

Motion-induced blindness for dynamic targets: Further explorations of the perceptual scotoma hypothesis

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Motion-induced blindness (MIB) is a striking phenomenon wherein fully visible and attended objects may repeatedly fluctuate into and out of conscious awareness when superimposed onto certain global moving patterns. Perhaps the most remarkable feature of MIB is that objects can disappear even when they are moving. Here we report several novel demonstrations of MIB for dynamic objects, including the observations that (a) MIB can occur for dynamic targets defined by various types of complex visual distortions (akin to those that may occur with various types of metamorphopsias), and (b) MIB is more robust for downward-drifting compared to upward-drifting objects (perhaps because of the related motions of floaters in the eye’s vitreous humor). To interpret these results, we focus on the idea that MIB may arise not from a limitation or failure of visual processing, but instead from a *perceptual scotoma*: MIB may reflect a functional inference in visual processing, eliminating some novel stimuli from awareness in much the same way that the visual system chronically eliminates percepts that would otherwise arise from visual impairments (such as scotomas) or features that are not in the external world in the first place (such as shadows from retinal blood vessels).

Introduction: Motion-induced blindness

One of the most striking phenomena of visual awareness is *motion-induced blindness* (MIB; Bonneh, Cooperman, & Sagi, 2001). A typical MIB display is exceedingly simple (see Figure 1): an observer fixates at the center of the display, and views two stimuli: (1) a bright yellow disc (the “target”), and (2) a grid of blue crosses (the “mask”) that rotates continuously about the fixation point. Though the target is always present in the display, it disappears from conscious awareness—often for several seconds at a time, over and over, and despite observers’ full knowledge of the

nature of the display. This is a remarkable phenomenon, since (unlike phenomena such as inattentional blindness or change blindness) it occurs repeatedly even when the target is the most salient object in the display, and is the explicit focus of attention. MIB is, however, a phenomenon only of conscious experience: targets that are rendered invisible due to MIB nevertheless continue to be subject to other types of nonconscious visual processing (e.g., Dieter, Tadin, & Pearson, 2015; Mitroff & Scholl, 2005; Montaser-Kouhsari, Moradi, Zandvakili, & Esteky, 2004), and can even continue to interact with objects within awareness (Meital-Kfir, Bonneh, & Sagi, 2016).

Researchers have now uncovered many factors that influence the strength of MIB—ranging from lower-level factors such as stimulus intensity (Bonneh et al., 2001; Libedinsky, Savage, & Livingstone, 2009), microsaccades (Bonneh et al., 2010; Hsieh & Tse, 2009), and adaptation (Gorea & Caetta, 2009; Hsu, Yeh, & Kramer, 2006) to more central processes such as grouping (Bonneh et al., 2001; Mitroff & Scholl, 2005; Shibata, Kawachi, & Gyoba, 2010) and decision thresholds (Caetta, Gorea, & Bonneh, 2007). Other studies have also investigated the relationship of MIB to various other types of manipulations such as stereoscopic depth (Graf, Adams, & Lages, 2002; Lages, Adams, & Graf, 2009; Sparrow, LaBarre, & Merrill, 2017), visual transients (Kawabe, Yamada, & Miura, 2007), mask properties (Thomas, Davidson, Zakavi, Tsuchya, & von Boxtel, 2017; Wells & Leber, 2014; Wells, Leber, & Sparrow, 2011), and target-mask similarity (Hsu, Yeh, & Kramer, 2004, 2006). And there has now been careful investigation of how MIB relates to the temporal dynamics and other properties of related phenomena such as binocular rivalry (e.g., Gallagher & Arnold, 2014; Jaworska & Lages, 2014) and Troxler fading (e.g., Bonneh, Donner, Cooperman, Heeger, & Sagi, 2014).

Finally, considerable work has now explored the neural substrates that contribute to MIB, focusing on

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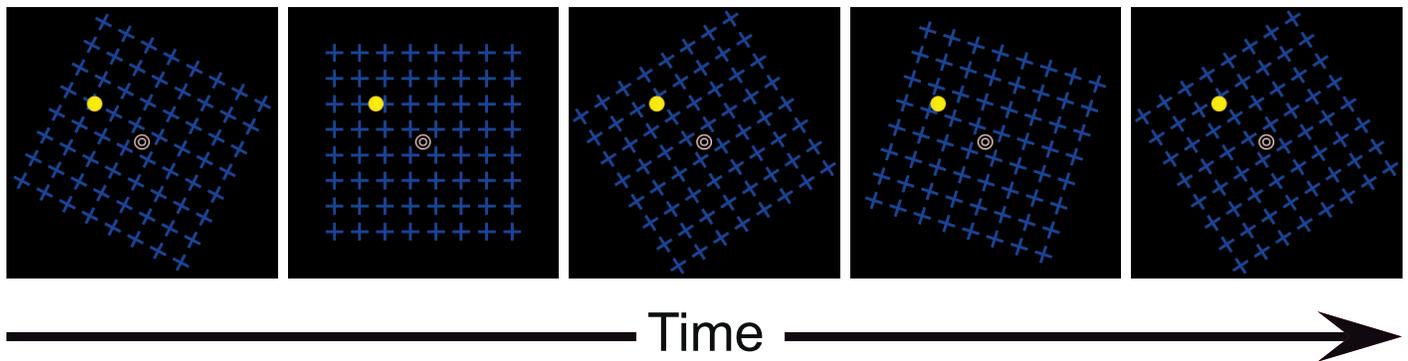


Figure 1. Still-frames of a typical MIB display as used in Experiment 1 (not to scale). Observers fixate the white concentric circles in the display center while attending to the solid yellow target disc in the upper left. When the mask made of crosses smoothly rotates, the target repeatedly disappears, even when attended.

visual cortical areas including V1, V2, V3ab, and V4 (Donner, Sagi, Bonneh, & Heeger, 2008, 2013; Libedinsky & Livingstone, 2011; Libedinsky et al., 2009; Schölvinck & Rees, 2010)—as well as V5/MT (Hsieh & Tse, 2009; Nuruki, Oliver, Campana, Walsh, & Rothwell, 2013; Schölvinck & Rees, 2010) and other regions such as the frontal eye fields (Libedinsky & Livingstone, 2011; Libedinsky et al., 2009), fusiform cortex (Matsuzaki, Juhász, & Asano, 2012), and right posterior parietal cortex (Nuruki et al., 2013).

