"Perceptual Scotomas" : A Functional Account of Motion-Induced Blindness

Joshua J. New and Brian J. Scholl
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Research Article

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Joshua J. New and Brian J. Scholl

Yale University

ABSTRACT—*In* motion-induced blindness *(MIB), salient objects in full view can repeatedly fluctuate into and out of conscious awareness when superimposed onto certain global moving patterns. Here we suggest a new account of this striking phenomenon: Rather than being a failure of visual processing, MIB may be a functional product of the visual system's attempt to separate distal stimuli from artifacts of damage to the visual system itself. When a small object is invariant despite changes that are occurring to a global region of the surrounding visual field, the visual system may discount that stimulus as akin to a scotoma, and may thus expunge it from awareness. We describe three experiments demonstrating new phenomena predicted by this account and discuss how it can also explain several previous results.*

Many of the most exciting phenomena in the study of perception arise because of a disconnect between distal stimuli and their associated visual percepts. Perhaps nowhere are such disconnects greater than in the study of visual awareness itself, as observers can completely fail to be consciously aware of objects and events that are right in front of them. Vision scientists have now uncovered many ways to make clearly visible objects and events "invisible" in this way (Kim & Blake, 2005). However, most such methods rely on weakening observers' visual processing from the outset—by displaying stimuli especially rapidly (e.g., in the attentional blink or repetition blindness), to each eye in a different manner (e.g., in binocular rivalry), in the periphery (e.g., Troxler fading), or in an unexpected manner while attention is otherwise engaged (e.g., in inattentional blindness). Recently, however, vision scientists have also uncovered a striking case of stimuli disappearing from awareness in what seems to be a more pedestrian context.

Address correspondence to Joshua New or Brian Scholl, Department of Psychology, Yale University, Box 208205, New Haven, CT 06520-8205, e-mail: joshua.new@yale.edu or brian.scholl@yale.edu.

MOTION-INDUCED BLINDNESS

In motion-induced blindness (MIB), a target stimulus may disappear and reappear from conscious awareness when it is presented along with a global motion pattern (Bonneh, Cooperman, & Sagi, 2001). This disappearance can occur repeatedly, for surprisingly salient objects, and even when observers are fully knowledgeable about the relevant manipulations. Figure 1 illustrates a dynamic display that can produce MIB. While the observer fixates the concentric circles at the center of the display, the target disc in the upper left corner might repeatedly disappear from awareness for several seconds as the grid of crosses rotates. (In the actual color displays, this effect is even more striking, because the disappearing target disc is bright yellow and thus even more easily distinguished from the white fixation circles and dark-blue crosses. Animations of this phenomenon and of the other manipulations reported in this article can be viewed on-line at http://www.yale.edu/perception/MIB/.) The initial studies of MIB (Bonneh et al., 2001) found that the frequency or duration of the disappearances could be increased by manipulating a number of characteristics of both the target (e.g., higher contrast, smaller size, or less motion) and the mask (higher contrast, more mask elements, or greater speed).

Since the initial report of this phenomenon, further research has characterized its dependence on additional types of lower-level visual properties—for example, demonstrating that MIB is enhanced when the target is placed stereoscopically behind the mask (Graf, Adams, & Lages, 2002), is interrupted by nearby transients (Kawabe, Yamada, & Miura, 2007), and is affected by factors such as target size, boundary length, and target-mask similarity (Hsu, Yeh, & Kramer, 2004, 2006). At the same time, other results have characterized MIB as a more central process. For example, the targets rendered invisible by MIB can still be processed in various ways (Mitroff & Scholl, 2004)—fueling negative afterimages (Hofstoetter, Koch, & Kiper, 2004) and orientation adaptation (Montaser-Kouhsari, Moradi, Zandvakili, & Esteky, 2004), undergoing grouping (Bonneh et al., 2001), and contributing to continually updated representations of objects persisting over time (Mitroff & Scholl, 2005). MIB cannot be

