, both in the variable target condition (193 ms pre vs. 1,283 ms post), $t(11) = 4.10$, $p = .002$, $\eta^2 = .61$, and in the fixed target condition (200 ms pre vs. 1,132 ms post), $t(11) = 3.87$, $p = .003$, $\eta^2 = .58$.

We next analyzed the mean number of fixations during a trial and especially the fixations before versus after target

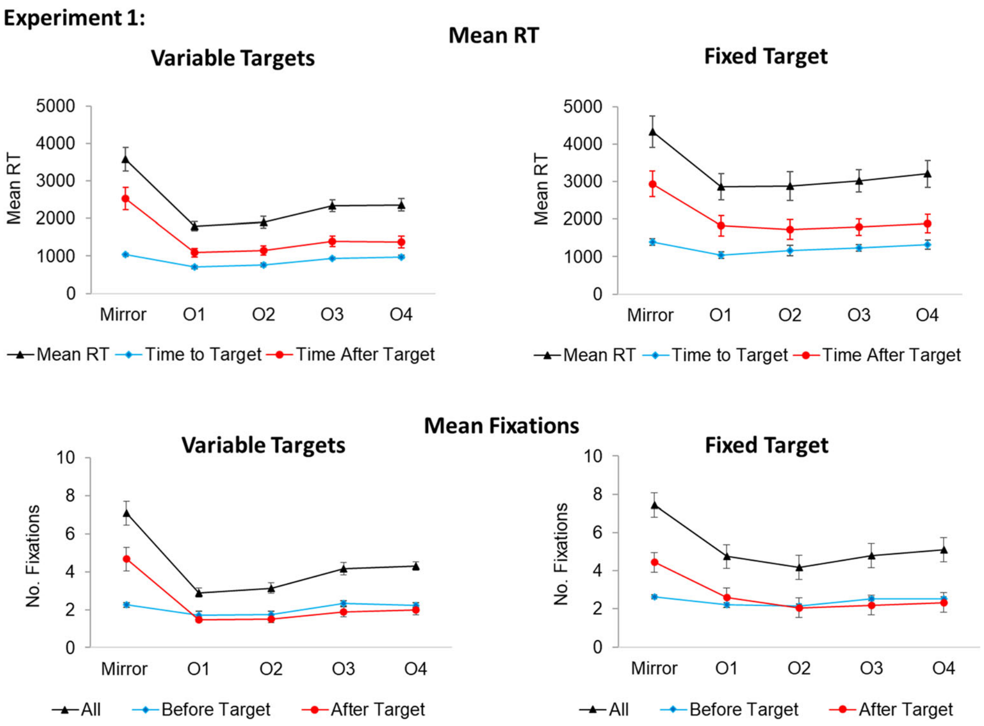

Fig. 2 Results of Experiment 1, depicted separately for the Variable Target and Fixed Target conditions (left, right). Mirror search produced large costs both in the mean response times (RTs; top panels) and the mean number of fixations per trial (bottom panels), compared to the other-oriented conditions (O1–O4). The large costs of the mirror item could not be fully explained by search-related processes (Time to Target and Fixations Before Target), but were largely due to later processes that commenced after the first fixation on the target (Time After Target; Fixations After Target). Error bars depict ± 1 SEM and may be smaller than the plotting symbol

selection, to test if observers indeed missed the mirror target and continued with the search.

Number of fixations The mean number of fixations showed a very similar results pattern to the mean RT (see Fig. 2, bottom). The 2 × 5 ANOVA revealed only a main effect of the non-target type, $F(4,44) = 17.56$, $p < .001$, $\eta^2 = .62$, no effect of target variability, $F<1$, but a significant interaction between the variabes, $F(4,44) = 3.29$, $p = .019$, $\eta^2 = .23$.

More non-target fixations were made in search for the target among mirror-reversed non-targets than among any other non-target items, both in the variable target condition, all *t*s > 4.2, *p*s = .001, η^2s > .62 (O1: $t(11) = 4.30$, $p = .001$; O2: $t(11) = 4.49$, $p = .001$, O3: $t(11) = 4.25$, $p = .001$; O4: $t(11) = 4.70$, $p = .001$), and in the fixed target condition, all *t*s > 3.7, *p*s ≤ .003, η^2s > .56 (O1: $t(11) = 3.75$, $p = .003$; O2: $t(11) = 4.23$, $p = .001$, O3: $t(11) = 3.73$, $p = .003$; O4: $t(11) = 3.92$, $p = .002$).

Again, attention-guiding processes could not fully account for this effect: In the variable target condition, the fixations prior to target selection were only significantly elevated for the mirror target compared to the O1 and O2 non-targets, $t(11) = 2.44$, $p = .033$ and $t(11) = 2.79$, $p = .018$, respectively (all other *p*s > .54). In the fixed target condition, finding the target among mirror-reversed non-targets only proved harder than finding it among O1 non-targets, $t(11) = 2.24$, $p = .045$, whereas mirror search did not differ from search among O2, O3, or O4 non-targets, all *p*s > .07.

By contrast, analyzing the number of fixations after the first target selection revealed that difficulties in target identification contributed significantly to elevated fixations for mirror items: There were significantly more non-target fixations after target selection among the mirror-reversed non-targets than all other non-targets, both in the variable target condition, all *t*s > 4.0, all *p*s ≤ .002, η^2s > .53 (O1: $t(11) = 4.0$, $p = .002$; O2: $t(11) = 4.15$, $p = .002$; O3: $t(11) = 4.31$, $p = .001$; O4: $t(11) = 4.26$, $p = .001$), and in the constant target condition (O1: $t(11) = 3.56$, $p = .004$; O2: $t(11) = 4.56$, $p = .001$; O3: $t(11) = 4.12$, $p = .001$; O4: $t(11) = 4.29$, $p = .001$).

Comparing mirror costs between fixations prior to target selection (pre) versus fixations post target selection revealed that mirror costs were significantly larger post-target selection than pre-selection, both in the variable target condition (0.24 pre vs. 3.0 post extra fixations in mirror search), $t(11) = 3.71$, $p = .003$, $\eta^2 = .56$, and in the fixed target condition (0.29 pre vs. 2.1 post extra fixations in mirror search), $t(11) = 4.01$, $p = .002$, $\eta^2 = .59$.

Discussion

The results of Experiment 1 clearly indicated that the costs of searching for mirror-items is not solely or mainly due to early attention-guiding processes, as suggested by prior studies (e.g., Davis et al., 2003, 2006; Gilden et al., 2010; Treisman & Souther, 1985; Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992). In this case, it should have been more difficult to find a mirror target, which should have been reflected in a longer time required to fixate on the target, or a larger number of fixations to find the target. Instead, the results of Experiment 1 revealed that the bulk of the costs of mirror search occurred after participants had first fixated the target ("found the target"). Computing the difference values (mirror-reversed − average of other orientated non-targets) for each of the dependent variables revealed that the time *after target selection* explained 87% of the mirror costs in the variable target condition (post-selection mirror cost of 1,283 ms out of overall RT mirror cost of 1,476 ms), and 85% of the mirror costs in the fixed target condition (post-selection costs of 1,132 ms out of total RT mirror cost of 1,334 ms). This suggests that we have difficulties recognizing a mirror target, or distinguishing it from the mirror-reversed non-targets. In other words, there seems to be a *mirror blindness effect* in that observers seem to be prone to missing the search target when they are fixating on it.

Interestingly, mirror blindness was observed not only when the target was variable, but also when the target orientation was fixed and observers knew the exact target orientation. The similar result patterns in the variable and fixed target conditions suggests that observers did not use a very precise target representation to identify the target in the fixed condition, even though the conditions allowed for it.