Why does MIB occur?

Despite these many studies, part of the lasting appeal of MIB has been its underlying mystery: why does it occur in the first place? Most accounts of MIB have treated it as arising from some sort of limitation or failure in visual processing. This is true, for example, of the account sketched in the initial report of MIB (Bonneh et al., 2001), which was based on the idea of attentional competition: the mask and the target compete with each other for attention, with the mask sometimes “winning” this competition due to its complexity, leading to the disappearance of the “losing” stimulus. This sort of competition is thought to occur continuously, but usually goes unnoticed due to fast attentional switching (Bonneh et al., 2001).

This sort of attentional explanation for MIB is appealing, perhaps, because it is continuous with the explanations of other phenomena of visual awareness. On this account, we fail to see the target in MIB for the same underlying reason that we fail to notice the unexpected events in inattention blindness displays (Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005), for example, due to an underlying attentional limitation. More generally, many other failures of visual awareness are similarly explained by appealing to either limitations of the underlying processing (such as delayed attentional engagement, in

the attentional blink) or by weaknesses of the stimuli themselves (such as the graded boundaries that lead to adaptation in Troxler fading).

Further investigation, however, raises doubts about this sort of attentional-limitation account. In the first place, the rotating mask in MIB displays doesn’t actually seem so complex, relative to many real-world visual scenes. Indeed, part of the appeal of MIB for many observers is that the inducing stimuli seem so simple and straightforward. More generally, studies that have looked carefully at attention itself suggest a role that is the opposite of what might be expected: the more a target in an MIB display is attended, the *more* likely it is to disappear (e.g., Schölvinck & Rees, 2009).

Attentional competition is only one of several accounts that have been proposed to explain various aspects of MIB. For example, other theories have appealed to limitations based on interhemispheric competition (Carter & Pettigrew, 2003; Funk & Pettigrew, 2003), boundary adaptation (Hsu et al., 2006), and depth ordering (Graf et al., 2002; Hsu et al., 2006). All of these accounts are similar in one key sense, however, which is that MIB is treated as a failure, resulting from some sort of underlying limitation.

Perceptual scotomas: A functional account of MIB

In contrast to most other types of visual disappearances, we have proposed that MIB doesn’t arise from any sort of underlying limitation or artifact at all, but rather reflects a functional inference in perception. The targets in MIB displays don’t disappear due to some lack of processing or resources, but rather because the visual system is effectively inferring that the target *is not there* in the world in the first place. Why should such an unconscious inference occur? We proposed in the *perceptual scotoma* account of MIB (New & Scholl,

2008) that the target disappears for the same reason that the visual system discounts actual visual scotomas.

A *scotoma* refers to the lack of visual sensitivity in some circumscribed region of the visual field, usually due to damage (from injury or disease) to the underlying neural substrate responsible for processing in that region of the visual field (anywhere from the retina to visual cortex). Scotomas become increasingly common as we age, and they present a very particular sort of stimulus, as they remain invariant with respect to changes that are occurring in the surrounding global region of the visual field. The visual system apparently recognizes in such situations that this sort of stimulation does not arise in the world, but rather has its origin in the visual system itself. And because the goal of visual processing is to determine the nature of the local visual environment, the visual system simply expunges most scotomas from awareness—filling in the affected regions based on the surrounding visual input (e.g., Gerrits & Timmerman, 1969; Zur & Ullman, 2003). In fact, such compensation can be problematic from a clinical standpoint, since it may delay awareness of increasing visual field loss caused by disease or injury (e.g., Gassel & Williams, 1963).

This same sort of processing may occur almost continuously during intact vision, with respect to other sorts of stimulation. Consider, for example: Why don't we constantly see shadows from the blood vessels that line the surface of the retina? After all, these stimuli can be quite salient, and can even be mapped in visual cortex (e.g., Adams & Horton, 2002). It would obviously be maladaptive to walk around the world seeing parts of our own eyes, however, and so the visual system functionally erases such stimulation from our awareness, just as it does a scotoma. Moreover, the fact that this compensation and erasure occurs as an online functional inference is clear from those rare exceptions in which you *do* see your own retinal blood vessels. While using an ophthalmoscope, for example, an optometrist may move a bright light very near to the pupil, such that the shadows cast by blood vessels actually *move* on the retina for a moment—at which point they momentarily jump into awareness.

The perceptual scotoma account of MIB essentially says that the target in an MIB display disappears for the same adaptive reason that an actual scotoma or shadow from a retinal blood vessel disappears: the visual system has decided that it is not “out there” in the world in the first place. Why should the visual system make this inference in the case of MIB? The MIB stimulus effectively replicates the essential features of actual visual scotomas: an otherwise salient and retinally stable local region of contrast fails to participate in the global behavior of the rest of the visual field. In contrast, it would be very unlikely for an actual object in the world to remain invariant against

the background of our moving visual environment in this way. As a result, the visual system treats the target in MIB as if it were a scotoma and removes it from visual awareness. This is a *functional* theory in that the disappearance is thought to serve an underlying purpose, and is not thought to reflect any sort of capacity limitation.¹