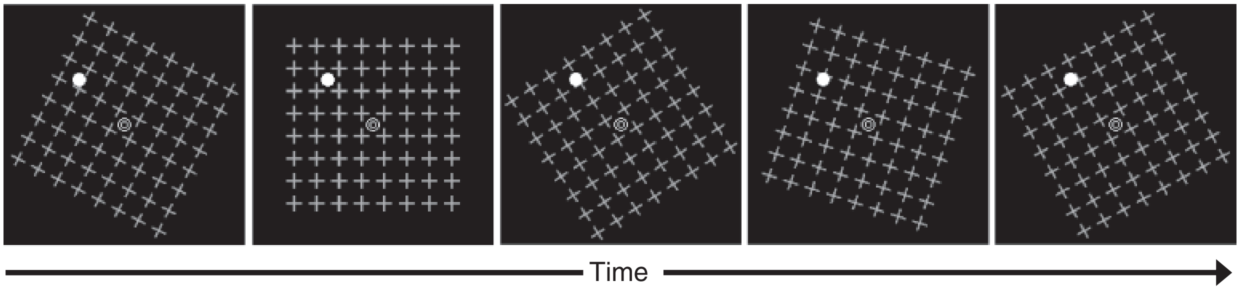

Fig. 1. Still frames of a typical motion-induced blindness display (not to scale). Observers fixate the center circles while attending to the target disc in the upper left quadrant. The mask made of crosses rotates smoothly counterclockwise. In the typical display, the center circles are white, the target is bright yellow, and the crosses are blue.

fully explained by appeal to sensory suppression or adaptation, because it occurs even with slowly moving targets (Bonneh et al., 2001), more readily for higher-contrast targets than for lower-contrast targets (Bonneh et al., 2001), and within seconds of display onset (Hsu et al., 2004). In addition, signal detection studies involving stimuli rendered invisible by MIB suggest a role for both decisional processes and sensitivity (Caetta, Gorea, & Bonneh, 2007).

Explaining Motion-Induced Blindness

Much of the interest generated by MIB is due to its mystery: Why does it occur at all? Other examples of perceptual disappearances can now be largely explained in terms of factors such as interocular suppression (in binocular rivalry; e.g., Blake, 1989), boundary adaptation (in Troxler fading; e.g., Krauskopf, 1963), lack of attention (in change blindness and inattentional blindness; e.g., Mack & Rock, 1998; Rensink, O'Regan, & Clark, 1997), or delayed attentional engagement (in the attentional blink; e.g., Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005). None of these factors, though, seems to account for MIB—in which even moving, attended, and fully visible objects may frequently disappear. To date, we can distinguish four approaches that address various aspects of MIB:

- *Attentional competition*. Inspired by similarities between MIB and impairments of visual awareness such as simultanagnosia (e.g., Rafal, 1997), Bonneh et al. (2001) initially suggested that MIB may reflect a disruption of the attentional competition that normally determines what observers are and are not aware of. In MIB, this disruption may be due to the salience of the mask, which slows attentional shifts and produces a winner-take-all competition for awareness (Bonneh et al., 2001; Keysers & Perrett, 2002).
- *Interhemispheric rivalry*. Because MIB shares features such as oscillation dynamics with binocular rivalry (Bonneh et al., 2001; Carter & Pettigrew, 2003), the same underlying interhemispheric competition may contribute to both phenomena (Carter & Pettigrew, 2003; Funk & Pettigrew, 2003). This possibility is supported by evidence that transcranial magnetic stimulation can enhance or disrupt MIB depending on the hemisphere to which it is applied (Funk & Pettigrew, 2003).
- *Boundary adaptation*. Analogies between MIB and perceptual *filling in* have suggested to some researchers that the same underlying mechanism of boundary adaptation may be involved in both phenomena (Hsu et al., 2004, 2006).
- *Surface completion*. Inspired by the demonstration that the relative stereoscopic depth of the mask and target can affect MIB, other researchers have suggested a link to visual surface processing: Perhaps the mask elements are integrated into a single visual surface, which is then taken to occlude the static target "underneath" (Graf et al., 2002).

