THE FLICK OF THE WRIST AND THE WAVE OF THE WAND:
LOW-LEVEL MECHANISMS FOR INDUCING CHANGE BLINDNESS

BY
RICHARD YAO

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Doctoral Committee:
Professor Daniel J. Simons, Chair
Professor Kara D. Federmeier
Professor Arthur F. Kramer
Associate Professor Diane M. Beck
Associate Professor Alejandro Lleras
**ABSTRACT**

This dissertation explores a new paradigm for inducing change blindness as an avenue for understanding the stimulus conditions that give rise to change blindness in general. Participants are asked to detect an instantaneous change in orientation of a single item in an array of Gabor patches. While looking for the orientation change, the array moves across the display, abruptly changing its direction of motion at a single point of flexion. Observers show little trouble spotting the rotation if it occurs while the array is moving continuously along a straight path; however, detection is impaired when the rotation occurs simultaneous with an abrupt change in direction of at least 90°. A potential neural mechanism is proposed involving the interference of excitatory signals to motion receptors in visual cortex, and that theory is extended to the creation of new paradigms for suppressing change detection. In one-shot and continuous change detection tasks, transient color-change signals conceal targets that change color and transient motion signals conceal targets that generate motion, but each one is relatively ineffective at hiding the other. Based on these data, this thesis proposes a theory of “change camouflage” as a means of explaining the variety of change blindness phenomena found here and the change blindness literature at large.
Dedicated to my loving wife and advisor.
May future generations be forever perplexed by my syntactic ambiguity.
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CHAPTER 1: BACKGROUND INFORMATION

1.1. Introduction

The motion-induced change blindness effect represents a previously unreported means of inducing change blindness and provides an exciting new avenue of research for understanding attention and visual perception. When participants track a moving array of Gabor patches, they fail to detect a change in orientation of a single patch as long as the change occurs simultaneously with an abrupt change in the direction of motion. This differs from previous paradigms, as it is the only example of an instantaneous change being rendered invisible while maintaining constant visibility of the target stimuli without any onsets or offsets. This dissertation project therefore has two major goals: first, to understand the nature of this new paradigm and why it induces change blindness. Second, in understanding how this motion-based effect relates to other examples of change blindness in the literature, we stand to gain a more complete picture of change blindness as a psychological phenomenon and, by extension, the underlying functionality of attention and memory in the perception of a continuous visual world.

Change blindness itself can be best understood as a failure of the change identification process. As there are multiple steps to detecting a change, there are multiple ways in which change blindness can occur (Simons, 2000). As a necessary precondition to detecting a change, a person must attend to the location or object that is going to undergo a change. Theories of object recognition (e.g., feature integration theory [Treisman & Gelade, 1980], object files [Kahneman, Treisman, & Gibbs, 1992], nexus theory [Rensink, 2002]) have posited the need for attention to generate a coherent mental representation, which is necessary to the other steps toward change detection. Second, the person has to represent the target object or location in memory before the change occurs. Third, the location or object must be attended after the
change occurs, and then represented in memory again. Finally, the pre- and post-change representations must be compared and recognized as different. Only then will a person successfully detect the change and avoid experiencing change blindness (Simons, 2000).

1.2. The Visual Transient

When something changes in the world, it is often accompanied by some potentially observable visual signal of its occurrence. For example, if an object changes locations, it necessarily undergoes an observable process of motion that takes it from its starting point to its destination, carrying it through points in space in between. If a friend has a new haircut, they undergo an observable process in a stylist’s chair that transforms his or her hair in progressive stages from its previous state to its new one. If a conversation partner magically transforms into another person, the trick necessarily involves some observable process, such as one person sneaking away while someone else sneaks in to take the original person’s place. Even instantaneous changes, such as a changing traffic light or alternations between images on a computer screen, creates a sudden drop or increase in the physical energy coming from their locations. Changes carry signals to their occurrence, some smaller or bigger, faster or slower.

Many paradigms induce change blindness by means of a short-lived visual signal (herein a “transient”) that in some way conceals the change’s visual signal from the viewer. These transients have included blank screens (Rensink, O’Regan, & Clark, 1997), “mud splashes” (Rensink, O’Regan, & Clark, 2000), film cuts (Levin & Simons, 1997), physical occlusion (Simons & Levin, 1998), contrast polarity reversals (Turatto et al., 2003), global luminance changes (Arrington, Varakin, & Levin, 2006), and the global onset/offset of color (ibid). The authors generally agree that these transient signals somehow force the observer to represent the
pre-change state of the world in memory and compare it to a post-change memory representation to know what changed. However, there is no unifying theory for how this wide variety of transient signals induces change blindness. Consequently, there is currently no means of predicting what sorts of stimuli can and will induce change blindness under a given circumstance and to what degree. By treating the abrupt change in direction of motion as another one of these transient signals, I will develop such a theory of visual transients and validate its predictions through a series of experiments.

Before launching into a deeper examination of visual transients, it is worth noting that they are not strictly necessary for inducing change blindness. For instance, the gradual change paradigm (Simons, Franconeri, & Reimer, 2000) does not involve any transient visual stimuli—in fact, it depends on the lack of any transient visual signal, including from the change itself. Changes to an image occur so gradually, they fail to reach awareness unless a person focuses gaze and attention on the change location for long enough (or at the appropriate points in time) to perceive them. Successfully detecting a change still involves the full detection process described above, and can likewise fail at any of those steps. Even if a subject directs attention to the change location at different points in time, memory failures could preclude detection of the change. Alternatively, the visual characteristics of the change location may not differ enough from one time the subject attended it to the next in order to signal any indication a change occurred.

Furthermore, other factors may play just as important a role in predicting change blindness as the presence of a visual transient. The classic Simons and Levin (1998, and Levin & Simons, 1997) change blindness studies, though illustrating the importance of visual transients to some degree, also demonstrate the importance of memory representation resolution in detecting a
change. Subjects fail to notice a change in identity or other details of appearance from one shot to another in video clips in part because the scenes maintain semantic continuity. A man gets up to answer the phone. Two women have a conversation. Because changing the actor playing the man and rearranging the objects around the women do not involve anything that interferes with a high-level, semantic representation of the scene, the changes get lost in the process of long-term encoding as peripheral details. These sorts of “peripheral interest” changes are harder to detect even in an extended flicker paradigm where subjects know to look for the change (Rensink, 2002).

The “door study” (Simons and Levin, 1998) more directly addressed the importance of the resolution of memory representations in detecting a change. By exploiting the out-group homogeneity effect (Quattrone & Jones, 1980) and dressing up as construction workers, the experimenters demonstrated that change detection in the same population could be modulated by the detail of representations in memory. When experimenters surreptitiously changed into another person mid-conversation behind a door, fewer participants noticed the change when the roughly-college-aged-looking experimenters were dressed as construction works than when they were dressed as casual pedestrians. College students most likely encoded a less detailed representation of the construction workers (members of an outgroup) than their fellow young scholars, and were therefore less likely to notice the change in identity. When dealing with two different construction workers, the qualitative, categorical representations the students had encoded before and after the change were—to the comparison process—the same.

In fact, such a comparison process likely did not even take place. In a similar study (Levin et al., 2002), participants who missed a real-life change (a basketball that appeared in or disappeared from the experimenter’s hands) only reported noticing anything had changed when
pressed by the experimenter to think if anything was different from when they first began their conversation. Subjects had encoded the pre-change states of the visual world, yet failed to make the comparison process that brought the difference to awareness. Mitroff, Simons, and Levin (2004) later found further evidence for the importance of the comparison process in the laboratory by demonstrating that subjects had represented pre- and post-change objects in memory, even if they had not carried out the comparison process to notice a change occurred.

As eye movement researchers have argued, little is stored in visual memory from fixation to fixation, moment to moment (Bridgeman & Heijden, 1994; Irwin, 1991). Although a higher-level mental representation of one’s environment can be fairly rich in memory after some time encoding it, the visual system only uses a sparse set of information to quickly stitch together the individual snapshots the eyes take with each fixation. Because that alone sufficiently gives us a sense of where we are and how to interact with the environment, the visual system need only keep track of little information from moment to moment. It is therefore implausible to expect the visual system to have enough information to know something changed from one point in time to another without deliberately focusing attention on it—let alone execute an exhaustive comparison process when we do not what or where something will change. Understanding what does or does not trigger focused attention and the comparison process and how that leads to awareness of change is a vast area of possible investigation, but falls outside the scope of this dissertation. All this is to say that factors other than low-level visual transients can cause and modulate change blindness.

This brings us back to the question of visual transients. How do we define them, and what are they doing? The visual perception literature generally defines transients as a shorthand term for stimuli that introduce a transient burst of neural activity, typically a sudden change to
the luminance signal (Stelmach, Bourassa, & DiLollo, 1984). For much of the change blindness literature in particular, transients have typically referred to a stimulus that is literally transient—some stimulus that briefly onsets and offsets. The flicker and “mudsplash” (Rensink, O’Regan, Clark, 2000) paradigms embody this definition, as they involve the brief onset and offset of stimuli coincident with the change. The broader neural activity account captures most other cases, such as change blindness across a movie cut. Although the cut is not a physical, spatiotemporal stimulus in and of itself, it constitutes a huge change to the luminance signal across the entire scene.