It is possible that the variability of the non-target context prevented the use of a more specific target template. Of note, in Experiment 1, the orientation of the non-targets varied randomly across trials, and on the majority of trials, the target was easily distinguishable because it was the only upright item. Hence, observers may have failed to recognize mirror targets because they mostly used a less specific template for target identification (e.g., "upright item"), because it was convenient and may have been deemed sufficient. Alternatively, it is possible that observers would have needed to know how the target differs from the non-targets to form a more precise target template. Experiment 2 was designed to probe into these possible explanations by always keeping the target constant and varying non-target certainty.

Experiment 2

In Experiment 2, the target was certain, not variable; specifically, Target 1 in Fig. 1. In the *Variable Non-target* condition, the non-targets varied randomly from trial to trial, whereas in the *Fixed Non-target* condition, the non-target orientation was always constant across five mini blocks of trials, the order of which was determined randomly for each observer. Experiment 2 allowed us to assess if mirror blindness arises only when the context of the target varies or, alternatively, if observers continue to show mirror blindness under conditions where target and distractor items remain constant and observers have perfect knowledge of the task.

If mirror blindness is due to hard-wired factors (i.e., an inability to distinguish items from their mirror counterparts), then the costs of mirror search should persist regardless of whether the context items are variable or constant. On the other hand, if mirror blindness in Experiment 1 was due to variable non-targets discouraging the formation of a precise target template, then keeping the non-target context constant might eliminate the costs of mirror search.

Method

The stimuli, design and procedure were exactly the same as in Experiment 1, except that the target was fixed (Target 1). Across two blocks of trials, the non-targets either varied randomly (as in Experiment 1; *variable non-target condition*), or they remained constant within a mini-block (*fixed non-target condition*). In the fixed non-target condition, the target was presented among non-targets of a single type that was kept constant during a mini-block of trials. The order of the five mini-blocks was randomized for each participant. In total, participants completed 300 trials in the fixed and variable non-target condition; 600 trials in total.

Results

Data Using the same outlier criteria as in Experiment 1 led to a loss of 1.93% of the data; 1.43% because of a failure to fixate on the target, and 0.49% because of anticipatory or delayed responses.

Mean RT Figure 3 shows the results of Experiment 2. There is still an effect on RT of the mirror items in the fixed condition and that effect is largely attributable to added time after the target is found. However, as might be expected, the effect is smaller than what was seen in Experiment 1. A 2 × 5 ANOVA computed over the mean RT showed a significant main effect of non-target variability (fixed vs. variable non-targets), $F(1,11) = 11.70$, $p < .001$, $\eta^2 = .51$, non-target type (mirror, O1, O2, O3, O4), $F(4,44) = 20.87$, $p < .001$, $\eta^2 = .65$, and a significant interaction between the two variables, $F(4,44) = 2.93$, $p = .031$, $\eta^2 = .21$. Pairwise, two-tailed t-tests revealed that the RT costs for mirror search were highly significant, both in the variable non-target condition, all ts > 4.8, ps≤.001, η^2s > .65 (O1: $t(11) = 4.81$, $p = .001$; O2: $t(11) = 6.78$, $p < .001$, O3: $t(11) = 5.47$, $p < .001$; O4: $t(11) = 5.53$, $p < .001$), and in the fixed non-target condition, all ts > 2.7, ps ≤ .019, η^2s > .41 (O1: $t(11) = 3.83$, $p = .003$; O2: $t(11) = 3.79$, $p = .003$, O3: $t(11) =$

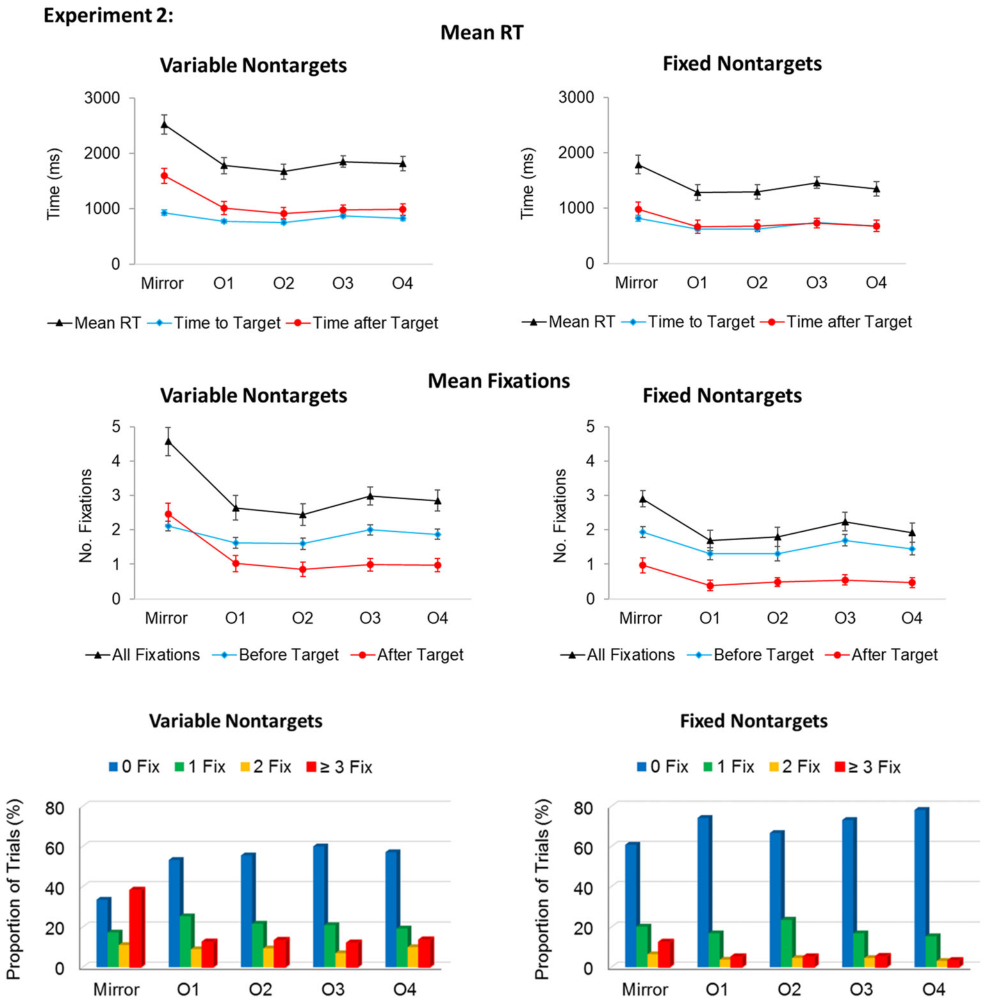

Fig. 3 Results of Experiment 2, depicted separately for the variable vs. fixed non-target condition (left, right). Mirror search produced significant costs compared to other orientations (O1–O4), which could not be explained solely by delays in finding the target, but were mainly due to difficulties in identifying mirror targets. The distribution analysis of all fixations (bottom) showed that observers were less likely to immediately identify a mirror target (0 Fix; blue histograms) than in the other conditions, and more likely to make three or more fixations after target selection (≥ 3 Fix; red histograms)

2.76, $p = .019$; O4: $t(11) = 4.28$, $p = .001$). The costs of mirror search (computed as RT for mirror search minus the average of the O1 to O4 conditions) were also significantly larger in the variable non-target condition (743 ms) than in the fixed non-target condition (440 ms), $t(11) = 2.69$, $p = .021$, $\eta^2 = .40$.

Early attentional processes could not fully account for these RT costs: In the variable non-target condition, the time until observers fixated on the target (for the first time) was longer for the mirror item than for only two of the other-oriented non-target stimuli, O1, $t(11) = 2.87$, $p = .015$, $\eta^2 = .43$, and O2, $t(11) = 2.96$, $p = .013$, $\eta^2 = .43$, but not for the other two (all *ts* < 1.8, *ps* > .10). In the fixed non-target condition, the mirror item produced longer search times than three of the other-oriented non-targets; O1: $t(11) = 3.31$, $p = .007$, $\eta^2 = .50$, O2: $t(11) = 3.23$, $p = .008$, $\eta^2 = .49$, and O4: $t(11) = 2.70$, $p = .021$, $\eta^2 = .40$, but mirror search did not differ from the O3 condition, $t(11) = 1.49$, $p = .16$, *n.s.* Search costs for the mirror target also did not differ significantly between the variable non-target condition (122 ms) and the fixed non-target condition (152 ms), $t < 1$.

