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Last but not least

Seeing the disappearance of unseen objects

Abstract. Because of the massive amount of incoming visual information, perception is fundamentally *selective*. We are aware of only a small subset of our visual input at any given moment, and a great deal of activity can occur right in front of our eyes without reaching awareness. While previous work has shown that even salient visual objects can go unseen, here we demonstrate the opposite pattern, wherein observers perceive stimuli which are not physically present. In particular, we show in two *motion-induced blindness* experiments that unseen objects can momentarily reenter awareness when they physically disappear: in some situations, you can see the disappearance of something you can't see. Moreover, when a stimulus changes outside of awareness in this situation and then physically disappears, observers momentarily see the altered version—thus perceiving properties of an object that they had never seen before, after that object is already gone. This phenomenon of 'perceptual reentry' yields new insights into the relationship between visual memory and conscious awareness.

1 Introduction

Many experiments over the past few decades have uncovered surprising situations in which observers fail to become aware of salient objects and events in their visual fields. Many such phenomena occur in the context of various types of perceptual 'blindnesses', including change blindness (eg Rensink 2002; Simons 2000), inattentional blindness (eg Mack and Rock 1998; Most et al, in press), repetition blindness (eg Chun 1997; Kanwisher 1987), and the attentional blink (eg Chun and Potter 1995; Shapiro et al 1997). The hallmark of these effects is the inability to consciously perceive physically present visual information. Here we employ a different type of blindness—*motion-induced blindness* (MIB)—to explore the opposite type of effect, wherein we *do* consciously perceive visual information which is *not* physically present.

In MIB, a salient target is presented along with a complex global motion pattern—for example a bright-yellow disc presented along with a rotating grid of blue crosses (see figure 1). When observers maintain fixation, a novel form of perceptual blindness occurs: the yellow disc fluctuates into and out of awareness (Bonneh et al 2001). Even slowly moving targets will disappear in this manner, ruling out a simple account based on adaptation, and local interactions between the grid and the target are not required, since MIB also occurs when the background motion never overlaps the target region

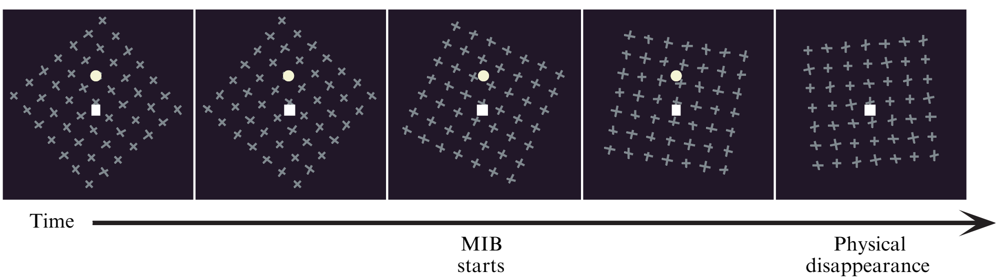

Figure 1. Snapshots of the critical stimulus from experiment 1 (not to scale). Observers fixate on a white square and attend to a bright yellow target disc while a grid of blue crosses rotates in the background. Eventually the target perceptually disappears due to motion-induced blindness, after which it is physically removed from the display (shown in black-and-white here, but in colour on the *Perception* website: http://www.perceptionweb.com/misc/p5341/; see also demonstration at http://www.yale.edu/perception/reentry/ or on the *Perception* website and annual CD Rom).

(Bonneh et al 2001). There is currently no consensus on why MIB occurs, but there have been several tentative proposals. MIB may arise from an attentional competition between the target object and the motion grid, resulting in a winner-take-all outcome: when a complex dynamic pattern consumes all of the available resources, none are left for processing the target, which thus fades from awareness (eg Bonneh et al 2001). Alternatively, MIB may arise from surface-level competition wherein the target and the moving pattern are seen to reside in separate depth planes, and when the pattern is perceived to be in front, it perceptually blocks the perception of the target (Graf et al 2002). There is similar disagreement as to the neurophysiological locus of MIB: some have suggested that MIB may be linked to early visual processing (Wilke et al 2003), while others have suggested that MIB occurs after V1 (Montaser-Kouhsari et al 2004) or have tried to explain MIB in terms of interhemispheric competition (Carter and Pettigrew 2003; Funk and Pettigrew 2003).