Rensink (2002) has previously alluded to the idea that any visual signal that sufficiently “swamps out” the visual signal produced by the change will lead to change blindness. Although a thoroughly encompassing theory, the idea of what it means for one signal to “swamp out” another signal remains vague. For some transients, this means completely obscuring any visual signal of a change from the viewer. Flickers, blinks, saccades, occlusion, and film cuts all keep someone from directly observing a change as it occurs. The vagueness of the signal-swamping theory keeps it from precisely explaining how we can be blind to changes that occur in full view, as in the mudsplash paradigm, increasing or decreasing global luminance, or adding or subtracting color to a scene. It is not clear exactly what about those visual signals is swamping out the visual signal of the change, nor is it clear how much of that swamping signal is necessary to conceal the change.

Different types of change signals could have greater or lesser visibility amidst different types of transients (similar to how a visual search target’s salience varies as a function of its surroundings). For instance, a transient increment in luminance across the image should conceal a target change in luminance better than it would conceal an onset/offset target change.
Unfortunately, extant published data do not provide the detail necessary to adequately verify this prediction. Testing this hypothesis quantitatively could be straightforward for simple stimuli (such as Gabor patches and colors, as in Experiment 5 of Chapter 3), but scaling up to complex objects and scenes introduces difficulties from top-down semantic influences. For example, bottom-up salience of a change does not appear to predict the probability of its detection (Stirk & Underwood, 2007), whereas top-down factors do—such as semantic consistency within a scene (ibid), task relevance (Wallis & Bulthoff, 2000), and the centrality of the changing object to understanding the scene (O’Regan, Deubel, Clark, & Rensink, 2000).

Unifying the different change blindness paradigms will most likely require a functional definition of a transient; that is, defining it by the function it plays in interrupting the change detection process rather than mere physical or spatiotemporal parameters. A major risk in trying to characterize transients in this way, however, is the threat of circularity; a transient can become “whatever works.” Therefore, I will endeavor to narrow the scope of this definition into a testable theory by identifying and understanding the underlying commonalities across the paradigms found in the change blindness literature.

A full understanding of the mechanisms of change blindness first requires understanding the nature of the target changes themselves—in particular, what visual signal they create, and how that signal can get swamped out. Rensink (2002) defines change as any structural transformation of a single object over time. (Incidentally, it is perhaps worth adding that the change occurs to the object’s mental representation in working memory—not necessarily the physical object itself. In the door study, the experimenter himself obviously does not transform, but the person occupying the role of “conversation partner” for the subject does.) Rensink’s discussion explains how motion is dissociable from change; for example, the motion of a stream
does not change our structural representation of the stream. Still, we cannot disregard the role of motion inherent to that transformation process. Many changes will be accompanied by motion and other low-level visual properties that could potentially signal their occurrence.

Once again, understanding the changes we miss benefits from analyzing them as a breakdown of normal change conditions. Under normal circumstances (that is, when a change occurs without an experimenter somehow purposefully concealing it), a change carries a detectable signal with it. As an example, instantaneous changes to images in the laboratory involve alternating pre- and post-change images. Doing so without any sort of interruption generates an apparent motion signal at the location of the change. These are particularly attention-grabbing, as the motion appears on a uniformly static background, leading to pop-out and capturing attention (Franconeri & Simons, 2003). Consequently, subjects easily detect these changes. The same principle generalizes to changes that occur in the world, which may be more spatiotemporally extended; the accompanying change signal is important to detection insofar as it has the potential to attract attention, the first pre-condition to successful change detection.

In the most general terms, change blindness manipulations that use transients conceal the aforementioned motion signals that normally accompany a change. In real-world instances of change blindness, the changes simply occur outside of a person’s view. The flicker paradigm appears superficially similar in that it conceals the change event from the subject; however, it informs a more general principle of change blindness. As discussed above, an instantaneous change captures attention by virtue of being the only motion—generated by a sudden change in the light signal at the target location—in a static environment. A blank inter-stimulus interval (ISI) between the pre- and post-change images serves to change the light signal across the entire search area, thus eliminating the static environment that led to the change popping out.
Mudspashes similarly introduce motion signals in the form of onsets and offsets distributed across the image. Blinks and saccades behave similarly to the flickers in their ability to induce change blindness when changes occur coincident with them (Grimes, 1996; O’Regan, Deubel, Clark, & Rensink, 2000). Again, the low-level signals that normally occur with the change get obscured completely. The common result is that the target change’s motion signal is no longer alone and localizable in the image.

More recent paradigms use subtler means of inducing change blindness that involve relatively less visual disruption. Turatto, Bettella, Umiltà, and Bridgeman (2003) reversed the contrast polarity in their test stimuli in place of a blank ISI. They emphasize the uniqueness of their paradigm in that reversing contrast polarity maintains all the low-level edge information in the images as the changes occur. This is not the case in the flicker or mudsplash paradigms (Rensink, O’Regan, & Clark, 2000), which both involve occluding some or all of the image. Just like the flicker task, however, their task changes the light signal across the entire image, swamping out the motion signal that accompanies the change. Arrington, Levin, and Varakin (2006) performed a similar experiment using the onset and offset of color in the stimuli that occurred simultaneously with the target change. Again, although the edge information does remain in full view during the entire task, the change in light signal across the search area swamps out the change in the light signal at the target location.

These recent studies lend credence to the scalability of the swamping account to various levels of perceptual magnitude or salience beyond extreme cases like flickers and occlusion. For instance, the onset of color in a grayscale image and a global change in the scene’s luminance induced change blindness less often than a blank flicker. The magnitude of change in the light signal across the image will be greater in the flicker paradigm than in a mere color onset/offset,
which maintains much more of the edge and luminance information of the original image. Therefore, the change in the light signal accompanying a structural transformation of an object has more potential to exceed that of the color onset/offset (compared to a flicker), making it more likely to capture attention. Not all visual disruptions are equally disruptive, and this idea is open for psychophysical inquiry.

One could conceivably quantify the magnitude of physical change in the light signal that a global transient introduces to an image and compare that to the target. For example, we could measure the average distance in LAB color space between the stimulus image and the transient. It follows from the above discussion that the transient will conceal the target change as long as it represents a perceptual change in the light signal that is equal to or greater than that of the target change. Psychophysical testing is necessary to estimate the perceptual magnitude of changes and transients as they relate to one another. According to the swamping theory, the transient should impede change detection only when its perceptual intensity is at least as great as the target change’s. A simple experiment might make a luminance change to a single object in a search array serve as the target, and a global luminance change as the transient. A shift in global luminance smaller than the target’s shift should impair detection little (if at all), whereas a larger global shift should greatly impede detection.

Thus far, we have accounted for global visual transients as a means of swamping out a localized change, as they reduce or eliminate pop-out of the target. In essence, occluders, saccades, blinks, flickers, mudsplashes, contrast polarity reversals, and color/luminance onsets attenuate the exogenous cue to attention, forcing the subject to endogenously direct attention in search of the change. Another possibility is that transient stimuli can actively misdirect the viewer, exogenously pulling attention away from a target change. Studies using exogenous cues
find attenuation of change detection as a result of invalid spatial cues (Scholl, 2000; Smith & Schenk, 2008). Task demands likewise have a similar effect on misleading attention; a driver is more likely to miss changes as they occur farther away from the road, as the task requires focused attention on the path ahead (Wallis & Bulthoff, 2000). Thus, we have another avenue for inducing change blindness with transient visual signals: a stimulus (or task) that serves to direct attention away from a change location can induce change blindness.

Similar top-down factors may also aid in the effectiveness of movie cuts as a means of inducing change blindness (Levin and Simons, 1998). In those studies, the movie clips carry with them a great deal of semantic information that can both guide the spatial direction of attention and influence higher-level interpretations of the scene. For example, in one scene, a young man looks up and gets up from his desk; in the next cut, a completely different young man walks down a hall and answers the phone. In another scene, two women have a conversation while various changes are introduced into the women’s surroundings and posture. At a shallow level of analysis that does not take semantics into account, the two examples can appear to represent a contradiction. In the first scene, we perceive two different actors as embodying the same role; yet, in the second scene, we correctly recognize two different actors as two separate people. The only difference is the semantic environment in which the changes took place: whereas the first clip leads us to believe a single person is getting up to answer a phone, a single person would not be having a conversation with herself (except, perhaps, in the saddest of romantic comedies).

Visual transients act primarily on the viewer’s ability to focus spatial attention on the location of the change signal. This notion becomes particularly apparent when a person knows the location of a change. With knowledge of where to direct attention (as well as when and how
the change will occur), the transient no longer holds any power over the viewer; endogenous attention can override the effects of the transient and change blindness no longer occurs. In fact, the change often appears (anecdotally) to pop out for viewers. This top-down knowledge effect even has the ability to override specific task goals; people tend to fixate locations and objects that had previously changed, particularly in the same scene context or repeated image (Becker & Rasmussen, 2008; Takahashi & Watanabe, 2008). Transients prevent attention from localizing the change signal, but once that location is found, they are easily overcome.