Each of these accounts has been supported by impressive experimental demonstrations, and the perspective we offer in this article is not meant to compete with them. However, we suggest that these accounts do a better job of explaining the details of *how* MIB works than of *why* it occurs in the first place, perhaps because many of them are closely tailored to specific experimental results. Of course, these accounts are not mutually exclusive, and several of them may be combined, but even collectively they still do not give a clear sense of why MIB occurs. One reason for this may be that some of these accounts treat MIB at least implicitly as a *failure* of visual processing—due to overloaded attention, sensory overstimulation, or interhemispheric competition, for example. In contrast, we suggest that MIB could represent a *functional* response in visual processing; that is, it may be an example of the implicit "logic of perception" (Rock, 1983), rather than a failure to cope with the visual input in some way.[1]

[1]It remains an open question, however, whether the sort of functional account offered here could be applicable to other forms of perceptual disappearance, beyond MIB. Disappearances can arise from many different factors (Kim & Blake, 2005), and in some situations there may simply not be any additional explanation for why the stimuli disappear. Some other forms of perceptual disappearance, for example, are less temporally stochastic than MIB, being more refractory, time-locked responses to various kinds of transients (e.g., Kanai & Kamitani, 2003; May, Tsiappoutas, & Flanagan, 2003; Wilke, Logothetis, & Leopold, 2003); these phenomena may simply be a result of "low-level manipulations, directly impacting the early sensory representations" (Wilke et al., 2003, p. 1051). In other words, such disappearances may simply be an *artifact*, or inadvertent consequence, of the mechanics of how sensory representations are formed and maintained, rather than the result of a type of perceptual "logic."

A Perceptual-Scotoma Account

Here we explore the idea that MIB is a product of the visual system's attempt to separate distal stimuli from artifacts of damage to the visual system itself. When a small object is invariant with respect to changes that are occurring to a global region of the surrounding visual field, the visual system may discount that stimulus as akin to a scotoma, and may thus expunge it from awareness. According to this framework, the motion pattern in typical MIB displays poses a problem in constructing a coherent interpretation: How is it possible that the target stimulus is not participating in the global behavior of the rest of the visual field? This situation would be rare in real-world visual experience. It is exactly what would arise, however, from a stimulus in the visual system itself: a scotoma, a piece of detached retina, or even the ocular blood supply. These sorts of stimuli cannot participate in global motion patterns in the world, because they are not in "the world" in the first place. If the visual system is sensitive to this distinction, then typical MIB displays may serve as useful cues to fuel the inference that the target is not an actual object in the world. As a result, the target stimulus may suffer the same fate as a true scotoma, disappearing from view and being filled in by the background. We term this a *perceptual-scotoma* account of MIB. (This term is similar to "artificial scotomas," introduced by Ramachandran and Gregory, 1991, to discuss the phenomenon of perceptual filling in. Whereas they were motivated primarily by the fact of filling in itself, our usage is driven by potential similarities in the underlying logic of how and when some stimuli may be seen to be anomalous in the first place.)

Because the perceptual-scotoma account is intended to help explain why MIB occurs rather than how it occurs—and because it thus complements rather than contrasts with the accounts we noted earlier—it is not clear that a direct empirical test could support one view over the others. However, characterizing MIB in adaptive and functional terms can be empirically valuable, by directly leading to new key discoveries about the nature of MIB. Here we report tests of three novel predictions that were generated directly from the perceptual-scotoma account.