By contrast, the time after the first target fixation until a response showed strong and consistent costs of the mirror item over the other-oriented non-targets, both in the variable non-target condition, all *ts* > 5.4, *ps* < .001, η^2s > .73 (O1: $t(11) = 5.47$, $p < .001$; O2: $t(11) = 8.24$, $p < .001$, O3: $t(11) = 6.54$, $p < .001$; O4: $t(11) = 6.97$, $p < .001$), and in the fixed non-target condition, all *ts* > 2.6, *ps* ≤ .021, η^2s > .39 (O1: $t(11) = 3.62$, $p = .004$; O2: $t(11) = 3.24$, $p = .008$, O3: $t(11) = 2.69$, $p = .021$; O4: $t(11) = 4.10$, $p = .002$). The costs of responding to a mirror target was also significantly larger in the variable non-target condition (620 ms) than in the fixed non-target condition (287 ms), $t(11) = 3.84$, $p = .003$, $\eta^2 = .57$.

Comparing the costs for mirror items across the two dependent variables revealed that the main portion of the costs of mirror search were due to later processes that commence after target selection. In the variable non-target condition, mirror costs (computed as mirror – average of O1, O2, O3, O4) were significantly larger post target selection (621 ms) than prior to selecting the target (122 ms), $t(11) = 7.38$, $p < .001$, $\eta^2 = .57$. In the fixed non-target condition, mirror costs were also larger post-selection (287 ms) than prior to selection of the target (152 ms), but this difference just failed to reach significance, $t(11) = 1.86$, $p = .090$, $\eta^2 = .24$.

Taken together, the results show that the major portion of mirror costs should be attributed to late processes that commence after the target has been selected. Although non-target variability significantly modulated the mirror effect, the fixed non-target condition demonstrated that mirror blindness persists even when both the target and the non-targets are known and remain constant.

Mean fixations The same 2 × 5 ANOVA computed over the mean number of fixations during a search trial showed a significant main effect of non-target variability (fixed vs. variable non-targets), $F(1,11) = 8.56$, $p = .014$ $\eta^2 = .44$, non-target type (mirror, O1, O2, O3, O4), $F(4,44) = 21.90$, $p < .001$, $\eta^2 = .67$, as well as a significant interaction between the two variables, $F(4,44) = 3.12$, $p = .024$, $\eta^2 = .22$. The main effect of non-target variability and the significant interaction were due to the fact that the mean number of fixations was reduced in the fixed non-target condition, as well as the mirror effect (see Fig. 2). Still, the costs for mirror items were significant both in the variable non-target condition, all ts > 5.0, ps < .001, η^2s > .70 (O1: $t(11) = 5.02$, $p < .001$; O2: $t(11) = 7.41$, $p < .001$; O3: $t(11) = 6.07$, $p < .001$; O4: $t(11) = 6.28$, $p < .001$, and in the constant non-targets condition, all ts > 2.86, ps ≤ .015, η^2s > .43 (O1: $t(11) = 3.84$, $p = .005$; O2: $t(11) = 3.21$, $p = .008$; O3: $t(11) = 2.86$, $p = .015$; O4: $t(11) = 4.33$, $p = .001$).

Again, these difficulties could not be fully accounted for by search-related processes: In the variable non-target condition, fixations prior to target selection were only significantly higher in mirror search than in two conditions with other-oriented non-targets; O1, $t(11) = 2.84$, $p = .016$, and O2, $t(11) = 3.32$, $p = .007$, all other ps > .077. In the constant non-target condition, there were more fixations prior to selecting the target in mirror search than in search among O1, $t(11) = 3.44$, $p = .006$, O2, $t(11) = 2.70$, $p = .021$, and O4 non-targets, $t(11) = 2.51$, $p = .029$, but not the O3 non-target, p>.15).

In turn, difficulties in identifying the target were pronounced and explained a large portion of the costs of mirror items: In the variable non-target condition, there were more fixations after target selection in the mirror-reversed condition than all other non-target conditions, all ts > 6.0, ps < .001, η^2s > .77 (O1: $t(11) = 6.03$, $p < .001$; O2: $t(11) = 8.05$, $p < .001$; O3: $t(11) = 7.06$, $p < .001$, O4: $t(11) = 7.23$, $p < .001$). In the constant non-target condition, the mirror conditions showed more non-target fixations after target selection than three of the other-oriented conditions, O1, $t(11) = 2.57$, $p = .026$; O2, $t(11) = 2.30$, $p = .042$, and O4, $t(11) = 2.91$, $p = .014$, whereas the differences to the O3 condition just failed to reach significance, $t(11) = 2.00$, $p = .075$.

Comparing the mirror costs (mirror – average of O1, O2, O3, and O4) across the number of fixations pre versus post target selection in the variable non-target condition showed significantly larger mirror costs for fixations after the target (mean difference: 1.5 fixations) than prior to the target (mean difference: 0.34 fixations), $t(11) = 6.52$, $p < .001$, $\eta^2 = .79$. In the fixed non-target condition, mirror costs were equally large in fixations prior to target and post target (mean difference: 0.49 fixations for both), $t < 1$.

Thus, mirror costs were significantly reduced but not eliminated when both the target and the non-target features were known in advance and continuously repeated across trials.

Fixation distribution analysis

The results of Experiment 2 showed a large reduction in the costs of mirror search: When the non-targets remained constant, far fewer fixations were made, and the difference between mirror search and search for other-oriented items decreased drastically. Is this reduction due to a higher probability of immediately identifying a mirror target, and hence a lower probability of continuing the search? Or is it due to a reduction in the number of fixations made after fixating on the target (e.g., 1 fixation rather than 2−3)? To address this question, we analyzed the distribution of fixations in the variable versus fixed non-target condition to compare the probabilities of observers making 0, 1, 2, or 3 or more fixations after target selection in Experiment 2.

As shown in Fig. 3 (bottom), in the variable non-target condition, observers were less likely to identify a mirror target after the first fixation on the target (33%) than in the other conditions (56%; range: 53−60%), and very likely to make three or more fixations even after they had already fixated on the mirror target (on 38% of all trials). In the other-oriented control conditions, observers only rarely made three or more fixations (13% of all trials; range: 12−14%).

When the non-targets were constant and repeated across all trials, the probability of making three or more fixations remained higher in this condition than in the other search conditions (O1–O4), but was dramatically reduced compared to the variable non-target condition. This indicates that observers are more prone to miss a mirror-reversed target and continue search after target selection even when the non-targets are constant. This points to a genuine mirror blindness effect, with observers failing to identify the target even after they have looked at it. This effect is reduced but not completely eliminated when the target and non-targets are both constant.

Discussion

The results of the Experiments 1 and 2 showed that mirror search incurs costs that are not solely or mainly due to difficulties in finding the target. Instead, the major proportion of the costs of mirror search was due to observers selecting more non-targets after they had already fixated on the target. Specifically, delays occurring after target selection accounted for 84% of the RT costs of mirror targets in the variable non-target condition of Experiment 2 (the 621-ms mirror cost after target selection is 84% of the total mirror costs of 743 ms). This result is very similar to the equivalent condition of Experiment 1, where post-selection costs accounted for 85% of the overall mirror costs in the mean RT. In the fixed non-target condition, post-selection RTs accounted for 65% (287 ms/440 ms) of the mirror costs in the mean RT.[1]

The distribution analysis moreover showed that the costs of mirror search predominantly reside in observers making several extra eye movements (≥ 3 fixations) after they had already fixated on the target, not in a higher probability of making a single eye movement after target selection. These results provide strong evidence that the costs of mirror search are to a large part due to a failure to recognize the search target even after fixating on it (and presumably, attending to it).