To summarize, visual transients in the change blindness literature consist of stimuli that prevent or delay the focusing of attention on a visual change signal. They can do so in two ways. First, they can indirectly affect attention by swamping out visual signals associated with the change, forcing a person to endogenously search for and focus attention on it. Saccades, blinks, occluders, flickers, polarity reversals, and color/luminance changes all behave that way. Alternatively, transients can directly act on attention by actively misdirecting it away from a change. Invalid exogenous spatial cues (and mudsplashes, it has been argued) induce change blindness in this manner. It is worth noting that these two effects are not necessarily exclusive of one another; global transients could lead to modulations in the direction of attention, and the effectiveness of exogenous cues could be subject to the relative salience of the changes and transients.

These varied paradigms connect to the broader phenomenon of change blindness in that they all require a person to compare memory representations for objects and/or features of a scene in order to detect them (as opposed to simply recognizing low-level signals associated with the change). Coarse or inaccurate representations in memory and the uncertainty of initiating a comparison process make change detection much more difficult and unlikely. The same holds
true for instances of change blindness that involve no visual transient, such as gradual changes or simply missing a change to an environment that occurred between two temporally separated encounters with it.

Given the outlined theory of transients and how they interfere with change detection, we are now in a position to generate hypotheses and seek out theories to explain heretofore-unaddressed means of inducing change blindness. In particular, we now have a framework for understanding the ability of abrupt changes in motion to induce change blindness.

1.3. The Magical Origins of Motion-Induced Change Blindness

Magician Dariel Fitzkee makes an observation in his book, *Magic by Misdirection*, that “a sudden change in the direction of a movement, as from a horizontal path of action to a vertical one, in making a pass, is a distraction” (p. 171). Insofar as a “pass,” a maneuver in stage magic, constitutes a change to the visual scene, Fitzkee appears to be describing a form of change blindness. Initial testing indicates that an abrupt change in the direction of movement does indeed conceal changes. In my experiment, an array of six randomly oriented Gabor patches moved across the computer screen in an “L” shape. Subjects had to respond with which of the six patches rotated (the target change) during the trial. When the rotation occurred at the vertex of the L-shaped movement, subjects were at chance accuracy for reporting the change; however, having the rotation occur while the array was moving along a straight path at the same velocity led to ceiling-level performance.

As the motion-induced change blindness experiment described above constitutes a new paradigm for the literature, we do not yet have a direct explanation as to why it works. We can, however, make some educated (and testable) guesses. To the author’s knowledge, the literature
contains only two experiments that resemble this new paradigm. First is a study by Blackmore, Brelsta, Nelson, and Troscianko (1995) in which they had subjects detect changes that occurred either to stationary scenes or scenes that were moved unpredictably. The movement forced subjects to make a saccade, during which the change occurred in the scene. The authors intended to demonstrate that the visual system does not represent and store enough information about the scene for subjects to notice the change across saccades. This is relevant to a motion-based paradigm in that any stimulus that induces a saccade can potentially induce change blindness through saccadic suppression.

Schofield, Bishop, Allan, and Allan (2006) came closer to the new motion-induced change blindness paradigm, once again using moving scenes. The authors moved a scene back and forth along a line segment path, alternating between the pre- and post-change images whenever the image was at the endpoints of its path (i.e., changed direction). As a control, they had subjects search for changes in stationary, blurred images, meant to simulate visual artifacts of streaking due to the motion. The photo manipulation, however, had no effect on people’s ability to detect the changes, ruling out a low-level visibility explanation for the blindness. Their manipulation does not, however, address the issue of attention and the degree to which the changes could be localized when the stimuli were moving steadily along the straight path. In each of these paradigms, there is possible application of the swamping-out hypothesis. The changes to the scenes normally generate a transient localized motion signal that gets lost amidst a transient global motion signal.

We turn now to the other hypothesis, that the motion in the new paradigm somehow misdirects attention away from the change. Past findings that relate motion processing and awareness make this a plausible explanation for our change blindness effect. The flash-lag effect
(Nijhawan, 1994) demonstrates how motion can affect attention and awareness. In one flash-lag demonstration, an annulus moves along a circular path, and a circle is quickly flashed inside it during its motion. Although the circle always appears inside the annulus, the conscious percept is that the circle “lags behind” and appears when the annulus is already past that point in its movement path. Although actively debated, one theory for why the effect occurs suggests that the visual system extrapolates the direction of motion for moving objects in order to correct for the delay caused by signal transmission and processing (Nijhawan, 2002). This allows us to attend and act upon moving objects based on their veridical location without sensory delay. A side effect is that attention and awareness can dissociate from a physical stimulus as a result of its motion, impairing a person’s ability to attend to a change signal.

The experiments described in the next chapter look to test for and elucidate these swamping-out and misdirection hypotheses with respect to the motion-induced change blindness effect.
### Table 1.1. Summary of Transients Used in Change Blindness Experiments

<table>
<thead>
<tr>
<th>Transient stimulus</th>
<th>Description</th>
<th>Example Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusion</td>
<td>Subject’s view of the target object is obscured at the moment the change occurs.</td>
<td>Simons &amp; Levin, 1998; Simons, Chabris, Schnur, &amp; Levin, 2002</td>
</tr>
<tr>
<td>Film cuts</td>
<td>A change occurs to actors or their environment from one film cut to the next.</td>
<td>Levin &amp; Simons, 1998</td>
</tr>
<tr>
<td>Saccades</td>
<td>Change occurs to natural scene or sparse array of objects when subject makes a saccade.</td>
<td>McConkie &amp; Zola, 1979; Grimes, 1996</td>
</tr>
<tr>
<td>Blinks</td>
<td>Change occurs to natural scene when subject blinks.</td>
<td>O’Regan, Deubel, Clark, &amp; Rensink, 2000</td>
</tr>
<tr>
<td>Exogenous spatial cues</td>
<td>Attention is drawn to an object in a stimulus array through an onset preceding a flicker paradigm.</td>
<td>Scholl, 2000; Smith &amp; Schenk, 2008</td>
</tr>
<tr>
<td>Mudsplash</td>
<td>High-contrast shapes distributed across a natural scene onset and quickly offset at the same moment a change occurs.</td>
<td>Rensink, O’Regan, Clark, 2000</td>
</tr>
<tr>
<td>Contrast polarity reversal</td>
<td>Same as flicker, but instead of a blank screen, subject sees a negative of the preceding natural scene.</td>
<td>Turatto, Bettella, Umiltà, &amp; Bridgeman, 2003</td>
</tr>
<tr>
<td>Global color onset/offset</td>
<td>A grayscale natural scene is “colorized” or a colored natural scene is turned grayscale at the moment the change occurs.</td>
<td>Arrington, Levin, &amp; Varakin, 2006</td>
</tr>
<tr>
<td>Global luminance change</td>
<td>Natural scene increases or decreases in luminance at the moment the change occurs.</td>
<td>Arrington, Levin, &amp; Varakin, 2006</td>
</tr>
<tr>
<td>Sinusoidal motion</td>
<td>A natural scene translates back and forth, alternating between images every time the scene reaches an endpoint of its trajectory.</td>
<td>Schofield, Bishop, Allan, &amp; Allan, 2006</td>
</tr>
</tbody>
</table>
CHAPTER 2: GENERAL METHODS

2.1. Software

All experiments were carried out using Psychophysics Toolbox, version 3 (Brainerd, 1997; Pelli, 1997; Kleiner et al, 2007), a set of extensions for Matlab and Octave. Experiments 1, 2, 4a, and 5a used Matlab 2007b (the Mathworks, 2007); Experiment 3 used Matlab 2011b (the Mathworks, 2011); and Experiments 4b, 5b, 6a, and 6b used Octave v. 3.6.4, an open-source Matlab alternative (http://www.octave.org).

2.2 Hardware

Experiments 1, 2, and 4a were conducted on an Apple eMac, which uses a built-in 17” CRT display. The screens subtended approximately 33°(horizontally) x 25°(vertically) of visual angle and were operating at a resolution of 1024 x 768 with a refresh rate of 89 Hz. Participants’ eyes were fixed at a distance of approximately 56-60 cm from the screen. This was accomplished through the use of a piece of specialized equipment built in the lab. A frame affixed a fabric tube connecting the computer screen to a small viewing aperture surrounded with a plastic eyepiece. Participants had to put their eyes up to the aperture to view the screen and perform the experiments.