EXPERIMENT 1: TARGET-FIXATION MOTION CONGRUENCE

MIB can persist through slow movements of the target, perhaps because the eye can be considered as akin to a snow globe, wherein particles drift slowly, but do not move quickly or coherently. (Indeed, floaters are sometimes referred to as "motile scotomas.") However, MIB is typically eliminated by saccadic eye movements (Bonneh et al., 2001). Though there are several likely reasons for the elimination of MIB by saccades, the perceptual-scotoma theory makes a clear prediction that targets moving relative to the retina, compared with those moving in a retinally stable manner, should be less likely to undergo MIB, because scotomas themselves are retinally stable (and even floaters tend to move congruently with the retina). We tested this hypothesis with visual tracking, predicting that MIB would be greater when the target and the fixation point moved in concert than when they moved relative to each other (as depicted in Fig. 2).

Method

Five naive observers from a Yale University undergraduate psychology course participated for course credit. The stimuli were displayed with custom software written using the VisionShell graphics libraries (Comtois, 2007) and were presented on a Macintosh computer with a 15-in. monitor. Observers sat approximately 50 cm from the display, which subtended 31.82° by 23.94°. Observers fixated two white concentric circles (0.60° and 0.30°, respectively) in the center of the display and were asked to peripherally attend to a yellow target disc (0.40°) positioned 4.60° from fixation in the upper left quadrant of the display. A uniform grid of blue crosses subtending 14.0° by 14.0° was centrally positioned on a black background and rotated counterclockwise at a rate of 312°/s.

Observers viewed six 1-min intervals in which the target and fixation point oscillated horizontally 2.0° at 2.26°/s. *Congruent-motion* intervals, in which the target and fixation point oscillated in concert (see Fig. 2a), alternated with *incongruent-motion* intervals, in which the target and fixation point oscillated in opposite directions (see Fig. 2b). Whenever the target was not visible during the motion, observers pressed a key and held it down. The magnitude of MIB for each condition was measured as the summation of these key-press durations across all motion intervals in that condition.

Results and Discussion

As predicted, the duration of MIB was dramatically increased in congruent-motion intervals (46 s, SD = 25.617 s), compared with incongruent-motion intervals (1 s, SD = 1.091 s), $t(4) = 4.06$, $p = .015$, $d = 1.593$. This pattern was demonstrated in all observers (and readers who view the on-line movies should readily experience the same effect). This effect is consistent with the possibility that relative visual motion serves as a cue for the visual system to rule out a "scotoma" interpretation of the target, thus eradicating MIB.

EXPERIMENT 2: FILLING IN DURING MIB

The term MIB directly adverts to a lack of awareness of a stimulus, and researchers typically describe such phenomena in terms of the target "disappearing." But what is left after such a disappearance? One possibility is that what is left is simply an empty hole in visual space—that is, a lack of any stimulation from that region. This hole would not necessarily be visible in most MIB displays because they typically have empty black backgrounds. In fact, however, some people with mild scotomas