Experiment 3

Experiments 1 and 2 provided evidence for mirror blindness – the phenomenon that we are prone to miss a mirror target, often continuing with visual search even after we have selected the target. However, the evidence for mirror blindness, or the failure to recognize the target, may still be regarded as somewhat indirect, as it relies on implicit measures such as fixations and time spent searching after target selection. More direct proof of mirror blindness could be provided by showing that observers indeed have no knowledge about the target location after having selected it.

The aim of Experiment 3 was to provide such a more direct test, by directly probing observer's awareness of the target location after they had selected the target. To that aim, we included a subset of "probe trials" in the experiment, in which all search stimuli were masked with blue-white checkerboards at a variable point during search and observers were asked to indicate the location of the target. Importantly, the masks could appear prior to observers selecting the target, or afterwards – either while observers were still fixating on the target, or once they had selected one or more non-targets after the target.

Knowledge of the target location was separately analyzed for three types of trials: (1) Trials in which the target had not been selected prior to the onset of the masks (*Before Target*), (2) trials in which the masks appeared while observers were looking at the target or shortly thereafter (i.e., when the target was the last selected item; *During Target*), and (3) trials in which the target had been selected and observers made one or more subsequent fixation on non-targets before the masks appeared (*Post Target*).

We expected that localization accuracy of the target would be close to chance when the masks appeared prior to the target, and that it would be close to 100% when the masks appear during fixations on the target or shortly thereafter (*During Target*). Critically, if the results of Experiments 1 and 2 demonstrate genuine blindness for mirror items, target localization accuracy should be at chance level (16.7%) for mirror search in the *Post Target* trials, and accuracy might be significantly lower for mirror targets than for other-oriented targets.

Method

Participants Data were collected from 12 new observers (one of whom was replaced because of excessively long RT, which led to masks appearing on 100% of the trials).

Stimuli, design, and procedure These were the same as in the variable non-target condition of Experiment 2, with the exception that, at a random point during a trial, the search stimuli were replaced with checkerboard masks (3.4° × 3.6°) that consisted of a large black number (1−6) superimposed on 9 × 12 blue and white squares and completely covered the search stimuli (see Fig. 4). Masks were more likely to appear as time elapsed during a trial and were on average present on 42.5% of all trials. The masks and numbers remained on screen until the response, and participants were asked to report the location of the target by pressing the corresponding number. Participants were asked to guess and select a number randomly (1−6) if they did not know the target location.

Results

The mean RTs or number of fixations were not analyzed, because the appearance of the masks was more likely as the trial progressed, rendering it less likely to find the signature mirror blindness effect (i.e., a large number of non-target fixations after target selection; see Figs. 2 and 3).

The results of the awareness test (see Fig. 4c) showed that, prior to target selection, target localization was significantly *worse* than chance (Prior Target: 6.4% correct; chance:

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[1] If we use the number of fixations for these computations, the number of fixations post target would explain 50% of the overall costs of mirror items – less than the estimate of 65% arising from the comparison of time to respond after target selection and RT. The time after target selection seems to be a better indicator for post-selective processes, as it includes dwell times on the target, which can be elongated when perceptual decisions are (more) difficult (e.g., Becker, 2011; Horstmann et al., 2020).

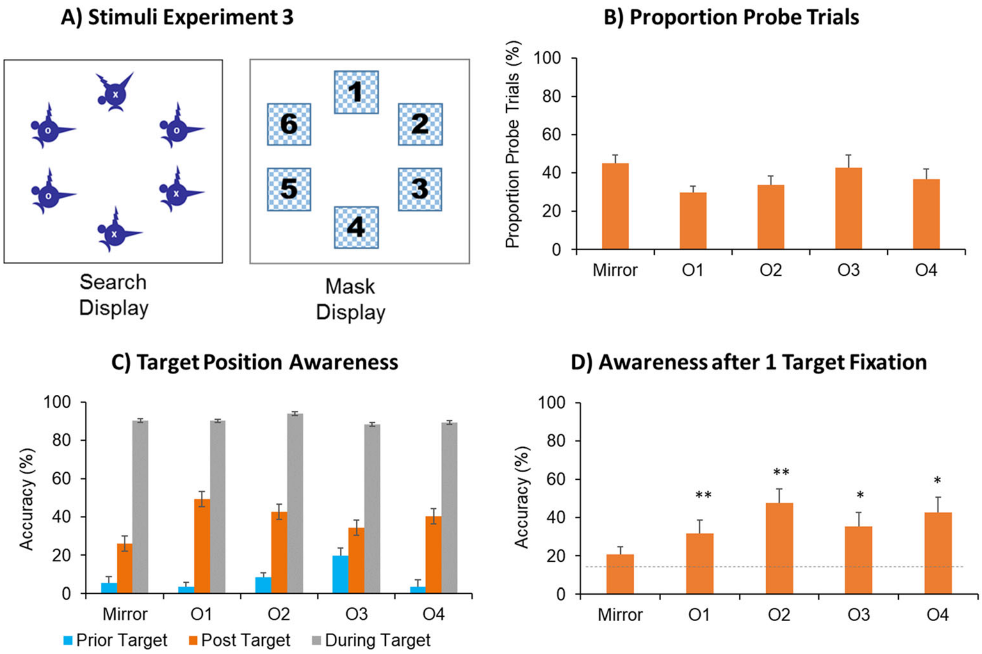

Fig. 4 **a** Examples of the search display and mask display. **b** Proportion of trials in which masks appeared and the observer's awareness of the target location could be probed. **c** The percentage of correct target localization reports. Performance was low when the masks were presented prior to fixating on the target (Prior Target). Accuracy was high when the masks appeared while observers were fixating on the target (During Target), and intermediate when the target had already been fixated previously but one or more non-targets had been selected afterwards (Post Target). Awareness of the mirror target was lower than in the other-oriented conditions (O1–O4) post target. **d** When considering only Post Target trials in which the target had been selected once before the masks appeared, target localization accuracy was lower and only significantly above chance for conditions O1–O4, not for the mirror target. Error bars signify 1 SEM. *$p < .05$, **$p < .01$ compared to chance (16.7%)

16.7%), $t(12) = 3.4$, $p = .005$. These results suggest that observers had a bias to choose one of the already fixated positions as the target location. Accuracy in the mirror condition (5.55%) did not significantly differ from any of the other-oriented non-targets (8.7%; all $t\text{s} \leq 1$; $p\text{s} > .35$), not even when awareness rates were averaged across all other non-target orientations and compared to the awareness rates of the mirror-reversed target, $t < 1$, highlighting that awareness of the target position did not differ between the mirror-reversed condition and other orientations prior to selecting the target.

For the remaining conditions, performance strongly depended on whether the target had been selected as the last item (During Target) or whether a non-target had been selected as the last item (Post Target; see Fig. 4c). When the masks appeared while observers were fixating on the target (During Target), target localization accuracy was high (90.6%) and did not differ between the mirror target and the other targets, all $t\text{s} < 1.2$, $p\text{s} > .25$, not even when performance was averaged across the other-oriented non-target conditions and compared to the mirror-reversed condition, $t < 1$.

When the masks appeared *after* observers had fixated on one or more non-targets after selecting the target (Post Target), accuracy was generally lower (38.6%). Accuracy Post Target was lowest for the mirror target (26.1%), significantly lower than for the averaged awareness rates of the other-oriented targets (mean: 41.8%; range: 34.5–49.5%), $t(11) = 2.4$, $p = .035$, $\eta^2 = .34$. Accuracy on Post Target trials was significantly above chance across all non-target conditions, including the mirror condition, all $t\text{s} > 2.29$, $p\text{s} \leq .042$, $\eta^2\text{s} \geq .32$. However, masks were more likely to appear in the mirror-reversed condition (45.0%) than in the other conditions (mean: 35.8%; range: 29.9–42.8%; see Fig. 4b), and on a substantial proportion of probe trials, the mirror target had been selected more than once, which probably inflated the awareness scores.