Experiment 3 was conducted on a Dell Optiplex GX280 desktop computer. Stimuli were presented on a 21” ViewSonic CRT display set to 1024x768 resolution and a refresh rate of 85 hz. Subjects sat with their heads affixed in a desktop-mounted chin and forehead rest that positioned their eyes 60 cm from the monitor. This made the screen subtend 43.9° (vertically) x 32.9° (horizontally). The eye-tracker machine was of identical make and model as the stimulus machine (Dell Optiplex) and used the SR Research Eyelink II/CL v 2.32 eye-tracking software running from DOS. While performing the task, participants’ gaze was measured using a
desktop-mounted Eyelink1000 (SR Research). Recordings were monocular, taken from the left eye at a sampling rate of 250 hz.

Experiments 4b, 5a, 5b, 6a, and 6b were conducted on Apple Mac Mini computers. Stimuli were presented on 24” BenQ 2420TX model LCD monitors at a resolution of 1920x1080 (1080p) and refresh rate of 100 Hz. Participants’ eye and head positions were not fixed, but comfortable seating at the computers placed them at approximately 30” (76.2 cm) from the screen. At this distance, the displays subtended approximately 39.9° (horizontally) x 22.4° (vertically) of visual angle.
CHAPTER 3: MOTION-INDUCED CHANGE BLINDNESS AND ITS MECHANISMS

3.1. Experiment 1

Experiment 1 examines the effect of abrupt changes in motion to the perception of stimulus change—in this case, rotation of an element in an array of Gabor patches. An array of six Gabor patches traveled together along the same L-shaped path: down the left side of the computer screen, and rightward along the bottom. One of the patches, randomly chosen on each trial, underwent an instantaneous 15˚ rotation. The analyses measured participants’ accuracy for reporting which of the six patches rotated on a given trial. As a control, some trials had the Gabor patch rotate while the array continued along a straight path in order to see if motion alone could conceal the change (as suggested by Schofield et al., 2006), or an abrupt change in trajectory was necessary.

3.1.1. Experiment 1 Methods

Subjects

Twenty-one University of Illinois undergraduates participated in Experiment 1 in exchange for psychology course credit.

Materials

The Gabor stimuli each subtended 56 pixels (1.6˚ of visual angle) and had a spatial frequency of approximately 1.5 cycles per degree. Arrays were generated automatically for each trial by evenly distributing six Gabor patches a fixed distance from a central fixation cross (75 pixels, or 2.30˚, measured from the center of the cross to the center of the Gabor). A Gabor appeared at 30˚, 90˚, 150˚, 210˚, 270˚, and 330˚ relative to the horizontal. Individual orientations were set randomly by the computer. Targets were defined by a 15˚ (clockwise) instantaneous rotation in orientation.
Every trial began with a 500 ms fixation cross. As soon as the array of Gabor patches onset, they immediately began moving downward on the screen for a distance of 13.09° of visual angle (426 pixels on the screen) at a constant velocity of 19.14° per second (7 pixels per refresh). Just as the gabor array approached the lower left corner of the screen, it immediately broke rightward at a 90° angle and continued at the same speed for 18.99° (618 pixels). At that point, the array offset and reappeared (with post-rotation orientations) at the center of the display under the words “Click the one that rotated.”

Conditions were defined by the point in the movement path at which the target Gabor’s orientation changed. In the “Flexion” condition, the target rotated at the point of flexion in the lower-left corner of the screen. In the “Control” condition, the target rotated halfway along the horizontal path of motion at the screen midline.

Each possible target location was represented five times per condition for a total of 60 trials. Target location and condition (flexion vs. control) were randomized between trials.

Procedure

Subjects participated in the change detection task after completing an unrelated experiment involving rapid object recognition. For the change detection task, they were instructed to follow the array with their eyes as it moved around the screen by staring at the fixation cross centered among the Gabors. They were told one of the “striped patches” would rotate slightly on every trial, and they would need to report its location by clicking on the array when prompted. Subjects were told the experiment was designed to make the rotation invisible at times, and they should take their best guesses if they missed it on a given trial.

After completing the experiment, participants were debriefed on its hypotheses and probed for feedback on overall perceptual impressions and strategies employed on the task.
3.1.2. Experiment 1 Results

Experiment 1 established empirical evidence for the motion-induced change blindness effect: a change in direction of motion concealed a visual signal in a way continuous motion alone could not. While continuous, linear translation did little to hide the target rotation, having the rotation occur at the point of deflection led to nearly chance-level detection accuracy. Fitzkee’s intuition is correct: change in the direction of motion can indeed hide a normally visible visual signal to a degree that continuous motion alone cannot.

Change detection rates were significantly lower in the flexion condition than in the control condition, \( t(20) = 16.203, p < .001 \). These results support Fitzkee’s intuition that a sudden change in direction can conceal a visual signal. Furthermore, they indicate that a change in the direction of motion is significantly more effective for concealing a change than continuous motion alone. From a physical perspective, these data suggest that the introduction of an acceleration vector to the array’s path of motion is necessary to induce change blindness. Whereas the velocity vector of the array changes at the point of flexion, it remains constant along the straight paths (where detection accuracy remained high in spite of the stimulus array moving).

3.2. Experiment 2

Experiment 1 demonstrated that a change in the direction of motion could conceal the target rotation and do so in a way that continuous motion cannot. However, there is a possibility that the change in direction was not solely responsible for the change blindness. Blackmore et al. (1995) and Grimes (1996) found that changes that occur across a saccade go unnoticed, as saccadic suppression can mask the transient change signal. It is possible that our abrupt change
in direction here induced a saccade, and the results are merely an artifact of saccadic suppression rather than changes in motion.

Still, participants should have been able to smooth pursue our array, despite the abrupt change in direction. The array was continuously visible and moved along the same, predictable path on every trial. Even with the 90° flexion, participants should have been able to track the array with little difficulty. Still, we could not be certain that participants maintained smooth pursuit of the array, and so made an attempt to address this concern in Experiment 2. The array again changed directions, but did so much more gradually to ensure participants could smooth pursue it through the entire trial.

A secondary issue addressed in Experiment 2 was the direction of the target rotation. In Experiment 1, rotation was always clockwise, and the direction of motion always changed from downwards-to-rightwards. As an exploratory measure, Experiment 2 also measured detection for counter-clockwise target rotations to see if the direction of rotation interacts with the change in global motion direction.

3.2.1. Experiment 2 Methods

Subjects

Eleven University of Illinois undergraduates participated in Experiment 2 in exchange for psychology course credit. Two subjects also participated in Experiment 4a after completing experiment 2. All eleven subjects also participated in Experiment 5a at the end of the experiment session.

Materials

Unless otherwise noted, experiment 2 was identical to Experiment 1. Stimulus velocity
was lowered slightly to aid smooth pursuit, 6 pixels per screen refresh (16.4° per second). Gabor locations were now located at the angles 0°, 60°, 120°, 180°, 240°, and 300° relative to the horizontal due to changes in the way the experiment was programmed compared to Experiment 1 (rather than any theoretical motivation).

The key difference in experiment 2 was a gradual change in direction of motion rather than an abrupt one. This was achieved by having the whole array travel along a 90° arc with a 100 pixel (3.07°) radius in the lower left corner of the screen. The array had the same beginning and end points as Experiment 1, and so followed the same path with the exception of the curved change in direction.

To match the gradual change in direction, the target rotation was also gradual, rather than occurring instantaneously. In the arc condition, the target rotated 10° as it traversed the 90° arc, which took 26 screen refreshes (approximately 292 ms). The target rotation in the control condition was matched to the arc condition, and so appeared as a 10° rotation that occurred over 26 screen refreshes (292 ms) beginning when the array crossed the screen’s vertical midline while moving horizontally.

The reasoning behind the gradual target rotation (instead of an instantaneous one) was that the gradual change in direction lacked a clear flexion point at which the array can be said to have changed direction. The current design makes experiments 1 and 2 comparable insofar as the target rotation occurs concurrently with the change in direction in both cases. As an added benefit, the temporal extension of the target rotation allows for the possibility of detection even if a saccade were to obscure part of the rotation.

Participants completed 72 trials total. Trials were divided evenly among three conditions: the control condition (clockwise rotation occurring halfway along the horizontal path
of motion), a clockwise condition (clockwise rotation along the 90° arc), and a counterclockwise condition (counterclockwise rotation along the 90° arc). Each of the six target locations were represented four times in each condition. Condition and target location were randomized across the trials.

Procedure

Experiment 2 proceeded identically to Experiment 1 with the exception that participants engaged in the change detection task immediately upon visiting the lab. Once again, the experimenter instructed participants to localize the target change that occurred on every trial—guessing when necessary—and to follow the fixation cross with their eyes.

3.2.2. Experiment 2 Results

Experiment 2 revealed a similar pattern of results to Experiment 1. A one-way repeated-measures ANOVA revealed that participants detected targets significantly less frequently when the rotation occurred simultaneously with the change in direction compared to when it occurred during horizontal translation, $F(2, 20) = 76.336, p < .001$. Post hoc pairwise comparisons, using a Bonferroni correction, revealed a significant difference between the control condition and the two arc conditions ($p < .001$), but no difference between clockwise and counterclockwise targets ($p = .348$).