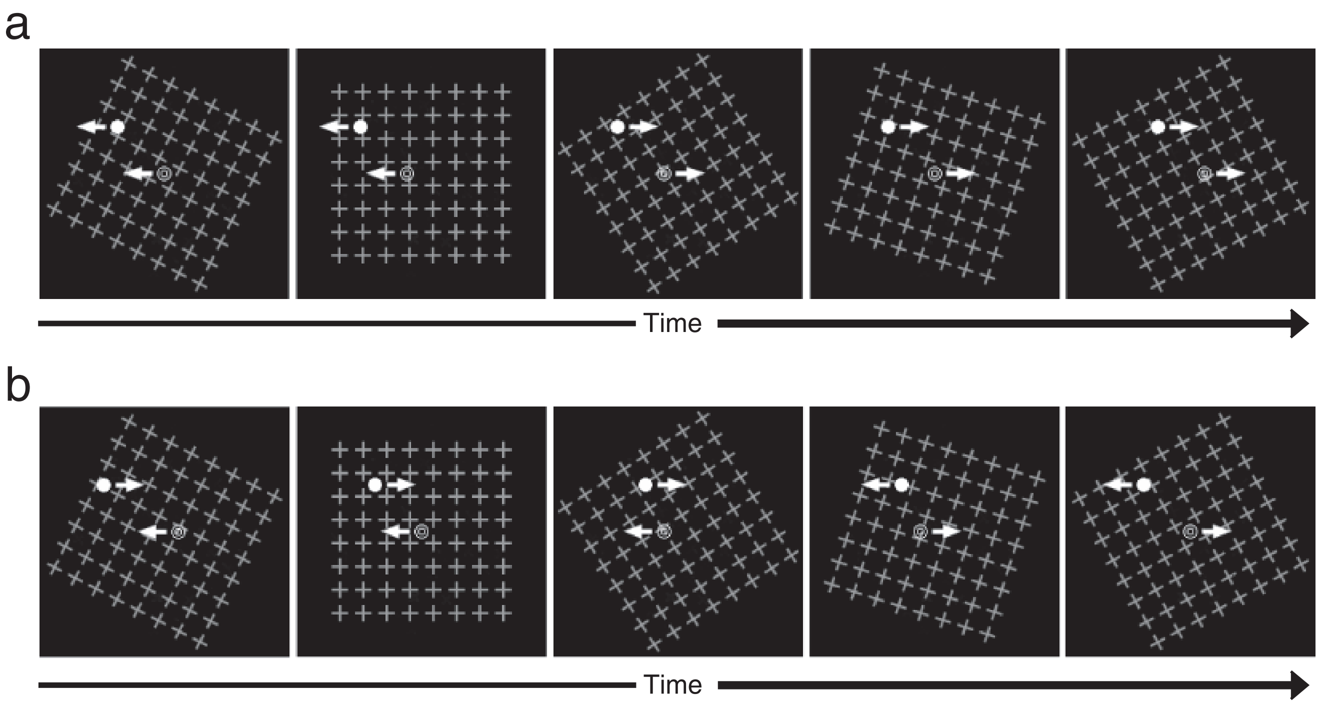

Fig. 2. Still frames of the displays used in Experiment 1. The white disc depicts the target (which was yellow in the actual displays). Arrows indicate motion and were not present in the displays. In the congruent-motion condition (a), the fixation point and target translated smoothly back and forth in concert. In the incongruent-motion condition (b), the fixation point and target oscillated in the same manner and at the same speed, but in opposite directions.

do not even know that their scotomas exist (e.g., Brown, Kylstra, & Mah, 2000) because the visual system copes with visual damage not by leaving a hole in visual space, but by filling in that region on the basis of the surrounding contextual cues. We predicted that the same logic should apply to MIB: When the target disappears, any surrounding texture should fill in that region of the visual field. We tested this hypothesis by contrasting a typical MIB display that had a textured target on a black background (Fig. 3b) with a new display in which the target was a "hole" in a densely textured background (Fig. 3a).

Method

The methods of this experiment were identical to those of Experiment 1 except as noted here. Six naive observers participated. The stimuli were presented on a 19-in. monitor with a viewable extent of 39.39° by 29.47°. They were presented within a black square (23.56°) centered on a blue background. Observers were asked to peripherally attend to a stationary target (0.744°) positioned in the upper left quadrant of the display, 8.77° from the fixation point. Radial arms each containing five blue mask discs were located every 20° around the fixation point, with the