When we only considered probe trials in which the target was selected *once* prior to the appearance of the masks (see Fig. 4d), awareness rates dropped to 20.7% for the mirror target, and were still significantly lower than for the other target orientations (M: 39.6%; range: 31.9–47.9), $t(11) = 2.77$, $p = .018$, $\eta^2 = .41$. Moreover, target localization accuracy for the mirror target was not significantly above chance (16.7%), $t < 1$, $p = .35$, but it was significantly above chance for all other-oriented targets, all $t\text{s} > 2.2$, $p\text{s} \leq .049$, $\eta^2\text{s} \geq .31$).

These results indicate that observers did not know the location of the mirror target after having fixated on it once. Moreover, these results were obtained despite the fact that observers apparently had a bias to choose one of the already selected positions as the target location (see the Before Target results). Such a bias for reporting an already selected position would artificially inflate accuracy for those trials in which the target had already been selected (i.e., our critical category for evaluating mirror blindness), and would thus work against finding low accuracies in the mirror condition.

To further analyze the bias, we additionally analyzed the proportion of trials in which participants reported the currently fixated item, separately for the different stimulus conditions (see Table 1). The results showed that observers were indeed biased to report the last selected item (on 65% of all trials); however, the bias was not especially strong for the mirror target and did not differ significantly across conditions, $F(4,44) = 1.06$, $p = .38$. Accuracy on trials in which the last selected item was reported was slightly higher (60.9% out of 100%) than accuracy on trials in which observers did *not* report the last selected item (53.6%), but these differences failed to reach significance, $F(1,11) = 1.46$, $p = .25$. However, accuracy significantly differed across the different search conditions, $F(1,11) = 4.22$, $p = .016$, $\eta^2 = .28$. Across both categories, accuracy was lowest for the mirror item, significantly lower than the average accuracy for reporting the target location in the other-oriented conditions (reported last: $t(11) = 2.26$; $p = .045$, $\eta^2 = .32$; not reported last: $t(11) = 2.4$; $p = .035$, $\eta^2 = .34$). Taken together, the results show that lower accuracy for reporting the mirror item was not driven by a bias to report the currently fixated item, but by a general perceptual deficit that applied regardless of whether the observers reported the last selected item or not.

Discussion

The results of Experiment 3 provide converging evidence for a mirror blindness effect: When observers made non-target fixations after target selection, they were largely unaware of the target location, showing that observers indeed failed to recognize the target and were genuinely continuing the search even after having fixated on the target. This makes one alternative scenario less likely, namely that processing of a mirror target simply takes longer and that observers fixated elsewhere while still processing the mirror target (as has for instance been reported in reading and other sequential tasks; e.g., Remington et al., 2011; Remington et al., 2018).

Moreover, the data convincingly show that mirror search does not differ from other-oriented targets in the pre-attentive phase, prior to shifting attention or the gaze to the target: Awareness scores did not differ between the mirror target and other-oriented targets prior to fixating on the target. In fact, the awareness scores for the mirror target were (non-significantly) *higher* than for two other-oriented targets (O1, O4) and (non-significantly) lower than for another two targets (O2, O3), suggesting no differences in processing mirror targets prior to target selection (see Fig. 4c). This result provides more evidence for the view that mirror search does not differ from other searches in pre-attentive, attention-guiding processes, but in later, target identification processes.

In line with this view, awareness scores collected after target selection were lowest for the mirror target, lower than for all other targets (see Fig. 4c), and this was the case even though awareness scores for the mirror target were inflated due to observers often fixating more than once on a mirror target. When observers had fixated only once on a target, awareness scores for the mirror target were indistinguishable from chance, indicating that observers were guessing and had no solid knowledge of the target location when they continued the search (i.e., fixated on another non-target; see Fig. 4d).

Another noteworthy finding was that awareness scores were very high and did not differ across conditions when the masks appeared while observers were fixating on the target. In cases where the currently fixated item was not the target, observers still had a bias to report the last fixated item as the target location. However, accuracies for the mirror target were lower than for the other-oriented items both when the last fixated was reported and when another item was reported. Moreover, the bias could not fully account for the high accuracies when observers were fixating on the target when the masks appeared ("during target"; see Fig. 4 and Table 1). The high accuracies during target fixations suggest that observers are apparently able to identify mirror targets when search is artificially interrupted by the masks. This indicates that, while there might be processes that tell the observer that the mirror target and distractors are all "the same," if the search is interrupted, the observer can interrogate an immediate

Table 1 Percentage of trials reporting the last selected item versus not the last selected item, and percentage correct for each category, with SEM in parentheses

	Mirror	O1	O2	O3	O4
Report Last	67.1 % (3.6)	63.2 % (3.7)	64.7 % (2.7)	62.1 % (3.0)	68.1 % (3.9)
Correct Last (out of 100%)	50.5 % (6.0)	62.7 % (6.6)	68.0 % (5.3)	62.9 % (6.3)	60.3 % (7.3)
Correct Not Last (out of 100%)	41.3 % (5.8)	49.4 % (9.1)	64.0 % (6.9)	50.1 % (8.9)	63.0 (8.3)

memory and successfully retrieve the information that distinguishes an item from its mirror. In other words, part of the difficulty of identifying mirror items may be due to the fact that observers did not identify the target within a (self-prescribed) time limit and continued with the search (e.g., Chun & Wolfe, 1996; Wolfe & Horowitz, 2017).

Before drawing final conclusions, it seems prudent to reproduce the most important findings with a different stimulus set, to ensure that the reported effects are not specific to the stimuli used in Experiments 1 to 3.

Experiment 4: Replication with new stimuli

Experiment 4 was designed to replicate the mirror blindness effect using a different stimulus that consisted of eight black squares (see Fig. 5) assembled into a meaningless shape that could still be distinguished in various different orientations. As in Experiments 1−3 the target was always the same, and the different conditions (mirror target and other oriented targets O1 to O4) were created by varying the non-target orientation (to ensure that differences in the results were not due to differences in the recognizability of the target).

The stimuli were tested in the same conditions as Experiments 1 and 2, with target certainty and non-target uncertainty (i.e., non-targets varying randomly within a block), as this is the most frequently tested condition in the previous literature (e.g., Treisman & Souther, 1985; Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992). The main variables of interest were the same as in Experiments 1 and 2 (mean RT and number of fixations, as well as time and fixations prior vs. after selection of the target). An awareness measure was not included, as this may alter observers' search strategies and contaminate the main variables of search time and eye movement behavior.

If the difficulties of identifying the mirror target in Experiments 1 and 2 were due to the specific stimuli used, we would expect no mirror blindness effect in Experiment 4. If, on the other hand, the results of the study generalize to different stimulus sets, we would expect the same results as in Experiments 1 and 2, with mirror search being characterized both by difficulties in selecting mirror targets and identifying it.

Method

Participants Thirteen new observers participated in Experiment 4.

Stimuli, design, and procedure These were the same as in the variable non-target condition of Experiment 2, with the exception that we used a different stimulus set. As in Experiments 1−3, the stimuli were created to be complex enough to be discriminable across different orientations, and did not resemble any known objects (see Fig. 5a).