These results suggest that saccades alone cannot explain the effect of changes in motion direction. Even under circumstances designed to support smooth pursuit, there is a significant reduction in detection rates when a target rotation occurs simultaneously with a change in global motion direction compared to continuous motion.
3.3. Experiment 3

Experiment 3 served as a control experiment. Although experiment 2 was designed to rule out saccades as a mechanism for change blindness in the current paradigm, only eye-tracking could tell for sure. Eye-tracking also has the added benefit of exploring gaze behavior during the task. Experiment 3 had participants engage in a variant of the motion-induced change blindness task while their point of gaze was recorded.

3.3.1. Experiment 3 Methods

Subjects

A total of 12 subjects participated in Experiment 3. Eight subjects participated as part of the University of Illinois subject pool for course credit. The remaining four subjects were all volunteers: two were undergraduate assistants and the other two were graduate students, all from affiliated labs. The graduate students were aware Experiment 4 was testing whether saccades occurred at the point of flexion to induce change blindness, but did not know the theoretical reasons for the experiment. The task had a five-second time limit in which to make a response; two trials from one subject were discarded due to timing out on the trials without making a response.

Procedure

Participants completed a task similar to Experiments 1 and 2. The Gabor array began vertically centered at the left or right side of the screen, then proceeded to move towards the opposite side. At the center of the screen, a single Gabor patch rotated 30°, and the whole array continued on a straight path or made a turn towards the top or bottom of the screen. Participants then indicated which item they saw rotate by clicking the location on an array presented to them
after each trial. While doing the task, subjects’ gaze was tracked using a desktop-mounted Eyelink1000 eyetracker.

Materials

Saccades were defined by the default “normal” sensitivity values of the Eyelink parser: velocity threshold was 30˚ per second, acceleration threshold was 8000˚/sec², and motion threshold was 0.1˚.

The stimuli once again differed slightly due to presentation on different equipment. The eight Gabor patches subtended approximately 2.66˚ (62 pixels) and were distributed evenly around an invisible circle. A 0.17˚-wide (4 pixels) fixation dot was displayed at the center of the array, and the distance from the dot to the center of each Gabor was 3.30˚ (77 pixels). Each Gabor patch had a spatial frequency of approximately 0.94 cycles/degree with identical phase and a random angle of orientation.

Each trial began with the fixation dot appearing for 500 ms at a location 14.62˚ (341 pixels) to the left or right of fixation and centered vertically on the screen. As soon as the stimulus array onset, it began moving at a constant velocity of 14.57˚/sec (4 pixels per refresh) towards the center of the screen for 7.37˚ (172 pixels). Subjects were instructed to keep their eyes on the fixation dot throughout the trial, even when moving. As soon as the array reached the center of the screen, the target patch rotated 30˚, and the array continued onwards for another 7.37˚ (172 pixels) or changed directions to move straight up or straight down for 6.34˚ (148 pixels). The array offset for 100 ms before re-appearing centered on the display, where participants clicked on the patch they saw change.

The two direction conditions (left-to-right and right-to-left) were completely crossed with the three angle-of-flexion conditions (0˚, 90˚, and 270˚), and the eight stimulus array locations
could serve as the target location five times during the experiment, making for a total of 240
trials. The permutations of the conditions and target locations were randomly distributed
throughout the length of the experiment. Twelve practice trials preceded the 240 trials and
consisted of random permutations of the conditions and possible target locations.

The experiment began with a calibration of the eye tracker, and a drift correction
preceded every trial. Participants were given breaks every 50 trials, and the eyetracker was re-
calibrated halfway through the experiment after 150 trials or as needed (i.e., if drift correction
failed on multiple attempts).

3.3.2. Experiment 3 Results

The analysis for Experiment 3 tested whether participants’ eyes were engaged in a
saccade during the change, thus inducing change blindness by saccadic suppression. Of the 240
trials per each of the 12 participants, a saccade overlapped with the occurrence of the change on
a total of 0.66% of all trials. Despite the low co-occurrence of saccades with the change,
subjects still experienced change blindness comparable to the preceding experiments. A more
conservative test for saccadic suppression counted the number of trials on which a saccade
occurred within 100 ms of the moment of flexion. This brought the percentage of trials with an
overlapping saccade up to 6.64% (approximately 15.9 per participant), but still not enough to
fully account for the change blindness effect. A 2 (direction) x 3 (angle of flexion) repeated-
measures ANOVA of accuracy once again found a main effect of angle, $F(2,22) = 209.72, p <
.001$, but not direction of motion, $F(1,11) = .881, p = .368$. The interaction did not quite reach
significance, $F(2,22) = 3.138, p = .063$. According to Bonferroni-adjusted pairwise comparisons,
the 90° and 270° conditions were not different from each other ($p > .999$), but were both different
from the 0° control condition ($p < .001$).
Further analyses looked at gaze location relative to the array under the different conditions. Differences between the subject’s point of gaze and the location of the target at the moment of change were calculated for each trial. A 2 (direction of motion) x 3 (angle of flexion) repeated-measures ANOVA looked at the horizontal distance between the target and point of gaze and found a main effect of direction $F(1,11) = 6.042, p = .032$. The main effect of angle, $F(2,22) = .393, p = .68$, and interaction, $F(2,22) = 2.935, p = .063$, were not significant. Gaze tended to be the left of the target in the rightward-moving condition and right of the target in the leftward-moving condition. This pointed to a tendency for the eyes to trail behind the array. The data were transformed to reflect relative displacement from the array (i.e., ahead or behind rather than left or right); a 2 x 3 repeated-measures ANOVA found no significant main effects of direction, $F(1,11) = .582, p = .461$, or angle, $F(2,22) = .291, p = .750$, or an interaction $F(2,22) = .102, p = .904$, suggesting that participants’ eyes trailed behind the array by roughly the same amount, regardless of angle of flexion or direction of movement. When collapsed across all conditions, subjects’ gaze trailed behind the array by approximately 0.440˚ of visual angle (10.26 pixels) on average.

Similar analyses were carried out for the vertical distance between target and point of gaze. A 2 (direction) x 3 (angle of flexion) repeated-measures ANOVA found a significant main effect of direction, $F(1,11) = 6.042, p = .032$, but not angle of flexion, $F(2,22) = .393, p = .680$. The interaction did not reach significance, $F(2,22) = 2.935, p = .074$. On average, participants had a tendency to look above the target by 0.60˚ (14.01 pixels) when the array moved leftward and 0.38˚ (8.85 pixels) when the array moved rightward. These data suggest an overall slight bias towards gazing above and slightly behind the array as it moves.
Accuracy data (broken down by target array location) do not reflect an advantage at the point of gaze. On average, participants showed a slight preference towards the leading edge of the array (see figure 3.7) with a bias for the upper-right target location regardless of direction of motion. Although Experiment 4b and its accompanying discussion will explore the nature of attention during motion further, the current experiment points to a dissociation between attention and point of gaze. Accuracy for a target location was not dependent upon its proximity to the fovea.

Although interesting, these data do not reflect a new phenomenon. Neuroscience has directly observed spatial-attention-based modulations in cortical activity independent of gaze for years (e.g., Brefczynski & DeYoe, 1999), and inattentional blindness for an event or object can occur even when a person fixates directly upon it (Memmert, 2006). Even in the domain of magician-inspired visual cognition research, eye tracking found that subjects could directly fixate a magician’s method for executing a trick without awareness of it (Kuhn & Tatler, 2005; Kuhn et al., 2008). At the very least, these data suggest the target changes were sufficiently visible to detect outside of the fovea; more generous interpretations would say they point to anticipatory direction of endogenous attention in dynamic tasks. Realistically, the current experiment merely adds to the growing body of evidence that gaze and attention are not inextricably linked.

3.4. Experiment 4

Experiments 1-3 demonstrate that a change in the direction of motion can itself conceal a target visual signal; however, they tell us little about why the effect occurs. Experiment 4a served as an exploratory first step into answering that question by systematically manipulating the size of the direction change participants see on a given trial. An array of six Gabor patches moved horizontally along a straight path, then deflected from the midline by incremental angles
of flexion. In doing so, we hope to address the two hypotheses discussed in the introduction. The change in direction could serve as a misdirection; the motion directs the viewer’s attention to a location along the projected path, but the target change occurs at a different point in space. Alternatively, the change in direction could generate a transient visual signal that swamps out that of the target change.

The current design has the potential to disambiguate these two hypotheses depending on how the angle of flexion modulates detection rates. The signal-swamping theory suggests some physical parameter of the transient signal overpowers the change signal. If we look to ways of operationalizing the physical signal of a change in motion direction, the acceleration vector corresponding to the change in direction of movement increases in magnitude as the angle of deflection approaches 180°. The change, on the other hand, remains constant in its physical characteristics. If swamping depends on the physical parameters described here, we should expect detection rates to monotonically decrease as the angle of deflection from the horizontal midline approaches 180°, where accuracy should reach a minimum. Due to the vagueness of the signal swamping theory, however, we cannot be certain change blindness depends on these physical parameters. Swamping may occur at the level of neural responses; for example, any motion that triggers a neural response greater than that associated with the rotation should impair detection. One potential account is discussed in the experiment discussion.