The perceptual scotoma account suggests that MIB may be a fundamentally different sort of phenomenon than is supposed in some previous accounts. In the first place, MIB is not taken to be a form of blindness per se, since scotomas are actively filled in. This wasn't apparent in the initial studies of MIB: since they all used a black background, it wasn't possible to distinguish filling-in from a complete absence of any percept in the target region during the disappearance. The possibility of filling-in can be tested, however, by using a dense grid as the background of an MIB display, and using a *hole* in the grid as the target. In this situation, consistent with the perceptual scotoma account, it is the hole that disappears and is then filled in with the background texture (New & Scholl, 2008, experiment 2). Another central way in which the perceptual scotoma account recasts MIB is that motion is no longer seen as necessary. Instead, motion is just one example of a dynamic global pattern in which the target does not participate. This prediction has been confirmed for the case of cyclic luminance changes, which do not involve any motion, but still cause targets with an unchanging luminance to repeatedly disappear—and considerably more so than might occur from static filling-in without the dynamic luminance changes (New & Scholl, 2008, experiment 3).²

The current study: MIB for dynamic targets

We have proposed that the perceptual scotoma framework can also explain several other previously reported characteristics of MIB, and that it may be especially well suited to explaining *why* MIB occurs (New & Scholl, 2008). But there is at least one conspicuous feature of MIB that at first blush may seem to challenge this framework: objects in MIB displays can disappear even when they are (slowly) *moving* (Bonneh et al., 2001; Mitroff & Scholl, 2005). This might initially seem challenging for the perceptual scotoma framework, since scotomas typically *don't* (and can't) move. And this is obviously also true for the shadows cast by retinal blood vessels: the blood vessels themselves are fixed on the retinal surface, and their shadows would only move in situations that are exceptionally ecologically unlikely (e.g., involving a moving point light source very near the pupil).

The present study thus explores when and how MIB may occur for dynamic targets. The primary purpose of

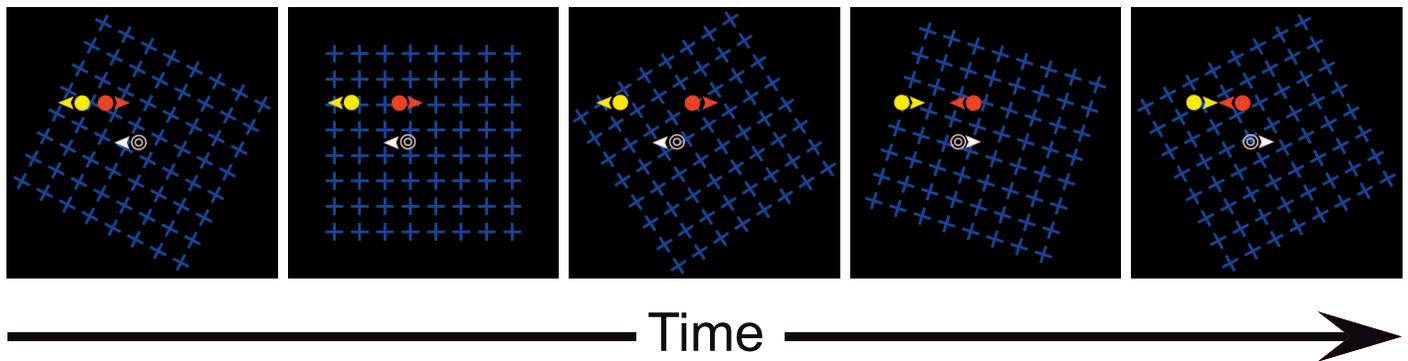


Figure 2. Still-frames of the displays used in Experiment 2, in which two discs simultaneously moved in opposite directions. Arrows indicate each disc's direction of motion, and were not present in the actual displays. Note that the yellow disc moves with the fixation circles, while the red disc moves in the opposite direction from the fixation circles.

the experiments reported here, however, is not to defend the perceptual scotoma framework, as it has already been articulated and empirically tested in previous work (New & Scholl, 2008). Instead, this study was intended to uncover and report a number of novel and interesting MIB phenomena, each of which was directly inspired and predicted by the perceptual scotoma framework. In particular, we used the perceptual scotoma framework to generate and test new predictions about (a) how MIB should behave in the context of multiple moving targets (only some of which may be consistent with a visual scotoma; Experiment 1); (b) dynamic targets that are not separate objects but rather are formed by local distortions of mask elements themselves (akin to phenomena that may occur with various types of metamorphosias; Experiment 2); and (c) targets that drift upward versus downward in the visual field (as may be related to motions of floaters in the eye's vitreous humor; Experiments 3a–3c).

Experiment 1: MIB with multiple targets moving in different directions

MIB is extinguished by saccadic eye movements (Bonneh et al., 2001) and nearly all MIB studies to date have therefore required observers to fixate a static central point. However, we have previously demonstrated that MIB can occur even with a moving fixation point. The perceptual scotoma hypothesis predicts that any stimulation that maintains a stable position in the visual field irrespective of eye movements should be readily construed as a scotoma, compared to an object that moves differently from fixation. As predicted, targets moving with fixation were more likely to

disappear than were targets moving against fixation in an MIB display (New & Scholl, 2008).

However, it has since been confirmed that microsaccades influence the likelihood of disappearances in MIB (e.g., Bonneh et al., 2010; Hsieh & Tse, 2009). This effect could have confounded the earlier demonstration of MIB with a moving fixation point, since incongruent target/fixation motion could give rise to more frequent microsaccades than congruent target/fixation motion. To test this possibility in the present experiment, both types of motion were presented in a single MIB display with two simultaneously moving targets (see Figure 2). (Dynamic animations of this display—and of each of the other experiments reported in this paper—are available online at <http://perception.yale.edu/MIB/>.) With the display equated in this way, the perceptual scotoma view still predicts that the target moving with fixation will disappear more readily than the target moving against fixation. The three goals of this first experiment were thus (a) to conceptually replicate the previous result, (b) to preclude any confounding contributions of microsaccades (or attentional shifts) in this case, and (c) to provide an especially compelling demonstration of the importance of stability on the retina in MIB.