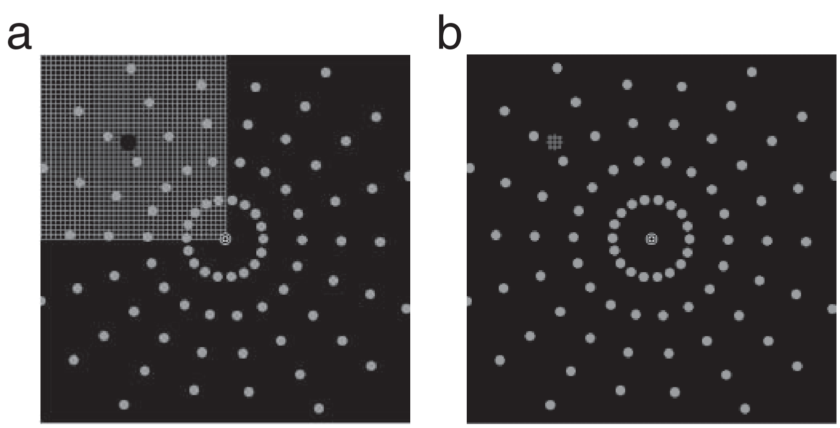

Fig. 3. Still frames of the motion-induced blindness display used in Experiment 2. The mask dots rotated smoothly clockwise at 205°/s, and the target was either (a) the circular hole in the grid in the upper left quadrant or (b) the circular gridlike object in the upper left quadrant.

individual discs located at eccentricities of 2.48°, 4.96°, 7.44°, 9.92°, and 12.40° (see Fig. 3). These discs rotated clockwise at 205°/s.

Each observer viewed twelve 30-s intervals that alternated between *hole* intervals, in which the target was a circular hole (0.99° in diameter) in a grid of vertical and horizontal lines (0.06° wide, positioned every 0.25°, and covering the entire upper left quadrant of the display), and *object* intervals, in which the target (0.99° in diameter) was a circular grid consisting of lines of the same dimensions.

Results and Discussion

All participants experienced robust MIB for the target in the object-condition intervals (summed duration of 37 s, SD = 13.931 s), which simply confirms that this type of display can give rise to MIB. Our key question involved the hole-condition intervals: Would the gap in the grid disappear due to MIB and be filled in by the surrounding grid? Each observer did experience this percept, essentially seeing the hole itself undergoing robust MIB (summed duration of 28 s, SD = 14.473 s). Thus, MIB, like visual scotomas, involves not only a perceptual disappearance, but also an active filling-in process.

EXPERIMENT 3: MOTION-INDUCED BLINDNESS WITHOUT MOTION?

The very name MIB indicates that this phenomenon is thought to rely on motion; though MIB may differ in magnitude depending on the type of motion, the initial report found that in all cases "movement was critical" (Bonneh et al., 2001, p. 799). Note, however, that the perceptual-scotoma account does not require motion, but requires only sustained global visual changes. We thus predicted that "MIB" should occur even when such changes are implemented via cyclic changes in global luminance (as in Fig. 4), because an object that maintains a constant luminance despite rapid changes in the ambient light level is unlikely to be a distal stimulus. This type of luminance flickering may activate some motion mechanisms, but it does not yield any percept of motion. And unlike some other forms of perceptual disappearance, such as those due to random dynamic noise (e.g., Ramachandran & Gregory, 1991; Spillmann & Kurtenbach, 1992), here the target was clearly distinct from the changing stimuli, because of both its high contrast and its spatial separation.

Method

The methods of this experiment were identical to those of Experiment 2 except as noted here. The radial arms each containing five blue discs were located every 45° around the fixation point, at the same eccentricities used in Experiment 2. Five naive observers participated. Each observer viewed twelve 30-s intervals that alternated successively among three different types. In *luminance* intervals, the mask discs oscillated smoothly every 0.44 s between the brightest and darkest blue (28% and 96% of the available display luminance; see Fig. 4). In *motion* intervals, the mask elements were always the brightest blue but rotated at 205°/s. In *static* intervals, the mask elements were always the brightest blue but were stationary. The target disc was again a solid disc, as in Experiment 1.

Results and Discussion

As predicted, MIB occurred even with global luminance changes. Moreover, the duration of MIB in luminance intervals (29 s, SD = 18.752 s) was not reliably shorter compared with the duration of MIB in motion intervals (43 s, SD = 16.215 s), $t(4)$ = 1.04, p = .357, but was reliably greater compared with the duration of MIB in static intervals (18 s, SD = 18.605 s), $t(4)$ = 3.33, p = .029, d = 0.623. This pattern was demonstrated in all observers. Thus, motion may not be required for "motion"-induced blindness, as long as a sustained global change forces the visual system to question the interpretation of the target as a distal stimulus.