The attention misdirection hypothesis, on the other hand, predicts that accuracy should drop to floor as soon as the target change occurs outside the spotlight of attention. Assuming the spotlight is always guided to the same general location relative to the array when the point of flexion occurs (and if it is attached to gaze, Experiment 3 suggests it is), steeper angles should take the array further out of the spotlight of attention, but accuracy should not be impaired
further as soon as the angle of flexion takes it completely out of the spotlight. All angles of flexion that send the array in the opposite direction from where it was originally heading (i.e., angles between 90˚ and 270˚) should lead to equally poor performance.

Past research leads us to believe we can induce varying degrees of change blindness depending on the nature of the transient signal. Arrington and colleagues (2006) had changes occur simultaneously with the onset or offset of color in the scene (i.e., grayscale images became colored, colored images became grayscale) as well as increases or decreases in global luminance. Although these newer methods succeeded in impairing change detection, they were not as effective as a blank flicker. In the framework of the “signal swamping” theory, their results suggest that detection rates are modulated by the magnitude of change in the global visual signal relative to the target. On average, increasing or decreasing the luminance of every pixel in an image constitutes a smaller change to the visual signal than a blank flicker, which changes the luminance of every pixel in the image to a single level. It is worth noting that this proposition contradicts experiments by Rensink et al. (2000), which showed no significant difference between different types of flicker screens. In retrospect, that finding may constitute a floor effect; a blank screen is as effective as possible at inducing change blindness, and so changing features of the flicker, such as color or luminance, had no measurable effect.

3.4.1. Experiment 4a Methods

Subjects

Nine University of Illinois undergraduates participated in Experiment 4a in exchange for psychology course credit. Two participants in Experiment 4a first completed experiment 2 upon entering the lab. The remaining 7 only took part in the Experiment 4a task. The total number of
participants was low due to the timing of data collection for Experiment 4a; the study was carried out at the end of the university semester, when study enrollment was low.

**Materials**

Gabor arrays in Experiment 4a were identical to those in experiment 2 in appearance and movement velocity; however, targets were again a 15° instantaneous rotation, as in Experiment 1. Experiment 4a used a new path of motion. Every trial began with a 500 ms fixation cross centered vertically on the left side of the display. The array traveled rightward for 8.8° until it reached the center of the screen. At that point, two events occurred simultaneously: one target Gabor rotated and the array deflected by some multiple of 30° from 0° to 330°.

There were twelve conditions, one for each angle of flexion. Within each condition, every possible target location was represented 4 times (24 trials per condition) for a total of 288 trials.

**Procedure**

Instructions in Experiment 4a were identical to those in 1 and 2: participants were instructed to follow the fixation cross at the center of the array and locate the target change that occurred on every trial.

### 3.4.2. Experiment 4a Results

The following analyses combined conditions in which the angle of flexion was the same relative to horizontal (e.g., trials in the 60° condition and 300° condition were combined into a single 60° condition). A one-way repeated-measures ANOVA found a significant effect of angle of flexion, $F(6,48)=35.026, p<.001$. Pairwise comparisons, using a Bonferonni correction, found no significant difference between the 0° and 30° conditions ($p=.265$), followed by a significant decrease in accuracy between the 30° and 60° conditions ($p=.021$). There was no
significant difference between any of the conditions from 60° to 180° of flexion ($p > .936$).

Accuracy appeared to decrease steadily as the angle of flexion increased, reaching an asymptote by the 90° condition.

A one-way repeated-measures ANOVA found accuracy differed significantly among the different target locations overall, $F(5,40) = 5.131$, $p = .001$. The effect appeared to be driven primarily by particularly poor accuracy for detecting changes to the left-most Gabor patch, which was significantly worse than the lower-right ($p = .002$) and lower-left ($p = .048$) patches (with a Bonferroni adjustment applied to significance levels). The data hint at a slight advantage for the leading edge of the stimulus array in motion, though the analyses do not fully bear this out with statistical significance. Furthermore, the trend may reflect a bias to the right sides of objects rather than the leading side of a moving object; because the array always began moving in one direction, it is impossible to know. Experiment 4b will address this issue by having the array move either to the left or to the right.

Further harming the predictability of the attentional spotlight in this paradigm is the fact that the point of flexion always occurred at the same point in each trial at the same location on the screen. Participants may have learned to anticipate the deflection and therefore direct or distribute attention unpredictably in an attempt to catch the array as it changes direction. Experiment 4ab also refines the paradigm in this regard by making the point of flexion unpredictable.

Still, these results seem to point to the attention misdirection hypothesis. Accuracy decreases to a minimum as soon as the array begins moving in a direction perpendicular to where the path of motion presumably guided the spotlight of attention. Furthermore, the individual target analyses suggest a bias towards detecting changes at the “leading” target locations.
However, we still cannot rule out the “swamping out” hypothesis. First, the size of the orientation change remained constant at 15˚. It is possible that a motion signal of that size is simply swamped out completely by a 90° deflection in motion. The pattern may very well be a floor effect; a larger orientation change might continue to show a monotonic decrease as the angle of flexion increases (and, by extension, the perceptual magnitude of the visual transient associated with it).

One attempt to test the spotlight hypothesis involved analyzing accuracy for different target locations during different angles of flexion. Unfortunately, the current paradigm did not allow for much examination of the spatiotemporal characteristics of the spotlight, as the change always occurs instantaneously on the first screen refresh on which the stimulus array begins its new trajectory. Future approaches may, for instance, examine detection accuracy when the change occurs at various latencies after or locations past the point of flexion. This would allow an experimenter to see if and when attention falters and recovers selection of the entire array for the purposes of change detection.

As the current paradigm stands, the change and its accompanying visual signal always occurred at a location spatially adjacent to the point of flexion, and therefore consistently close to the spotlight of attention. A basic moving-spotlight model of attention predicts that angle of flexion should not interact with target location accuracy. The spotlight should always be focused on the whole of the array, and any angle flexion, which displace the target signal from the path of motion by .18° in Experiment 4a and .12° in Experiment 4b, should not take the localized change signal far outside the spotlight. Still, the deflection may be disruptive insofar as visual attention needs to be able to predict the path of motion of the array as a whole to detect the change. The array is, after all, somewhat large (subtending 6.91° in Experiment 3a and 6.27° in 3b) and
composed of 6 or 8 discrete items, and so may be onerous to attend. The results discuss a potential model *post hoc* in light of the data below.

Further complicating the issue are analyses of accuracy at each target location as a function of angle of flexion. A 6(location) x 12(angle of flexion) repeated-measures ANOVA found a main effect of angle, $F(11,88) = 19.540, p < .001$, and location, $F(5,40) = 5.131, p = .001$, as before; the interaction term is significant as well, $F(55,440) = 1.591, p = .006$. Fishing for a discernable pattern in the current data runs the risk of type I error, and so will require more constrained testing. One potential account is discussed after Experiment 4b.

Ultimately, it is difficult to interpret precisely what caused the effects we saw in the data. The motion of the stimulus array may have misdirected the spotlight of attention along its trajectory, and the deflection could have also contributed a low-level visual transient that affected change detection. Although the two accounts are not necessarily mutually exclusive, Experiment 4a does not provide much insight into how much each contributes to the effect—only that each may play some role. Further exacerbating the difficulty of interpreting these results is the fact that the deflection predictably occurred at the center of the screen on every trial. Participants may have spread or re-directed their attention in anticipation of the deflection as the array neared the center of the screen. Further testing will be necessary to tease apart the potential effects of spatial attention and the low-level visual transient in this particular paradigm. Experiment 4b seeks to address some of the issues with Experiment 4a and answer some of the remaining open questions.
3.4.3. Experiment 4b

Experiment 4b makes refinements to the methods of Experiment 4a to address some of the issues discussed above. First, the target change is larger (a 30° rotation rather than 15°) to see if the asymptote of Experiment 4a was merely a floor effect, and if detection accuracy continues to decrease as the angle of flexion increases. Second, the point of flexion now occurs randomly within a range of space along the horizontal axis to prevent anticipation. Third, the number of Gabor patches was increased to provide a more granular scale for mapping the spatial locus of attention with respect to the array. Finally, the array now moves from right to left in addition to left-to-right in order to test whether the slight accuracy advantage for the right side of the array in Experiment 4a was the result of attending the leading edge of the moving object or merely a rightward bias in attention. The increased number of trials as a result of including two directions of motion prompted the reduction of flexion angle conditions to eight (increments of 45° starting from 0°).

3.4.4. Experiment 4b Methods

Subjects

Twenty University of Illinois undergraduates participated in Experiment 4b in exchange for psychology course credit. All participants also completed Experiment 6b (next chapter) prior to performing the current experiment.