Method

Six naïve observers from a Yale undergraduate psychology course participated in exchange for course credit. This sample size was chosen in advance to match that used in one of the only previous studies of MIB with moving targets (New & Scholl, 2008); as reported below, the primary effect was observed in each and every observer. The stimuli were displayed with custom software, presented on a Macintosh computer with a 15-in. display. Observers sat without restraint approximately 50 cm from the display, which at this distance subtended 31.82° by 23.94° (this viewing distance was

used to calculate all of the extents below). Observers fixated two white concentric circles on a black background in the display's center (0.60° and 0.30° , respectively) and were asked to peripherally attend to both yellow and red target discs (0.40°) both initially positioned 4.60° from the mask center in the upper left quadrant of the display, with one disc randomly occluding the other at the beginning of each interval. A uniform grid of blue crosses subtending 14.0° by 14.0° was centrally positioned (surrounding the fixation circles) and rotated counterclockwise at a rate of $312^\circ/\text{s}$. The grid was constructed of 8 rows of 8 crosses each, with each cross subtending 1° , and separated by 2° from its nearest neighbor (measured from their centers).

Observers viewed six 1-min intervals in which the fixation stimulus oscillated horizontally over 2.0° at $2.26^\circ/\text{s}$, initially moving randomly either left or right from its beginning central position. Each of the target objects also moved throughout each interval, but in different ways. One of the targets moved in a *retinally stable* fashion, oscillating horizontally in step with the fixation circles. The other target moved in a *retinally variant* fashion, oscillating in the same manner and speed but always moving in the opposite direction as the fixation point, such that the two targets always moved as mirror images of each other (see Figure 2 for a static depiction or the online animation for the stimulus itself). The two targets were always different colors (red or yellow), with the assignment alternating for each interval.

Each of the targets was assigned to a response key on the keyboard, and during each interval observers pressed (and held) the corresponding key down whenever either target disappeared, immediately releasing the key when that target reappeared. The magnitude of MIB for each target type was measured as the summation of these keypress durations across each of the six intervals.

Results

The magnitude of MIB is reported in each experiment here as the average percentage of time that targets were reported to be invisible compared to their total presentation duration. In a 2×2 repeated measures MANOVA, target color did not influence MIB either as a main effect, $F(1, 5) = 4.075$, $p = 0.100$, $\eta_p^2 = 0.45$, or via an interaction with target motion type, $F(1, 5) = 0.710$, $p = 0.438$, $\eta_p^2 = 0.12$. As predicted, however, there was a significant main effect of the target motion type, $F(1, 5) = 8.124$, $p = 0.036$, $\eta_p^2 = 0.62$, in which MIB was twice as strong for retinally stable objects (10.38%, $SE = 3.21\%$) than for retinally variant objects (5.09%, $SE = 1.93\%$). This pattern was also true for each and every observer individually, and may be

appreciated as a vivid demonstration when viewing the online movies.

Discussion

The effect observed in this experiment, in which retinally stable targets disappeared for longer than retinally variant targets, is consistent with the perceptual scotoma hypothesis, since targets that change retinal position are less likely to be identified as scotomas, and are thus less susceptible to being removed from conscious awareness. The demonstration of this effect for multiple targets in a single display rules out the possibility that the initially reported effect (New & Scholl, 2008) was an artifact of differing microsaccade patterns in congruent versus incongruent displays. Note that this also effectively rules out the possibility that this difference is due to differing patterns of attentional shifting, which can also have an independent robust effect on MIB (e.g., Schölvinc & Rees, 2009). Indeed, the present results show that the effect of retinal stability has nothing to do with *any* properties of the display as a whole, since the effect is selective, with one target disappearing much more readily than a second target at the same time in the very same display, at the same time. According to the perceptual scotoma hypothesis, this is because one of the targets has a key property of a scotoma, while the other does not, even while both traverse identical trajectories. Although the retinally variant target was likely more salient, this by itself would predict the opposite pattern of results from the one we observed, since the more a target is attended, the more it disappears (Schölvinc & Rees, 2009); this is even true based on salience due to factors such as higher contrast (Hsu et al., 2004).

It should be noted that retinal stability has long been known to promote visual disappearances in many types of related phenomena, and retinal instability conversely forestalls and interrupts disappearances. This is typically held to result from lower-level processes including sensory suppression and adaptation. However, target disappearances in MIB displays have been shown to be a phenomenon almost entirely of subjective awareness, wherein targets, even during their “disappearances,” are nonetheless being actively processed. For example, “disappeared” targets still cause afterimages (Hofstoetter, Koch, & Kiper, 2004; Mitroff & Scholl, 2004) and orientation adaptation (Montaser-Kouhsari et al., 2004), can be grouped and ungrouped (Bonneh et al., 2001), are continually updated over time when changing position and orientation (Mitroff & Scholl, 2004, 2005), and can even interact with objects that remain within awareness (Meital-Kfir et al., 2016). These