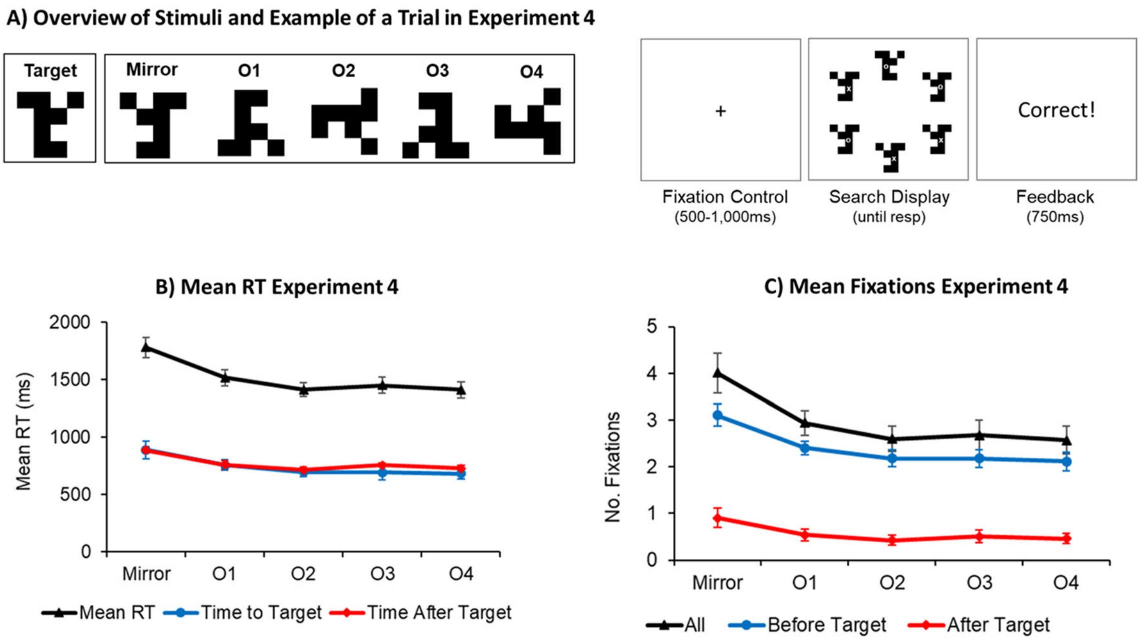

Fig. 5 **a** Overview of the stimuli used in the control experiment (Exp. 4; left panel) and depiction of an example trial (right panel). **b** The mean response time (RT) shows a significant RT cost for the mirror condition, which is about equally due to costs in finding the target (Time to Target) and costs in attempting to identify the target (Time After Target). **c** The analysis of the mean number of fixations showed similar results, with elevated fixations in mirror search being due to both increased fixations prior to finding the target, and after having fixated on the target (i.e., mirror blindness)

As in Experiments 1–3, the target always remained constant and the non-targets varied randomly, and observers were instructed to respond to a small x or o inside the target. Participants completed 60 trials per non-target condition for a total of 300 trials.

Results

Data Using the same outlier criteria as in Experiments 1 and 2 led to a loss of 1.56% of the data in Experiment 4; 1.53% because of a failure to look at the target, and 0.02% because of anticipatory or delayed responses.

Mean RT The mean RT and times prior versus after target fixation are depicted in Fig. 5. As shown in the figure, the results resemble the findings of Experiments 1 and 2, with mirror search incurring the longest RT, significantly longer than all other search conditions, all *t*s > 3.2, *p*s ≤ .007, η^2s ≥ .47 (O1: *t*(12) = 3.26, *p* = .007; O2: *t*(12) = 4.20, *p* = .001, O3: *t*(12) = 6.75, *p* < .001; O4: *t*(12) = 4.07, *p* = .002).

The RT costs of mirror search (331 ms) could be attributed to approximately equal amounts to early attention-guiding processes and later, target identification processes: The time until observers fixated on the target for the first time was longer for the mirror item than for the other-oriented non-target stimuli, all *t*s > 3.7, *p*s ≤ .003 (O1: *t*(12) = 3.78, *p* = .003; O2: *t*(12) = 6.23, *p* < .001; O3: *t*(12) = 7.10, *p* < .001; O4: *t*(12) = 5.49, *p* < .001). Similarly, the time after the first target fixation until a response reliably showed longer times required for the mirror item than the other-oriented non-targets, all *t*s > 2.3, *p*s < .032 (O1: *t*(12) = 2.43, *p* = .032; O2: *t*(12) = 2.54, *p* = .026; O3: *t*(12) = 3.41, *p* = .005; O4: *t*(12) = 2.36, *p* = .036).

Mean fixations The analysis of the mean number of fixations, and fixations prior versus after target selection showed similar results: Mirror search showed the highest number of fixations in a trial, significantly higher than all other orientation conditions, all *t*s > 3.3, *p*s < .006, η^2s > .48 (O1: *t*(12) = 3.35, *p* = .006; O2: *t*(12) = 3.95, *p* = .002; O3: *t*(12) = 5.69, *p* < .001; O4: *t*(12) = 3.92, *p* = .002).

Again, the difficulties with mirror search were due to both early attention-guiding processes and later, target identification processes: The number of fixations prior to target selection was significantly higher for mirror search than in all the other-oriented conditions; all *t*s > 3.4, *p*s ≤ .004, η^2s ≥ .50 (O1: *t*(12) = 3.49, *p* = .004; O2: *t*(12) = 4.46, *p* = .001; O3: *t*(12) = 5.87, *p* < .001; O4: *t*(12) = 4.59, *p* = .001), indicating that it took substantially longer to find the mirror target than all other-oriented targets. Moreover, the number of fixations after target selection was also significantly elevated for mirror items compared to all other-oriented non-targets, all *t*s > 2.7, *p*s ≤ .019, η^2s ≥ .42 (O1: *t*(12) = 2.96, *p* = .012; O2: *t*(12) = 3.00, *p* = .011; O3: *t*(12) = 4.25, *p* = .001; O4: *t*(12) = 2.72, *p* = .019), reflecting substantial contributions of later, target identification processes to the costs of mirror search.

Discussion

The results of Experiment 4 confirmed that mirror blindness generalizes to different stimulus sets. As in the previous experiments, observers were more prone to miss a mirror target than targets in the other-oriented control conditions (O1–O4). Analyzing the relative contributions of early attention-guiding and later target identification processes to the RT costs of mirror search revealed that early attention-guiding processes accounted for 55% of the RT costs, and that later target identification processes accounted for 45% of the overall RT costs. With this, the mirror blindness effect contributed less to the overall RT costs as in the equivalent conditions of Experiments 1 and 2, where mirror blindness accounted for 83% and 85% of the RT costs, respectively. The RT costs were also much smaller in Experiment 4 (331 ms) than in the previous experiments (> 1,000 ms), highlighting that different sets of stimuli can produce large variations in the magnitude of the effect. Yet, the failure to recognize mirror targets produced sizeable costs and accounted for a large portion of the overall costs of mirror search.

General discussion

The present study established that search for mirror items can incur costs after initial target selection. It could have been that mirror effects represent a failure to effectively guide attention to a target in the presence mirror-reversed non-targets, but our results show that, at least with some stimuli, the larger costs of searching for mirror items represent a failure to recognize the search target after it has been selected (or, at least, fixated). Across the different experiments and conditions, post-selection mirror blindness accounted for 87%, 85%, 82%, and 45% of the overall RT costs incurred by mirror targets.

In part, the small contribution of early, search-related factors may have been due to the fact that search was quite inefficient for these stimuli. On average, observers made two to three fixations per trial, which means that they fixated on half of all stimuli. This is a hallmark of an inefficient search where observe must fixate at random until they stumble onto the target (Treisman & Gelade, 1980; Treisman & Sato, 1990). There would not be much room for the effects of guidance to promising candidate targets in any condition, mirror or otherwise (Wolfe, 1994). This is not to say that pre-selection mirror effects do not exist. They are more likely to be seen with simpler search stimuli, like lines or simple drawings (e.g., Davis et al., 2003, 2006; Treisman & Souther, 1985; Wolfe & Friedman-Hill, 1992). The results with the present stimuli and other complex stimuli features (Gilden et al., 2010; Van Zoest et al., 2006) don't argue against pre-selection effects. Rather they argue for the existence of quite substantial post-selection effects when the correct stimuli are used.