Materials

Gabor arrays in Experiment 4b differed from Experiment 4a due to presentation on different equipment. The stimulus arrays were made up of eight Gabor stimuli that subtended approximately 1.78° of visual angle (86 pixels). They were distributed evenly in a ring with a radius of approximately 2.24° (108 pixels), making the full stimulus array subtend a circle 6.27°
(302 pixels) in diameter. Their spatial frequency was approximately 2 cycles per degree, and each Gabor had a random phase displacement and orientation.

Each trial began with a 500 ms fixation dot vertically centered but located 9.26° (446 pixels) to the left or right of the center of the display. Participants were instructed to fixate the dot and follow it as it moved throughout the trial. The stimulus array simultaneously onset and began moving horizontally towards the center of the screen at a constant velocity of 12.46° per second (6 pixels per refresh). At some point along its path, the array either continued straight onwards or deflected from the horizontal at some multiple of 45°. In order to prevent participants from anticipating the flexion point, the deflection occurred at a random point along the stimulus array’s path within 240 pixels/4.98° to the left or right of the center of the screen. At the exact same moment, one Gabor patch rotated 30° clockwise.

The trial ended as soon as any point in the array came in contact with an invisible border along the sides of the screen (320 pixels/6.64° from the left or right edges of the screen, 135 pixels/2.80° from the top or bottom edges). After a 100 ms blank, a probe screen appeared with the stimulus array centered under the words, “Click the patch that rotated.” Subjects had 5 seconds to make a response with the mouse, after which point the computer provided feedback for 500 ms and immediately begin the next trial. The experiment encouraged participants to take breaks after every 40 trials completed.

On any given trial, the stimulus array could move left or right (two direction conditions) and deflect at one of eight angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315°). Among every permutation of the two conditions, each of the eight stimulus array locations served as the target three times, making a total of 384 experiment trials. Permutations of direction, angle, and target
location were distributed randomly throughout the 384 trials. Each experiment session began with 10 practice trials consisting of a random direction, angle of flexion, and target location.

3.4.5. Experiment 4b Results

A 2 (direction of motion) x 8 (angle of flexion) repeated-measures ANOVA of accuracy revealed a main effect of angle of flexion $F(7,133) = 128.70, p < .001$. Direction of motion did not show a significant main effect, $F(1,19) = 2.95, p = .102$, or interaction with angle of flexion, $F(7,133) = 1.016, p = .423$. Angle of flexion was collapsed across the two directions of motion for pairwise comparisons between the different angle conditions. Based on Bonferroni-adjusted significance values, the $0^\circ$ condition was significantly greater than all other conditions ($p$-values < .001). The $45^\circ$ and $315^\circ$ conditions did not differ from each other ($p > 0.999$), but differed from all other conditions ($ps < .001$). The $90^\circ$, $135^\circ$, $180^\circ$, $215^\circ$, and $270^\circ$ conditions did not significantly differ from each other ($ps > .512$) with the exception of the $90^\circ$ and $180^\circ$ comparison, which reached significance ($p = .045$). The meaningfulness of the difference is difficult to interpret, however, as the $270^\circ$ and $180^\circ$ conditions were not significantly different ($p = .546$), and the $270^\circ$ condition was merely a reflection of the $90^\circ$ condition over the horizontal.

Collectively, these results refute the account that the increasing angles of flexion generate larger transient visual signals that increasingly swamp out the change signal. Despite a lower chance level (1/8 rather than 1/6, as in Experiment 4a) participants’ performance reached floor at just above 50% accuracy and remained at approximately the same level for angles of flexion between $90^\circ$ and $270^\circ$. The results replicate the general findings of Experiment 4a, despite the methodological differences. It is worth noting, however, that the mean accuracy levels for the leftward-moving condition do trend towards a continuous decrease that minimizes at $180^\circ$, as predicted by the swamping-out account. The lack of statistical significance for these differences
and the different trend in accuracy levels for the rightward-moving condition, however, make it difficult to read much meaning into this observation. A replication with more statistical power than the current experiment, however, may elucidate the underlying pattern more clearly.

A 2 (direction of motion) x 8 (target location) repeated-measures ANOVA of accuracy collapsed across all angles of flexion revealed no significant main effect of direction, $F(1,19) = 2.95, p = .102$, but did show a main effect of target location, $F(7,133) = 5.055, p < .001$, and an interaction between direction of motion and target location, $F(7,133) = 6.239, p < .001$. The main effect of location suggested a bias towards different areas of the array (perhaps a leading-edge bias as hypothesized), and so prompted a re-analysis of the data with target locations in the leftward-moving condition translated to reflect relative location in the array. For instance, the left-most patch was treated as the “trailing” location in the rightward-moving condition, whereas it was treated as the “leading” location in the leftward-moving condition. Although the transformation suggested a relatively overlapping trend in favoring the “leading” side of the array, the analyses did not tell so straightforward a story.

A one-way repeated-measures ANOVA analyzing accuracy at each of the eight target locations was carried out separately for each direction of motion. The rightward-moving condition once again showed a significant main effect of target location, $F(7,133) = 7.325, p < .001$. Bonferroni-corrected pairwise tests suggested the two most outlying locations were the upper-right and bottom positions of the array. Accuracy for the upper right location was significantly greater than the top ($p = .033$), left ($p = .029$), and bottom ($p = .003$) positions. The bottom position, in addition, had significantly lower accuracy than the rightmost ($p = .002$) and lower-right ($p = .049$) locations of the array. The leftward moving condition likewise showed a main effect of location $F(7,133) = 3.461, p = .002$; however, the only significant difference
among the locations was between the upper-left and rightmost locations \((p = .026)\). Although not statistically significant, accuracy among the target locations did not point to a bias towards attending the leading side of the array; in fact, the highest mean accuracy across angles of flexion in the leftward-moving condition was the upper-right target location, much like Experiment 3. Although somewhat unusual, the advantage may be the result of the English-speaking participants’ reading direction, which could have caused shifts of attention rightward as participants tracked the moving array (Spalek & Hammad, 2005).

As in Experiment 4a, an 8 (target location) x 8 (angle of flexion) repeated-measures ANOVA analyzed accuracy for the different target locations as a function of angle of flexion. As before, a simple spotlight model account suggests a consistent advantage for a set of locations falling inside the attentional spotlight. As in Experiment 4a, the analysis found a main effect of angle of flexion, \(F(7,133) = 134.37, p < .001\), a main effect of target location, \(F(7,133) = 7.484, p < .001\), and a significant interaction, \(F(49,931) = 5.881, p < .001\). The significant interaction once again suggests that the trend for biasing one set of locations over another varies across the different angles of flexion. Much like the results of Experiment 4a, however, the sheer number of levels of each variable makes it difficult to get an intuitive grasp on any real trends. The combined discussion below presents one potential explanatory model.

### 3.4.6 Experiments 4a & 4b Discussion

Experiments 4a and 4b both found accuracy reaching an asymptote in the 90° to 270° range of deflections. Although the spotlight model predicted that accuracy will reach floor levels as soon as the array moved in a direction away from the predicted path of motion, other results do not point to the spotlight account so cleanly. First, angle of flexion interacted with target location in determining detection accuracy, which the basic spotlight model did not predict.
However, that account requires that attention work like a literal spotlight, shining on a particular spatial location on the display without taking into account that the stimulus array is itself an object composed of objects. This potentially complicates the situation considerably, as attention can function over objects as well as spatial location, and location- and object-based attention can interact based on task demands and stimuli (see, for example, Vecera & Farah, 1994).

A mechanism for the motion-induced change blindness paradigm

Looking to the contour integration literature, I will propose an account to attempt to unify the findings of Experiment 4a and 4b and offer a potential model for a more straightforward analysis of the data with respect to the behavior of attention. Field, Hayes, and Hess (1992) asked participants to detect an extended contour formed by a set of oriented Gabor patches spaced out among a background of randomly oriented Gabors. The experimenters found that subjects reliably detected the contour as long as the path formed by the Gabors did not contain any bends greater than 60°. (Note the parallel to the angle at which subjects reached floor detection accuracy in Experiments 4a & 4b.) Based on their results, they suggest that orientation-tuned neurons in primary visual cortex have an “association field”; any given oriented segment in the visual field increases baseline activation of neighboring orientation-tuned cells that can potentially form a contour.

Other authors have proposed a similar mechanism may underlie the perception of motion and trajectory detection (Watamaniuk, McKee, & Grzywacz, 1995), such that a moving stimulus has a sort of association field, as well. In this account, an active motion detector sends an excitatory signal to neighboring motion detectors in visual cortex falling along potential paths based on an object’s current trajectory. This theory of motion perception provides a potential explanation for the results of the current experiment.
First, consider what the motion association field suggests happens in the control condition of Experiment 1. The moving stimulus triggers an excitatory signal that travels to motion detecting neurons along the stimulus’ path. When the orientation change occurs along the straight path, some subset of those neurons that had previously received an excitatory signal now get a second excitatory signal from the motion of the target. Detection occurs rather easily, as the neural signals for those motion receptors are temporally separated.