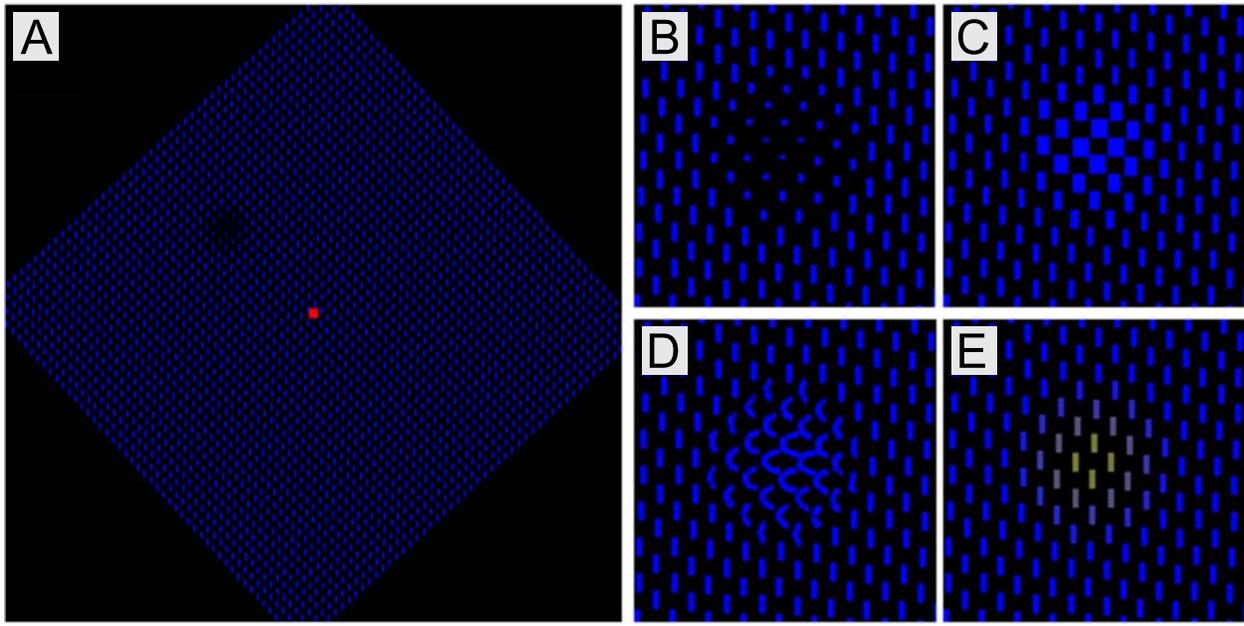


Figure 3. Still-frames of each manipulation used in Experiment 3. (A) The full display frame on the left shows the graduated Luminance decrease of the mask elements from 100% down to 9.80% of the available luminance. Expanded views of the other manipulations themselves depict: (B) a graduated Contraction in height of the elements from 0.30° down to 0.03° ; (C) a graduated Expansion of the mask lines into 0.24° squares; (D) a graduated Curvature of the mask lines into half-circles with a 0.61° radius; and (E) a graduated Color change from solid blue (RGB: 0, 0, 255) to yellow (RGB: 100, 100, 0).

features of MIB make an account based only on sensory suppression unlikely.

Experiment 2: Scotomas as visual field distortions

Nearly all studies of MIB to date have employed the same type of target: a solidly-contoured object (most commonly a small disc, as in Experiment 1) on a uniform background. This type of target effectively emulates the most familiar type of scotoma (termed an *absolute scotoma*), which presents a complete interruption of visual processing. However, there are several other types of scotomas that are also retinally stable but introduce different types of disorders in visual processing.

Here we explore whether MIB might compensate for three other ways in which scotomas can manifest. First, scotomas are often not completely opaque but only attenuate the perception of stimuli in local regions of the visual field; these are termed *relative scotomas* (see Figure 3A). Second, scotomas may produce spatial distortions of stimuli in local regions of the visual field, much like a bubble in a pane of glass; such distortions are termed *metamorphopsias* (e.g., la Cour & Friis, 2002; see figures 3b–3d). Such spatial distortions can commonly result from conditions such as macular degener-

ation, amblyopia, and retinal detachments. These visual irregularities, however, can go completely unnoticed by the viewer and are difficult to detect, even in standard ophthalmological examinations (e.g., Amsler grid reports), because of perceptual completion (Achard, Safran, Durel, & Ragama, 1995; Schuchard, 1993). Third, scotomas can produce locally color-blind or color-anomalous regions without any other distortions; these are termed *color scotomas* (see Figure 3E).

As with the more familiar case of opaque scotomas, each of these other sorts of disruptions is also the focus of automatic compensation in the visual system, such that they are frequently only apparent in certain special circumstances. As such, the perceptual scotoma account predicts that the “blindness” of MIB may also occur for dynamic but positionally stable distortions of the visual field, in cases where there is no discrete target object distinct from the background (here the rotating mask) itself. The demonstration of such an active and ongoing compensation would readily cohere with evidence that neural activity in regions representing targets actually increases during their disappearances (Schölvinck & Rees, 2010; but see Donner et al., 2008). We tested this possibility here for dynamic mask distortions analogous to the three other types of scotomas discussed above: spatial distortions, luminance distortions, and color distortions. In each case, the distortion applied to all and only the mask elements that were passing through the affected region in a given moment.

Method

Six naïve observers from a Yale undergraduate psychology course participated in exchange for course credit. This sample size was chosen in advance to match that of Experiment 1. Observers sat without restraint approximately 50 cm from the display (with this viewing distance used to calculate the extents below). The stimuli were displayed with custom software written with Processing 1.0 software (Reas & Fry, 2007) and preprocessed into Java for execution. The experiment was presented with a PC computer in a 26.45° square window in the center of a 19-in. display. A uniform square grid of mask elements (blue bars) subtended the center 25.67° by 25.67° region of the display. The mask elements each measured 0.10° by 0.30°, were spaced 0.40° apart vertically and horizontally from their centers, and maintained a straight vertical orientation as they rotated clockwise at a rate of 34.38°/s (see Figure 3 and the online animation).

Observers fixated a red square (0.40°) in the display's center and were asked to peripherally attend to a point in the upper left quadrant of the display. In a practice session (the results of which were not recorded), a yellow square (0.30°) was positioned diagonally 5.96° from the mask center in the upper left quadrant of the display, to indicate the target position. In the experimental session, observers viewed three 45-s intervals in which the display was focally distorted in each of five different manners (for 15 intervals in total, presented in a different random order for each observer; see Figure 3). These distortions were all centered on the same position as the practice target square and were effected in a linear gradient that increased inwards from the maximum radius of 1.68° (see Figure 3). These distortions were (a) a graduated *Luminance* decrease of the mask elements from 100% down to 9.80% of the available luminance (Figure 3A); (b) a graduated *Contraction* in height of the elements from 0.30° down to 0.03° (Figure 3B); (c) a graduated *Expansion* of the mask lines into 0.24° squares (Figure 3C); (d) a graduated *Curvature* of the mask lines into half-circles with a 0.61° radius (Figure 3D); and (e) a graduated *Color* change from solid blue (RGB: 0, 0, 255) to yellow (RGB: 100, 100, 0; Figure 3E). Each of these distortions affected a different group of mask elements from moment to moment as the mask rotated.