The work presented here may help to constrain theories of the underlying nature of MIB, but that is not our primary goal. Rather, we seek to exploit MIB as an especially apt tool for asking certain questions about how and when we can become consciously aware of representations of unseen visual information. MIB is ideal for this purpose because of several ways in which it differs from previously explored perceptual 'blindnesses'. Unlike repetition blindness and the attentional blink, for example, MIB does not impose strict timing constraints, and target stimuli can remain physically present for extended periods of time. Unlike most change-blindness demonstrations, which necessarily involve a single episode of blindness per trial, a target can fluctuate in and out of MIB indefinitely. Finally, unlike inattentional-blindness experiments, our studies allow for more than a single critical trial per observer, and occur even when observers are fully aware of the manipulations and are attending to the targets.

2 Experiment 1: Disappearing discs

We first used MIB as a tool to ask the following question: can observers detect the physical disappearance of an object already rendered invisible through MIB? This question seems somehow paradoxical: we are essentially asking whether observers can see the disappearance of an object which they cannot see. Nevertheless, the answer to this question is that such physical disappearances of unseen objects are easily detectable, a phenomenon we term *perceptual reentry*. Observers initially viewed a bright-yellow target disc superimposed on a rotating grid of crosses (see figure 1), and eventually the target perceptually disappeared because of MIB. Half of the time, the target would then physically disappear after some variable delay, and observers had to press a key as quickly as possible if and when they detected such disappearances.

In the experiment, observers fixated a central white square and attended to a stationary yellow disc (0.59 deg in diameter, 2.95 deg above fixation). Both were superimposed onto a uniform grid of blue crosses (13.76 deg across) which continuously rotated counterclockwise at 470 deg s^{-1} (see figure 1). Viewing distance was not restricted and all visual angle calculations are estimated from a typical distance of 40 cm. Eight observers participated in three 8-min testing sessions, each composed of two distinct blocks. In the first block, when observers reported MIB (by pressing and holding a key), there was a 50% chance that the yellow disc would physically disappear after a randomly predetermined interval of continuous MIB of either 200, 400, 600, 800, 1000, or 1200 ms. If observers detected the disappearance during the MIB episode, they were to press a second key as quickly as possible. Trials were aborted when MIB ended prematurely. In the second block, when observers were not reporting MIB, there was a 50% chance that the disc would disappear if enough time had passed (randomly predetermined as either 1200, 1400, 1600, 1800, or 2000 ms).

Observers' accuracy and response times to detect the disappearances are plotted in figure 2. The most important aspect of these results is simply the fact that observers were extremely accurate at detecting the physical disappearances, both when they occurred during awareness and during MIB [98% and 95%, respectively ($t_7 = 1.25$, $p = 0.253$)].[(1)] Note that this performance could not have been due to the fact that observers just happened to cycle out of MIB at the moment of the physical disappearance, since this event was temporally unpredictable, yet observers always reliably saw the disappearance in exactly the same manner (as an instantaneous flash). Moreover, observers were no slower to detect disappearances during MIB, after a quick leveling-off period at the shortest delays (figure 2).

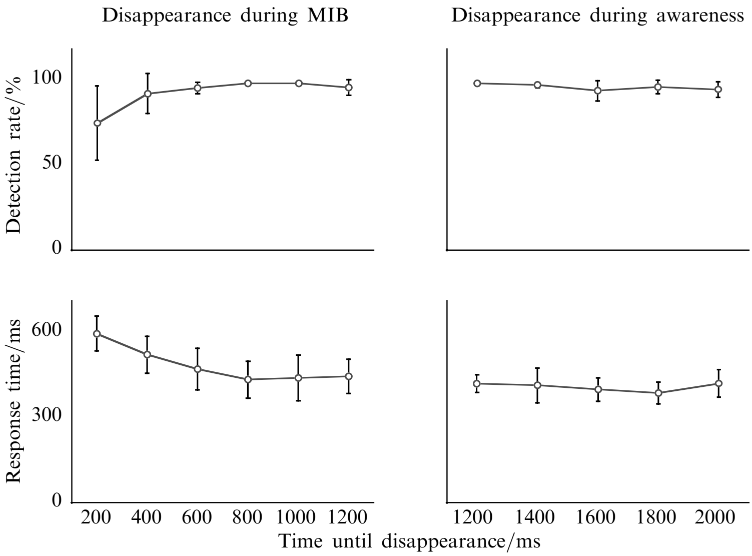

Figure 2. Detection rates and response times from experiment 1. Error bars are 95% confidence intervals.