Those "correct" stimuli do not need to be vastly complicated. It is interesting to note that Zhaoping and Frith (2011) found a large post-selection cost when observers had to search for an N among reversed-N non-targets, compared to another mirror condition where observers searched for the reversed-N among N's. In their study, observers typically only made one to two fixations to select the target in a large 12 × 16 grid, taking ~500 ms to select the target in both tasks (Zhaoping & Frith, 2011, Exp. 1). Large costs in responding to the letter N were almost entirely due to post-selection processes that commenced after the target had been selected. The results show the same search pattern as reported here, with observers arriving at the target location, and abandoning it to search elsewhere before they returned and executed a response. This behavior was found in both search tasks, but led to twice as long post-selection RTs in search for letter N than reversed-N and explained 92% of the overall costs in searching for letter N (Zhaoping & Frith, 2011, Exp. 1). As both of these tasks were mirror search tasks, the results do not directly speak to the origin of mirror search costs; however, they do indicate that large post-selective costs can also be observed when target and non-targets are relatively simple stimuli that can be found rather efficiently (see also Zhaoping & Guyader, 2007). Collectively, these results highlight the importance of using measures that can distinguish between early, attention-guiding processes and later, target identification processes, and caution against using mean RT to make inferences about early, attention-guiding processes.

Our analysis of fixation distributions revealed that mirror search differed from search among other-orientated non-targets in the probability of making three or more fixations after target selection (see Fig. 3, bottom). For other-oriented non-targets, search proceeded as expected. On the majority of trials, observers usually stopped searching once they fixated on the target. On a small number of trials, observers made one more eye movement before executing the response. By contrast, in search for mirror targets, the most frequently observed search pattern involved observers making three or more fixations after target selection before executing a response. This is somewhat remarkable since observers on average only needed two to three fixations to fixate the target after the start of the trial (see Fig. 3, middle left panel). The large number of fixations after that first target fixation could indicate that the observer failed to register the item as a possible target. Alternatively, observers might need to make several checking saccades, comparing the candidate target to distractors in order to be sure that they are different.

Last but not least, we also assessed observers' awareness of the target position by masking the search items at a random time during a trial and asking observers to report the target location (see Exp. 3). When the masks appeared prior to shifting the gaze to the target, accuracies were low and did not differ across conditions, indicating that mirror search does not differ from other orientation searches prior to attending to the target. Accuracies also did not differ when the masks appeared while observers were fixating on the target. Differences between mirror search and search for other-oriented items only emerged when the masks occurred during a fixation on a non-target *after* the target had already been selected. In this instance, accuracies for reporting the target position were lower for mirror items than other-oriented items, and accuracy for reporting the mirror item were at chance when the target had been fixated only once, indicating that observers genuinely missed the mirror target. These results were obtained despite a response bias artificially inflating accuracies for missed targets. Moreover, lower accuracies in mirror search were pervasive: they obtained regardless of whether one or more fixations were made on the target, and regardless of whether observers reported the last fixated item or not (see Fig. 4 and Table 1). These results imply that distinguishing the target from mirror items is impaired across a wide range of conditions.

Mirror blindness versus other forms of blindness

The kind of mirror blindness reported here and in previous studies on mirror search (Zhaoping & Frith, 2011) differs in important respects from other known forms of blindness such as Inattentional Blindness or Irrelevance-Induced Blindness (Eitam et al., 2013; Mack & Rock, 1998; Most et al., 2005).

Previous studies have already shown that we are prone to miss irrelevant items, both when they are unexpected (e.g., Inattentional Blindness; e.g., Mack & Rock, 1998) and, to a lesser degree, even when they are expected but irrelevant to the task (e.g., Irrelevance-induced Blindness; e.g., Eitam et al., 2013). However, these findings differ markedly from the mirror blindness effect reported here; as the missed items in these other studies were always task-irrelevant, and performance was often only assessed at the first occurrence or on rare trials (e.g., Godwin et al., 2015; Hout et al., 2015; Peltier & Becker, 2016). Correspondingly, Inattentional Blindness, Irrelevance-Induced Blindness and other reports of missed items have usually been attributed to the unexpectedness of the item, the fact that it was task-irrelevant and dissimilar to the search target, and/or the high cognitive load of the primary task (e.g., Eitam et al., 2013; Most et al., 2005).

By contrast, the present findings and previous findings on mirror search (Zhaoping & Frith, 2011) show that we can miss a highly relevant search item – the target. We can miss it repeatedly, despite perfect foreknowledge that the target will always be present, and even when the target is always the same across trials (see Exp. 2). Moreover, mirror blindness occurred even though there was no additional cognitive load, and the observer's single task was to select the target. This search task should have been fairly easy, as the non-targets were all the same, and the target differed in an elementary feature from the other non-targets (i.e., orientation; Treisman & Gelade, 1980).

The take-home message from these results is that it may be a fairly common phenomenon to miss target, also in other search tasks. Thus, we need to be skeptical when RT costs are used to make inferences about early, pre-attentive or search-related processes (e.g., Van Zoest et al., 2006; Wolfe & Friedman-Hill, 1992). Secondly, we cannot assume that target identification processes can be modelled as fixed cost at the end of the search processes, as there is a large variability in target identification processes with different stimuli and varying degrees of uncertainty (e.g., Becker, 2011; Horstmann & Becker, 2020; Horstmann, Ernst & Becker, 2019; Zhaoping & Frith, 2011).

The role of the non-target context in target identification

Experiment 2 revealed that mirror blindness for a known and constant target was stronger with variable than fixed non-targets. This result is unexpected on the basis of current theories of attention and object identification, which do not consider non-target uncertainty in computing target identification times, but instead have focused on target uncertainty and target-non-target similarity (e.g., Horstmann et al., 2019; Hout et al., 2015; Wolfe, 1994; Wolfe & Horowitz, 2017; Zelinsky, 2008).

One way in which non-targets could affect target identification processes is that contextual information about the non-target items may be part of the target template. It is well known that the non-target context can play a role in the guidance of attention and the gaze, in that attention and the gaze can be guided by the relative features of the target (or a "*relational target template*"; e.g., Becker, 2010). Although early, pre-attentive and later, target identification processes appear to operate on different templates (Hamblin-Frohman & Becker, 2021), it is possible that context-dependent representations can also play a role in later, target identification processes. In line with this contention, relational templates have been shown to determine attentional engagement in an Attentional Blink task (e.g., Becker, Atalla, & Folk, 2020a), and have also been shown to influence decisions in working memory tasks (e.g., Martin & Becker, 2018), suggesting that the non-target context could also play a role in later, decisional or memory-related processes. If the target template subserving target identification contains similar relational or otherwise context-dependent information, this could explain why target identification is more reliable when the non-targets are known and remain constant.

However, other explanations are also possible; amongst others that non-target variability affects target identification more indirectly, for instance, by coaxing observers to adopt a different target template (e.g., "upright"), or by shaping the observers' expectations about how quickly they should be able to identify a selected item as the target (or reject it as a non-target; e.g., Chun & Wolfe, 1996; Hooge & Erkelens, 1996; Zelinsky, 2008).

Another possibility supported by some previous studies is that the process of target identification may not involve comparing selected items to a target template, but (also) comparing the selected item to the other surrounding non-targets. In this case, difficulties in identification would be based on difficulties in discriminating mirror items – as the target is compared with other non-target items to determine if it is the odd-man-out, with a corresponding failure in discrimination leading to false rejection of the target (i.e., mirror blindness). Naturally, this manner of identifying the target only seems applicable in search tasks in which the target is the only deviant, and may require simultaneous selection of multiple items. Simultaneous selection of multiple items has been shown in some tasks (e.g., Reingold et al., 2001; Venini et al., 2014), and has been hypothesized to play a role in major models of visual search (e.g., Wolfe, 2021), but it remains an open question if simultaneous selection of multiple items is possible in sparse displays with more complex stimuli, as used in the present study.