Results

All observers except one experienced robust motion-induced disappearances of the target distortions in all five conditions.³ The average percentage of time that the target disappeared for each distortion type was, from greatest to least: Curvature (25.83%, $SE =$

10.34%), Expansion (24.30%, $SE = 9.27%$), Contraction (15.96%, $SE = 7.09%$), Color (13.66%, $SE = 6.46%$), and Luminance (11.95%, $SE = 5.00%$).

Discussion

While the perceptual scotoma theory does not make any clear predictions about the relative magnitudes of the effects with these different types of distortions, the key result here is that MIB is robust at all in such cases.⁴ Nevertheless, the particular pattern of responses that we observed may help to rule out some other alternative accounts of these effects. In particular, although they were intended to approximate the appearances (when perceived) of various types of scotomas, these distortions could also be interpreted as the results of partially transparent distorting objects positioned in front of the rotating mask elements. However, this alternative possibility would most readily account for distortions involving uniform alterations (i.e., Color) or attenuations (i.e., Contraction, Luminance) of the mask elements as they passed behind the putative transparent surface, whereas in practice, those three distortions were experienced *least* frequently. Instead, the most disappearances were reported for those distortions involving complex geometrical changes (Curvature) or an *increase* in stimulus amplitude (Expansion), which could not readily arise from a semitransparent object attenuating or filtering the masking elements passing behind them.

This experiment demonstrates that MIB does not depend on the relative lack of local visual transients in the target region: even dynamically defined target regions can disappear due to MIB, at least for some types of distortions that are consistent with the manifestations of actual visual scotomas. In contrast, other work has focused on transient manipulations that are *not* consistent with a scotoma interpretation and indeed, these manipulations have been shown to forestall or truncate the disappearances of targets in MIB displays. For example, MIB is hindered by a flickering cue closely circling the target (Kawabe et al., 2007), and truncated both by the abrupt onset of a cue near the MIB target (Kawabe et al. 2007), and by an abrupt offset of the target itself (Mitroff & Scholl, 2004).

Experiment 3a: Upward- versus downward-drifting blindspots

Throughout this paper we have stressed the importance of retinal stability both in the identification of actual visual scotomas and in the typical preconditions

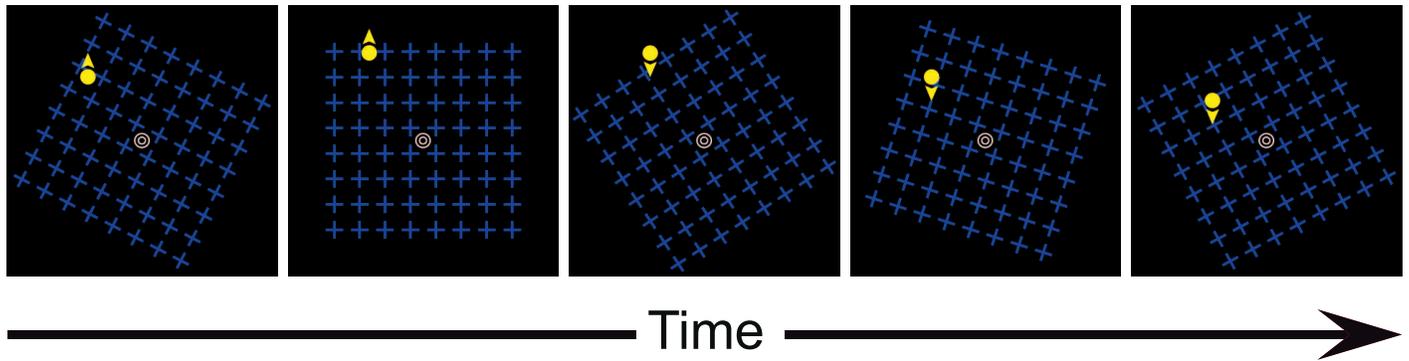


Figure 4. Still-frames of the displays used in Experiment 3 in which the yellow target oscillates vertically. Arrows indicate the object's direction of motion, and were not present in the actual experiment.

for MIB. However, it has been well established that slowly moving objects, even those that move relative to fixation, can disappear in MIB displays, albeit to a much smaller extent than retinally stable targets (Bonneh et al., 2001; Mitroff & Scholl, 2004, 2005). This can even be appreciated in the current Experiment 1, where the retinally stable target disappeared considerably more than the retinally variant target, but the retinally variant targets still did occasionally disappear. MIB for moving targets has long been held to militate against a simple sensory-adaptation account (Bonneh et al., 2001), but might it also argue against a perceptual scotoma interpretation?

Perhaps not. There is also another manner in which vision can be interrupted in a local region of the visual field, beyond the types of retinally stable scotomas that motivated our studies thus far. The eye itself is akin to a “snow globe” in that various bits of detritus, such as collagen fibrils or red blood cells, can be suspended within the eyes themselves. These irregular masses can produce focal opacities that float around, lurch with eye movements, and most commonly, appear to drift downward during fixation (these sorts of floaters most often float *upward* in the eyeball due to their buoyancy, but they *appear* to sink downward due to the inversion of the retinal image). These floaters are not as serious as the types of scotomas discussed above, but they are much more common; we often do not notice them, but most of us can easily do so if we stare at a blank white background. Floaters are often treated as distinct from scotomas, but in fact they pose the very same type of challenge: they produce local visual stimulation for downstream processes that (a) arises not from the world but from the visual system (here, from the eye) itself, and so (b) should be similarly discounted when possible. In fact, from this perspective, the only key difference of floaters relative to other scotomas is that they occur upstream from (rather than at, or downstream from) the retina. As such, floaters were even at one time referred to as *motile scotomas* (Fuchs, 1889/1899; May, 1922), but are now more commonly

referred to according to their underlying cause, as *vitreous opacities* (Coupland, 2008).