Observers reliably perceived the physical disappearance of the unseen target as a momentary flash in one of two ways: at the instant the yellow disc from figure 1 physically disappeared during MIB, observers momentarily perceived the disc reappear as either a dark-blue flash (what we call the 'after-image') or as the yellow disc itself (the 'actual-image'). (These effects can be experienced in online demonstrations at http://www.yale.edu/perception/reentry/.) All observers experienced the 'after-image' percept and five of the eight observers also experienced the 'actual-image' percept (on an average of 34.96% of the physical disappearances). Both types of percepts demonstrate the opposite result from most phenomena of perceptual blindness: observers can be at least momentarily consciously aware of information which is not physically present. This is particularly striking in the context of the 'actual-image', wherein observers perceived visual information (eg the color of the disc) which was no longer on the retina. This had to be the case here, since the display cue which caused the 'actual-image' percept was the instantaneous physical removal of that very information. (Moreover, this phenomenon differs in two ways from classical positive afterimages:

(1) It seems probable that these high detection rates may be due to the fact that the target stimulus had extremely high contrast with the background and was relatively close to fixation. One previous study (Montaser-Kouhsari et al 2004) employed a peripheral low-contrast stimulus which disappeared during MIB, which observers never detected. Those researchers suggested that the physical disappearances were not detected simply because they were "already perceptually invisible because of the MIB" (page 251), but our results show that this needn't be the case.

first, positive afterimages have only been documented with stimuli that are orders of magnitude brighter than ours and, second, positive afterimages fade gradually rather than appearing as a momentary flash; cf Holcombe et al 2004.) Perceptual reentry thus demonstrates the maintenance of a veridical visual representation of an unseen stimulus which can momentarily reenter awareness.

3 Experiment 2: Rotating lines

In experiment 1, we demonstrated that visual information can be brought back into awareness for a moment after its source has physically disappeared; but where do such memories come from? On the one hand, such a memory could have formed during the period of conscious awareness which preceded the onset of MIB, and this representation could then have simply persisted until the moment when the target physically disappeared. On the other hand, the representations of the targets which were brought back into awareness in perceptual reentry could have been formed (or refreshed) *during* MIB. The latter explanation (the *refresh hypothesis*) involves the persistence of this information in visual working memory for only a moment, but requires that such target memories be formed or refreshed even without awareness of the targets themselves. The former explanation (the *maintenance hypothesis*), in contrast, does not require the formation or updating of visual memories during MIB, but does require that such representations can be maintained for at least several seconds, through entire MIB episodes.

In this experiment we directly tested the refresh and maintenance hypotheses by changing the target object during MIB: when observers reported that a vertical line was no longer visible because of MIB, the line began rotating slowly to either the left or right before it physically disappeared (see figure 3). The critical question is then whether observers would perceive the physical disappearance as a sudden flash (as either an afterimage or actual image) of the original (maintained) vertical line or of the rotated (updated) diagonal line.

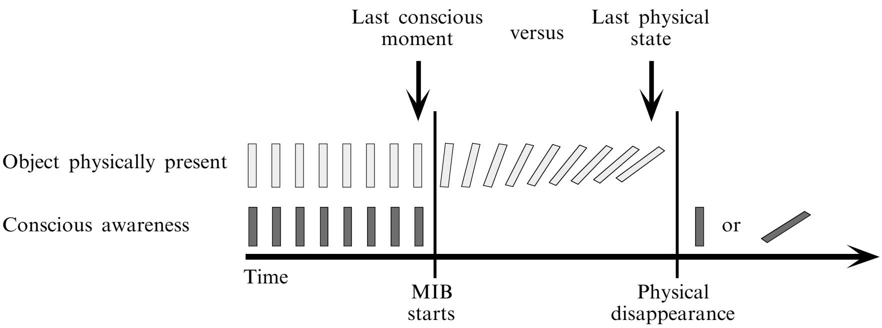

Figure 3. A depiction of the possible sources of the memory tested in experiment 2. A vertical target line eventually disappears owing to MIB, then rotates outside of awareness and physically disappears. The critical question is whether the physical disappearance will result in a momentary percept of the vertical line or the rotated line.

In the experiment, a vertical line (0.59 deg $\times$ 0.1 deg) rotated 45° to the left or right during each MIB episode. The rotation took 500 ms and would only complete if MIB lasted the full duration; if observers had any awareness of the physical rotation, the trial was aborted. 100 ms after the rotation completed, the rotated line would physically disappear. Five observers participated in three 5-min testing sessions. When observers detected the disappearance (on 86% of the trials, SD = 17.33%), they always perceived an afterimage or actual image of the *rotated* line and were 94% accurate at reporting its angle of rotation (SD = 9.46%). As in experiment 1, all observers experienced afterimage percepts and three out of the five observers also experienced actual-image percepts (on 22.33% of trials).