GENERAL DISCUSSION

Because visual input is typically insufficient to determine the structure of the external world, the visual system must make *unconscious inferences* about the distal stimuli that gave rise to its input (Helmholtz, 1910/1925; Rock, 1983). The output of

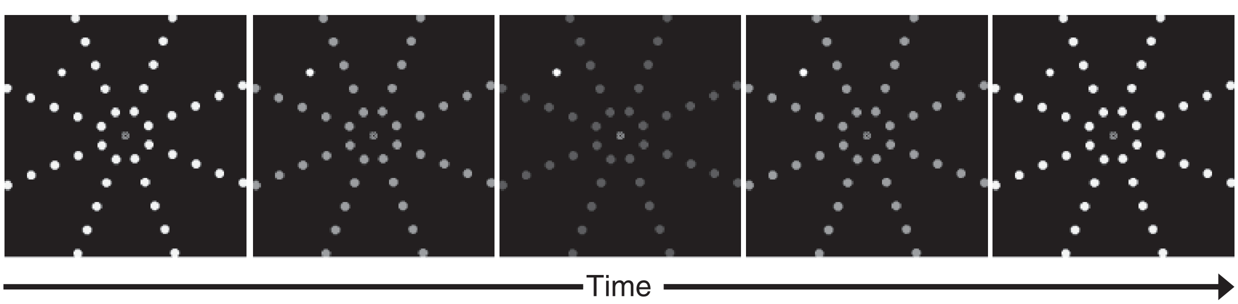

Fig. 4. Still frames of the display used in the luminance condition of Experiment 3. The static discs oscillated smoothly between the brightest and darkest blue (depicted here in gray scale). The disc that is white in all the frames depicts the target (which was yellow in the actual displays). The left-most frame by itself depicts the display used in the static condition.

such inferences often consists of perceptual decisions about particular visual features, such as shapes, colors, orientations, and the like. (Is the object a circle or an oval viewed obliquely? Is it red or bathed in red light? Is the facelike stimulus convex or concave?) The perceptual-scotoma account suggests that there may also be a more basic type of unconscious inference, about whether a bit of visual input reflects *any* distal stimuli in the first place. In some rare circumstances, the visual system may effectively infer that some bit of visual input corresponds to nothing at all in the world, but instead arises from some insult to the visual system itself—that is, that the input is caused by a scotoma. The result of this type of unconscious inference may be to expunge that stimulation from conscious awareness altogether, producing a perceptual scotoma. We suggest that such inferences may be invoked by a particular type of stimulation, wherein a small object is invariant with respect to changes that are occurring to a global region of the surrounding visual field. MIB involves just this type of situation.

The perceptual-scotoma framework explains how unconscious inferences could help give rise to MIB, but the inferences themselves may also be influenced by a multitude of independent cues that are integrated to arrive at an overall estimation of the likelihood that an object is actually externally present. This is the typical situation in visual processing, such as when many independently processed depth cues (e.g., occlusion, binocular disparity, motion parallax, aerial perspective) are integrated to arrive at a single percept of depth. Two such cues that plausibly influence the inferences giving rise to MIB were investigated in the experiments reported here: retinal stability and invariance with respect to global luminance transients. First, because most types of visual injuries are retinally stable, an anomalous target may be judged less likely to be in the outside world if it is moving with fixation rather than relative to fixation, as confirmed in Experiment 1. Second, because the logic of the perceptual-scotoma theory applies regardless of the type of global change to the visual field, an anomalous target may be judged as unlikely to be in the outside world even if the conflict does not involve any motion, as confirmed by the manipulation of global cyclic variation in luminance in Experiment 3. In addition, the demonstration of filling in during MIB (in Experiment 2) confirmed that, like visual scotomas, MIB is an active process that interpolates on the basis of the surrounding texture.