Of course, floaters do violate the key property of retinal stability that we have discussed as a primary diagnostic used by the visual system to identify scotomas. As such, we are not surprised that moving targets in MIB disappear much less readily than do retinally stable targets, and that they only disappear at all if they move especially slowly (Bonneh et al., 2001). This accords with the fact that floaters are much easier to see than are many types of fixed scotomas. However, this treatment suggests that MIB may be sensitive to another regularity of floaters relative to other moving targets in the world: during fixation, they most often appear to move slowly in only one direction—downward. As such, the perceptual scotoma hypothesis predicts that the direction of slowly moving targets may also be weakly diagnostic for whether a bit of local stimulation is in the world or in the eye. Accordingly, we predicted that downward-drifting targets might be more susceptible to motion-induced disappearances than upward-drifting targets, equating for absolute position in the visual field.

Method

This experiment was identical to Experiment 1 except as noted here. Seven naïve observers from a Yale undergraduate psychology course participated in exchange for course credit. (We scheduled testing sessions to match the sample size of Experiments 1 and 2, but this resulted in an extra observer also participating during the final morning of data collection. As reported below, the primary effect was observed in six of the seven observers.) Observers peripherally attended to a yellow target disc (0.40°) initially positioned 3.95° from the mask center in the upper left quadrant of the display (see Figure 4). Positioning the target in the upper left quadrant, as in the previous experiments, also served to minimize any possibly confounding

differences in directional motion sensitivity, since there is little or no anisotropy for detecting vertical (up/down) motion in the upper visual field (e.g., Ball & Sekuler, 1980; Ohtani & Ejima, 1997; Raymond, 1994; cf. Naito, Sato, & Osaka, 2010).

Observers viewed six 1-min intervals during which the target disc oscillated vertically over 2.0° at $1.46^\circ/\text{s}$. The initial motion direction (upward or downward) was randomly chosen for the first interval, and was then alternated for the subsequent intervals. The mask was also randomly chosen to rotate either clockwise or counterclockwise in the first interval, and its direction was then alternated for each subsequent interval, thus assuring that the local motion strength (taking into account the motion of both the target and the mask elements) was equated across both target-motion directions.

Results and discussion

As predicted, the target disc disappeared for a significantly greater amount of time when floating downward (23.84%, $SE = 2.91\%$) than when moving upward (18.86%, $SE = 2.05\%$), $t(6) = 2.61$, $p = 0.04$, $d = 1.08$. This pattern was robust in six of the seven observers, with almost no difference in the remaining observer (upward = 21.75% vs. downward = 21.60%). The overall difference between downward- and upward-drifting targets was relatively small (roughly 5%), but this magnitude is still considerable when expressed as a percentage of the average magnitude of MIB as a whole, such that MIB occurred 23.3% more often for downward-drifting targets.

This effect is consistent with the proposal that local stimulation that fails to participate in a surrounding global pattern is more likely to be identified as the result of a motile scotoma (and is thus more likely to disappear) when it drifts downward compared to upward, since perceived downward motion is more characteristic of floaters during fixation. This heuristic and the resulting occurrence of MIB may not constitute a significant benefit for the smaller, more particulate, and transparent floaters that invariably develop as we age. However, there are many cases in which vitreous opacities result from mechanical injury or disease (e.g., degeneration and infection), and these conditions can produce larger, more numerous, and more opaque floaters. Indeed, although the recommended care for benign floaters is highly conservative (e.g., patient education; Sendrowski & Bronstein, 2010), some serious cases may be treated with a vitrectomy (the draining and replacement of the vitreous humor), even in patients with otherwise full visual acuity (e.g., Hoerauf, Müller, & Laqua, 2003). Before the advent of modern medicine, however, the ability to perceptually

filter out persistent floaters to any degree may have constituted an advantage for sufferers of these perceptually impaired conditions.

Experiment 3b: Disappearances at inflection points

Experiment 3a contrasted upward- and downward-moving targets. Since these two motions were mirror images of each other, these two conditions were by definition controlled for eccentricity: at any particular position on the display, a target was presented equally often while moving upward and downward. And this control was important, insofar as MIB does increase with target eccentricity in some cases (Hsu et al., 2004). However, there is another more nuanced concern involving eccentricity that could still confound these results. We already know that transients can truncate episodes of MIB (Kawabe et al., 2007), so perhaps the sudden inflections in the target's oscillating trajectory could similarly serve to weaken MIB. In this case, however, the upper inflection point (after which downward motion ensues) might be less salient due to its greater eccentricity, such that an inflection-induced period of visibility is more likely when the target subsequently moves upward (i.e., following a less eccentric and thus more salient inflection transient). Under this alternate explanation, the difference observed in Experiment 3a would reflect not upward versus downward motion per se, but rather only motion following a more versus less salient inflection transient. We tested this possibility in two final control experiments. First, in the present experiment, we test directly whether the relative spatial positions of the two inflection points from Experiment 3a are themselves more or less likely to promote MIB. We do this simply by comparing disappearance rates for static targets presented at these two positions.

Method

This experiment was identical to Experiment 3a except as noted here. Nine naïve observers from a Barnard undergraduate psychology course participated in exchange for course credit. To ensure that any null effect (as expected here based on our viewing of the displays) could not be due to any relative lack of statistical power, we intentionally tested more observers in this experiment than were tested in the previous experiments. This sample size made no difference, however, since, to anticipate our results, we observed no reliable difference with any number of observers up to the actual preplanned sample size of nine. Observers

attended to a static yellow target disc (0.40°) in the upper left quadrant of the display that was presented at either the highest or lowest position reached by the oscillating targets in Experiment 3a. The initial position (highest or lowest) was randomly chosen for the first block, and then alternated positions for a total of six blocks.