In any case, the results of Experiment 2 indicate the need to modify existing accounts of target identification in visual search to account for the context effects, namely the strong differences in target identification with differences in the characteristics of the non-targets and their variability.

Is mirror blindness just a more severe form of a general target blindness?

The mirror blindness phenomenon suggest that a modification is needed for most current theories of visual search. Most models would concentrate on how attention and/or the gaze get to the target. Once the target is selected, we would typically consider that the search engine has done its job. Mirror blindness is a reminder that this view is too simple. Indeed, one could draw that conclusion from the other distractor conditions of the experiments presented here, as well. For example, if we return to Fig. 2, we see that observers are spending more time after the first fixation than before, not just in the mirror condition, but in the O1−O4 conditions, as well. They are making an average of about two fixations after the first fixation on the target in the O1−O4 conditions when the target or non-targets are variable. This strongly suggests that, on many trials, observers are failing to recognize the target on first fixation in all conditions, mirror or not. Mirror blindness might be an added blindness on top of a more general failure to 'see' what is right in front of the eyes.

As noted earlier, the mirror blindness effect may be due, in part, to hard-wired aspects of the representation of objects. Previous studies showed that humans and other primates have difficulty learning to discriminate between mirror images (e.g., Hill et al., 1997; Logothetis et al., 1994; see also Holmes & Gross, 1984), and that higher-order visual areas often do not discriminate between an item's specific orientation and its mirror orientation (e.g., Freiwald & Tsao, 2010; Kietzman et al., 2012; Perrett et al., 1991, 1998; Sasaki et al., 2000; Sereno & Maunsell, 1998). The failure to recognize a target among mirror non-targets may be rooted in the fact that neurons, recruited for target identification, respond similarly to an item and its mirror version, which leads observers to falsely categorize the target as a non-target and reject it, at least, at least until it is revisited later.

Something similar, if less dramatic, presumably occurs with the other-oriented non-targets. For many parts of the brain's object recognition apparatus, those rotated or mirrored non-targets are the same things as the target in the way that your pen needs to be coded as your pen, independent of its orientation on the desk. When a search task declares one of these items to be a target, the normal tendency to see all of the items as essentially the same gets in the way of the search task. This point is illustrated in Fig. 6.

In an important sense, all of the emojis in Fig. 6 are just hands. Under most circumstances, it would not be worthwhile to notice that one of them is vertically oriented and two of them are mirror reversed (even if that would turn them from right to left hands). Your nervous system is probably predisposed to represent all of these in a similar way and searching for one would probably elicit the problems described in these experiments.

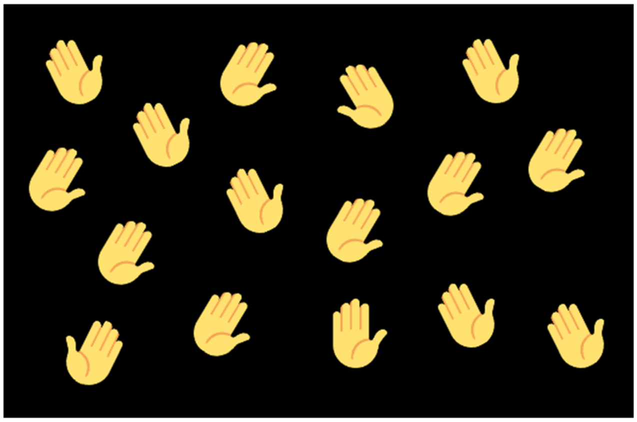

Fig. 6 All these emoji hands are, in some sense, the same. However, if asked, you could locate a vertical hand and you could find a mirror-reversed hand (with the thumb on the left). Actually, there are two mirror-reversed hands in the image. Did you find both?

Variability in guidance and identification

The present study also yielded some interesting findings with regard to attentional guidance, or gaze guidance (which are closely related; e.g., Deubel & Schneider, 1996). The main finding of the present study was that attention-guiding processes did not account for the total RT costs of mirror search, as has been previously suggested (e.g., Van Zoest et al., 2006). However, it is also interesting to note that difficulties in finding a mirror target, reflected in longer search times in the mirror condition than in the other-oriented conditions, did not vary as a function of target or non-target uncertainty. Target and non-target uncertainty both significantly modulated the mean time required to find the target, but did not interact with the effects different non-target stimuli had on search times. The fact that effects of target/non-target certainty and non-target type (mirror vs. other-oriented non-targets) were additive suggests different, independent processes underlying difficulties of finding mirror targets and general difficulties of finding targets when the targets and/or non-targets vary.

Another, perhaps somewhat puzzling, result is that the experiments appear to show substantial variation in the magnitude of the mirror blindness effect – with Experiments 1 and 2 seemingly showing relatively small costs of mirror search in attention-guiding processes that explained only a small fraction of the overall RT cost, and Experiment 4 indicating relatively large costs of searching for mirror items that explained more than half of the overall RT costs. However, closer inspection of the numbers reveals that the costs of mirror search in early attention-guiding measures were relatively constant, measuring 193−200 ms in Experiment 1, 122−152 ms in Experiment 2, and 184 ms in Experiment 4. Thus, what varied with varying degrees of target and non-target uncertainty was not so much the delay in *finding* mirror targets, but the costs of *identifying* a mirror target (which resulted in very different overall RT costs).

As noted earlier, the limited variance in attention-guiding processes across experiments and conditions may reflect that all experiments yielded quite inefficient search (e.g., Horstmann et al., 2020; Horstmann & Becker, 2020). While these speculations would need to be corroborated by further research, it is clear that the measures for attention-guiding processes showed markedly different results pattern from target identification times across the experiments and conditions, indicating that attention-guiding processes are based on different processes and mechanisms as target identification processes (see also Hamblin-Frohman & Becker, 2021; Yu et al., 2022). If this can be confirmed in further studies, it would also indicate the need to modify existing theories of visual search, which mostly assume that attention-guiding processes and target identification processes are based on the same target template and operate on similar processes that determine an item's match with the target template (e.g., Duncan &

Humphreys, 1989; Hout & Goldinger, 2015; Navalpakkam & Itti, 2007; Treisman & Sato, 1990; Wolfe, 1994; but see Hamblin-Frohman & Becker, 2021; Wolfe, 2021).

Conclusion

The present study reports a new mirror blindness effect in visual search, which demonstrates that we are more likely to miss a target among mirror items versus items of other orientations. These difficulties in visual search for mirror items were not solely due to early attention-guiding processes, but appear to be rooted in difficulties in distinguishing distractors from a mirror target. Using measures that could discriminate between early attention-guiding processes and later, target identification processes we discovered a *mirror blindness* effect that we attributed to observers being inclined to misclassify a mirror target as a non-target and to continue the search after they had already fixated on the target – without being able to notice or recall that they had already selected the target.

This mirror blindness effect differs from previous reports of Inattentional Blindness or Irrelevance-Induced blindness in that the mirror blindness effect is not dependent on any additional cognitive load. The item subject to blindness was not an irrelevant interloper; it was the target, itself. Nor was it unexpected or rare, but present on every trial. Moreover, mirror blindness was found to be frequent and led to large response time costs, even when the conditions were otherwise ideal for detecting and identifying the target (e.g., with perfect foreknowledge of target and non-target items).

Mirror blindness was significantly reduced but not eliminated when the non-targets were kept constant, which suggests that the effect is in part due to malleable, top-down controlled processes (which improved with the degree of target/non-target certainty), and in part due to potentially hard-wired, bottom-up factors (which remained despite perfect target/non-target certainty). Moreover, the finding that target identification varied with the variability of the non-targets suggests that target identification does not depend solely on matching visual inputs to a mental representation of the target (target template), but also to assuring that the item does not match what might be thought of as a non-target template.

Open practices statement The experiments of this study were not preregistered. All materials of the study including stimuli and program code, as well as all data are available upon request: Please contact s.becker@psy.uq.edu.au.

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