This experiment was phenomenologically interesting for observers: they always *knew* that the line was rotating, but had no idea in which direction it moved until it disappeared, when that information suddenly flashed into awareness. (We again invite readers to try to experience these effects for themselves in the online demonstrations.) These results are thus consistent with the refresh hypothesis: observers reliably perceived the reappearance of the object in its rotated form rather than as vertical. (See Mitroff and Scholl, in press, for a more in-depth look at what types of processing, or refreshing, can occur during MIB. In particular, it is shown that both object and group representations can be formed and updated without conscious access to the objects or groups themselves.) This is consistent with other recent evidence that orientation-specific adaptation can still be caused by the orientation of a Gabor patch which is rendered invisible owing to MIB (Montaser-Kouhsari et al 2004). Because the rotation in our experiment occurred entirely outside awareness, observers thus perceived not only something which was not physically present, but something which they had never seen before.

4 Discussion

As in many other perceptual 'blindnesses', observers in our MIB experiments often failed to consciously perceive salient visual information which was readily available (eg Bonneh et al 2001). The primary result of these experiments, however, was the opposite effect: observers were also able to become momentarily aware of visual information which was not physically present. This occurred in the context of 'perceptual reentry': when an object was rendered perceptually invisible because of MIB and then was physically removed, observers reliably perceived this disappearance. The most striking instances of perceptual reentry occurred when the target object was changed during MIB: when a vertical line rotated during MIB and then physically disappeared, observers saw a sudden flash of the rotated version. Moreover, some of these percepts occurred as 'actual-images', wherein observers saw momentary flashes of the yellow target objects themselves. Thus observers sometimes were consciously aware not only of visual information which was not physically present, but of visual information that they had never been aware of before it was physically removed from the display.

To our knowledge, no previous studies have demonstrated such phenomena.(2) Indeed, the only context in which related manipulations have been tested is with binocular rivalry, wherein different patterns are simultaneously presented to the left and right eyes, and the patterns compete for perceptual dominance such that one rises to awareness while the other is temporarily suppressed (for a review see Blake and Logothetis 2002). Two previous studies of binocular rivalry have explored the effects of manipulations that were made to patterns which were currently suppressed. In one study (Blake and Fox 1974) observers attempted to detect various types of changes which were made to suppressed gratings. They failed to reliably detect most such changes (eg in orientation, spatial frequency, or contrast decrements), and succeeded only for large contrast increments which dramatically increased the energy of the stimulus (see also O'Shea and Crassini 1981). In another study (Walker and Powell 1979), changes to the phase, orientation, or spatial frequency of a suppressed grating affected the perceptual

(2) It remains possible, however, that similar effects could occur in other contexts. For example, Alejandro Lleras (personal communication) reports that when a target is rendered perceptually invisible through Troxler fading (eg Lleras 2003; Luo 1999) and then physically disappears, observers can also detect such disappearances—though they seem to occur only as afterimages, not as 'actual-images'. Similar afterimages upon physical stimulus removal have recently been reported for perceptual disappearances elicited by contrast decrements (May et al 2003, page 768), though these researchers simply mention this observation in passing without reporting any experiments.

alternation rate such that it immediately reentered awareness, but observers often failed to detect the changes themselves. These demonstrations are importantly different from the perceptual reentry phenomenon reported above: in no case did these researchers test whether the *disappearance* of a suppressed stimulus would be detected, and, when changes were detected (or caused by the suppressed stimulus to reenter awareness), the stimulus was always still physically present.

The previous literature most closely connected with our results is perhaps that on 'postdictive' perception. In many types of apparent motion, for example, an object which is flashed at location A followed by location B is seen to traverse the space between A and B. This seems somehow paradoxical: the motion percept could not be computed until flash B had occurred, yet by that time it seems like it should be too late to impute motion leading up to B. Such phenomena thus illustrate how conscious visual perception is not an instantaneous moment-by-moment construction, but rather is formed by integrating information presented within brief temporal windows. Such results have been reported for several kinds of motion, from low-level apparent motion (eg Eagleman and Sejnowski 2003) to higher-level event perception (eg Choi and Scholl 2004). The current results demonstrate that such phenomena can occur even without motion. In our studies it seems somehow paradoxical that the instantaneous disappearance of an object could result in the brief perception of that object: once the object disappeared, it should have been too late to perceive that information. Instead, the phenomenon of perceptual reentry suggests that the contents of awareness can in some specialized circumstances be determined not only by the current state of the physical world, but by a form of visual memory. Though surprising amounts of visual information often fail to reach awareness while physically present, some visual information can enter awareness even after it is physically gone.

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