Results and discussion

MIB was no more likely at the lowest (23.8%, $SE = 3.90\%$) position compared to the highest position (24.6%, $SE = 3.11\%$), $t(8) = 0.36$, $p = 0.73$, $d = 0.13$. Thus, although eccentricity can enhance MIB in some cases (Hsu et al., 2004), the mild differential eccentricity of the two inflection points in Experiment 3a produced no such difference.

Experiment 3c: Controlling for eccentricity with horizontal oscillations

The alternate explanation tested in Experiment 3b involved a confound between upward-drifting target motion and motion following a more salient (because less eccentric) inflection transient. Under this alternate explanation, only the relative eccentricity (and thus salience) of the inflection points and not the resulting motion direction per se matters. So to test this even more directly, we also simply replicated Experiment 3a while using horizontal instead of vertical target oscillation. This alternate explanation suggests that the same effects should arise here, whereas the perceptual scotoma framework suggests that the mild difference observed in Experiment 3a should be specific to upward- versus downward-drifting motion per se.

Method

This experiment was identical to Experiment 3a, except as noted here. Nine naïve observers from a Barnard undergraduate psychology course participated in exchange for course credit. This sample size was chosen to match that of Experiment 3b, and again it made no difference since we observed no reliable difference for horizontal oscillation with any number of observers up to the actual preplanned sample size of nine. Observers viewed six 1-min intervals in which the yellow target disc oscillated horizontally directly to the left of fixation, with speeds and eccentricities matched to Experiment 3a. The initial motion direction (inward/

right or outward/left) was randomly chosen for the first interval, and was then alternated for the subsequent intervals.

Results and discussion

MIB was no more likely for targets that moved inward/rightward (12.0%, $SE = 2.43\%$) than for targets that moved outward/leftward (10.7%, $SE = 2.08\%$), $t(8) = 1.01$, $p = 0.34$, $d = 0.35$. This argues against any alternate explanation that appeals to eccentricity rather than to upward or downward motion, per se. It also provides further evidence against any account based on differences in directional motion sensitivity, as discussed in Experiment 3a: whereas studies have found comparable sensitivity to upward versus downward motion in the upper visual field (e.g., Ball & Sekuler, 1980; Raymond, 1994), they did observe differences in sensitivity for inward/centripetal versus outward/centrifugal motion along the horizontal median. This is of course the opposite of the pattern observed in the current experiments, where MIB differed for upward- versus downward-moving targets in this region, but not rightward- versus leftward-moving targets.

General discussion

MIB is a remarkable phenomenon, and perhaps its most remarkable manifestation is when even a *moving* target repeatedly disappears right in front of your eyes, even when the target is explicitly attended, and the disappearance is fully expected. Although such disappearances for dynamic targets were demonstrated in the initial report of MIB (Bonneh et al., 2001), to our knowledge, only two subsequent MIB studies (out of several dozen) have ever employed dynamic changes to targets (Mitroff & Scholl, 2005; New & Scholl, 2008). Here, in contrast, we have focused directly on MIB for dynamic targets in the context of the perceptual scotoma framework, and this led to three discoveries: (a) As demonstrated in Experiment 1, MIB is stronger for moving targets that remain retinally stable, even in displays that simultaneously contain multiple moving targets. This may be because scotomas (and other “stimuli” such as the shadows cast by retinal blood vessels) are typically retinally invariant, and can occur amid other moving targets in the world. (b) As demonstrated in Experiment 2, MIB occurs not only for static targets, but also for active target regions formed by various types of dynamic visual distortions. This may be because scotomas come in many varieties including relative scotomas, color scotomas, and metamorphopsias, which give rise to the same kinds of

distortions implemented as MIB targets here. (c) Finally, as demonstrated in Experiment 3, MIB is stronger for downward-drifting targets than for upward-drifting targets during fixation. This may be because floaters (motile scotomas) most commonly appear to drift downward during fixation.

We conclude by stressing two key features of these results. First, they should be of interest and import for our understanding of MIB regardless of one's theoretical perspective, and independent of the particular theory that was used to motivate them. Second, however, we note that the perceptual scotoma framework may be unique in its ability to accommodate such results. For example, we know of no other theoretical perspective that would predict any difference between upward and downward target motion. In the end, the perceptual scotoma theory is not a direct competitor with many other accounts of specific features of MIB (see New & Scholl, 2008, for discussion), but one of its strengths may be its ability to encompass many different facets of this striking phenomenon.

Keywords: motion-induced blindness, scotoma, visual awareness

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Footnotes

¹ In one sense, this account thus poses an analogy to actual naturally-occurring visual scotomas. But in another sense, this account is not meant to be “analogical” at all: we suggest that the disappearances of targets in MIB displays and scotomas in real life may both result from the very same underlying mechanisms.

² One other report also proposes a functional account of MIB, but one with a very different character. Wallis and Arnold (2009) suggest that MIB is adaptive in the more specific sense that it enhances the perception of moving objects by suppressing motion streaking on the retina. Note that this is a much more specific account than the perceptual scotoma

framework, and that it would not apply to situations that do not involve motion.

³ In line with previous reports of large individual differences in motion-induced blindness (Sparrow et al., 2017), one observer experienced a far smaller extent of motion-induced disappearances in total relative to the other five participants (2.25% vs. an average of 21.51%) and failed to report any disappearances of the Luminance and Contraction distortions.

⁴ If such differences proved reliable with larger sample sizes, they could be interesting to correlate with data about the relative incidence of these various types of actual scotomas in the population as a whole, but we are not aware of any such data in the literature.

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