None of these three findings directly conflicts with any prior accounts of how MIB actually operates. (Theories that invoke attentional competition, boundary adaptation, interhemispheric rivalry, or surface processing could incorporate manipulations of luminance in addition to manipulations of motion, and can be supplemented by a filling-in process.) The results of the three experiments reported here do illustrate the empirical value of the perceptual-scotoma account of why MIB occurs, however, because they were directly (and necessarily) predicted by this framework. We also suggest that each of the discoveries in our three experiments is quite central to the nature of MIB. Indeed, these results suggest that "motion-induced blindness" might be an inapt term in two ways. First, the demonstration of MIB without perceived motion in Experiment 3 suggests that the underlying explanation of this phenomenon has little necessary connection to motion per se. Second, the active filling in observed in Experiment 2 suggests that there is more going on than simple blindness. MIB, in the end, may simply be a subset of a larger phenomenon of perceptual scotomas.

The perceptual-scotoma account of why MIB occurs cannot exist in isolation from other accounts of how MIB is actually implemented, because it does not directly predict effects such as those involving stereoscopic depth (Graf et al., 2002) or the disappearance of only one of two spatially overlapped objects (Bonneh et al., 2001). (That said, these other results do not conflict with the perceptual-scotoma view. Note, e.g., that visual scotomas are not always single disclike regions, but can also occur in many other shapes, including rings with islands of preserved internal vision.) However, beyond generating novel predictions about the nature of MIB, the perceptual-scotoma framework could also help to explain why certain other previously discovered effects occur. We note seven examples.

- MIB may be enhanced for small anomalous targets (Bonneh et al., 2001) because actual retinal degeneration generally begins in small regions and only gradually increases in size.
- MIB may be enhanced for especially high-contrast anomalous targets, fast mask speeds, and high-quality mask motion (Bonneh et al., 2001) because these factors all enhance the magnitude of the contrast between the mask and the target, thus enhancing the anomaly itself.
- MIB may be enhanced by attention to the targets (Carter, Luedeman, Mitroff, & Nakayama, 2008; Geng, Song, Li, Xu, & Zhu, 2007) for a similar reason: Such attention may serve to highlight the underlying conflict, whereas unattended targets may already go unnoticed without such effort, even without inducing a perceptual scotoma.
- At the same time, MIB may be enhanced for especially low-contrast anomalous targets (Hsu et al., 2004) because such targets provide relatively little bottom-up stimulation (constituting an anomaly that must then be explained away) in the first place.
- MIB may be sharply curtailed by any types of changes or local transients in the anomalous target region (Kawabe et al., 2007; Mitroff & Scholl, 2004) because actual scotomas do not undergo such changes. In other words, such changes may serve as sudden disconfirmations of the underlying inference that the anomalous target is not in the world.
- MIB may be enhanced when anomalous targets have extended boundary lengths due to convolution of their external contours (Hsu et al., 2006) because actual visual-field defects are typically simpler, bloblike, amorphous shapes.
- MIB may be enhanced by grouping cues such as connectivity (Bonneh et al., 2001; Mitroff & Scholl, 2005) because such

cues eliminate types of internal structure that actual scotomas do not have. For example, a dumbbell (consisting of two discs connected by a line) may disappear more readily as a unit (compared with two unconnected discs) because scotomas more typically consist of unitary areas, rather than separate, unconnected islands.

Going beyond the details of *how* the manipulations in these cases influence MIB, the perceptual-scotoma theory helps to explain *why* they do so, and it is striking that the account is able to unify such a seemingly unrelated set of findings. Most important, this framework differs from previous accounts in that it is functional: MIB, in this view, is an adaptive result of an unconscious inference about the likelihood of a bit of visual input being in the world. In this way, the perceptual-scotoma framework accounts for MIB via the same type of unconscious inferential process that has been appealed to in order to explain many other forms of visual processing (Rock, 1983).

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