Now, consider what happens when the change occurs simultaneously with the change in orientation. As soon as the array deviates from its predictable trajectory, the previously activated association field for the array’s motion is now invalid. The visual system must now recruit a new population of motion detecting neurons in response to the new trajectory, and therefore activates a new association field. This means motion detectors in the association field of the stimulus array’s new trajectory, which were previously inactive, now receive an excitatory signal. If the rotation occurs simultaneously with this change in trajectory, populations of motion detecting neurons are now receiving two signals simultaneously: an excitatory signal from the association field of the new path of motion, and an excitatory signal from the target rotation. As a result, the signals generated by the change in direction and the target rotation become difficult to separate, making the segregation and detection of the target rotation difficult.

This theory not only accounts for the extant data, but also makes some testable predictions. For one, changes that recruit different neurons from those excited by the change in trajectory—for instance, a color change—should create an easily separable signal that survives the change blindness effect. Experiment 5 in the next chapter demonstrates that this prediction holds true.
Attentional Selection Under the Proposed Model

Returning to the role of the attentional spotlight in Experiments 4a & 4b, we still need to disentangle the results in accuracy as a function of location. Attention can serve the function of increasing the gain on motion detection at the location of a participant’s focus. Attending to a particular target location while doing the current task makes detection of the target rotation possible even when it occurs simultaneously with the deflection. Because of the relatively salient motion signal the target rotation creates, detecting the change while the array is on a straight path may not require focused attention to the degree that detecting it during flexion does. It stands to reason, then, that change detection for the flexion conditions at or below 60˚ from the horizontal should not show an advantage to any particular location, attended or not, whereas the conditions past 60˚ should.

In the process of oral debriefing, several subjects made reports consistent with a spatial bias to attending particular portions of the array. Some participants reported feeling that changes were easier to spot in the upper right section of the array. One participant explicitly reported devoting more attention to one half of the array, then guessing randomly from the other half when he did not see the change in the attended half. Although such informal reports should always be taken with a grain of salt, the results above suggest a few somewhat consistent biases for and against certain target locations.

The accuracy levels also point to strategic attending. For instance, assume in Experiment 4b that participants could consistently attend two or three of the eight Gabor patches while tracking the array. Such a strategy would almost guarantee that trials on which the attended locations contained the target were answered correctly, and all other trials would be at chance guessing among the unattended patches. This would mean that participants using such a strategy
could be expected to score between $2/8$ (accuracy for the attended patches) + $1/6$ (accuracy expected with chance guessing among the unattended patches) = $41.67\%$ and $3/8 + 1/5 = 57.5\%$.

Accuracy bottomed out in Experiment 4b just above 50%, precisely within the range predicted for the strategy. The same logic works when applied to Experiment 4a assuming participants could reliably attend one $(1/6 + 1/5 = 27.5\%)$ or two $(2/6 + 1/4 = 43.75\%)$ patches on every trial. Still, a skeptic might reasonably wonder why subjects could attend fewer patches in Experiment 4a than 4b, and furthermore question whether the stimulus differences between the experiments (i.e., movement speed; size, spacing, and spatial frequency of the Gabors; predictability of the point of flexion) are enough to explain the difference.

To test the attentional bias theory, trials were coded on the basis of where the target change occurred in the array: an “attended” target or “unattended” target location. Locations with the highest overall accuracy across all angles of flexion were presumed attended, and all others were unattended. Therefore, among rightward-moving trials, changes occurring in the upper-right and rightmost locations of the array were coded as attended. The same goes for changes in the upper-left and upper-right locations of the leftward-moving condition. In the analyses above, accuracy did not originally show any straightforward bias towards particular locations when considering each location alone and aggregated across all angles of flexion. The new analysis compared average accuracy for all attended locations to average accuracy for all unattended locations at each angle of flexion separately. The model above predicted a significant advantage for the attended locations, but only for angles of flexion past $60^\circ$.

Paired-samples t-tests comparing unattended to attended locations’ accuracies at each angle of flexion almost completely fit the predicted pattern. A Bonferroni adjustment set alpha at $.05/8 = .00625$ to correct for the multiple comparisons. The attended locations have a
statistically significant accuracy advantage in the 90° \( t(19) = 4.072, p = .001 \), 135° \( t(19) = 3.354, p = .003 \), 180° \( t(19) = 4.312, p < .001 \), and 225° \( t(19) = 7.901, p < .001 \) conditions. However, the 0° \( t(19) = -.914, p = .372 \), 45° \( t(19) = 2.274, p = .035 \), 270° \( t(19) = 1.743, p = .097 \), and 315° \( t(19) = -.533, p = .6 \) conditions did not. The data appear to support the proposed attentional model. Still, it is still possible that the lack of a difference found in the shallower subset of flexion angles is simply due to a ceiling effect in those conditions.

Further complicating the story are the results from applying this method of analysis to Experiment 4a. Based on accuracy, the rightmost and lower-right target locations were treated as “attended” and all others as “unattended.” Paired-sample t-tests once again compared attended to unattended locations’ accuracies separately for each angle of flexion, this time with a Bonferroni-corrected alpha level of \( .05/12 = .0042 \). Although the difference between attended and unattended accuracies at each angle of flexion roughly fit the predicted trend, none reached significance except the 270° condition, \( t(8) = 3.970, p = .004 \). Calling the null results into question, however, Experiment 4a also had fewer trials, less than half the participants, and a predictable point of flexion, all of which could increase noise in the data. Indeed, SEM for the paired differences in Experiment 4a ranged between .056 and .100 compared to Experiment 4b, in which they ranged from .012 to .045. A clearer pattern may very well have appeared with the refinements of Experiment 4b and greater statistical power.

3.5. Chapter 3 Discussion

Chapter 3 established a new, motion-based paradigm for inducing change blindness in which changes remain in full view of the participant. Experiments 1 and 2 provided behavioral data for the phenomenon, and Experiment 3 ruled out saccades as a potential mechanism. Experiments 4a and 4b provided the groundwork for a theory explaining the mechanism behind
the new change blindness effect. Although the previous experiment’s discussion lays out a theory for explaining change blindness induced by a sudden change in the trajectory of a stimulus, we have yet to fit the paradigm into the larger literature. Extant data on association fields lines up rather nicely with the results of this paradigm, but they cannot fully explain the breadth of effective transients found in the change blindness literature.

Chapter 1 introduced the idea that visual transients in change blindness are a means of disrupting attention from localizing a visual signal associated with a change. In this broad sense, the association field theory does exactly the same. The change’s motion signal must be separated from a background of “noise” motion. When the ratio of signal to noise is high, the change draws attention exogenously; when that ratio is low, the viewer must exercise endogenous attention to selectively attend to the location of the change to find it.

Other paradigms represent a similar signal detection problem. Most changes occurring on their own generate a localized visual signal. Transient signals, however, create an environment in which the target change’s signal is not alone. Rather than a localized motion signal, for instance, an effective change blindness paradigm presents the viewer with a diffused motion signal across the search space. Although the mudsplash paradigm has been characterized as a form of exogenous misdirection (O’Regan et al., 1999), this framework puts forward a different story. Many instantaneous changes in the flicker and mudsplash paradigms involve the onset/offset of an object or abrupt change to a local luminance signal. The mudsplashes do not conceal the change by actively taking attention away from the change signal; rather, they passively embed the change signal in an environment where it is not the only onset/offset in the display. Finding the change then requires deploying endogenous attention to the particular spatial location containing the change to recognize it.
The association field theory invoked to explain the new motion-induced change blindness paradigm also raises potential parallels to the attentional blink (Raymond, Shapiro, & Arnell, 1992). Participants are asked to detect two targets (T1 and T2) in a rapid serial visual presentation (RSVP) of stimuli, typically letters or numbers. Detection of T2 is attenuated when presented in a window of approximately 200-500 ms following the detection of T1. Although particular theories vary from researcher to researcher, this “blink” in awareness following detection of the first target is believed to result from some sort of an attentional bottleneck that only allows processing of one stimulus at a time (Dux & Marois, 2009). The current paradigm may reflect a similar effect insofar as processing and updating the trajectory of the array at the point of flexion creates an attentional bottleneck that prevents the target rotation from reaching awareness.

Still, numerous details separate the new change blindness paradigm presented in this chapter from the attentional blink. First, attentional blink paradigms have found “lag-1 sparing,” such that participants detect both T1 and T2 if they occur immediately after one another. Detection worsens as they are separated by more stimuli in the RSVP stream, reaching a minimum in the aforementioned 200-500 ms window before returning to normal. The motion-induced change blindness paradigm greatly suppressed awareness of the change in spite of the simultaneous occurrence of the array’s change in trajectory and the target rotation. Further experimentation (such as replicating the paradigm with the target change occurring at incremental latencies after the point of flexion) may reveal a similar pattern of attenuation in detection accuracy in a temporal window following the change in trajectory, but the current design cannot speak to that possibility. Second, when participants were not required to report T1, the original attentional blink finding disappeared (Raymond et al., 1992). Participants were
not required to attend to or report any specific information about the point of flexion, similar to the control condition that did not yield an attentional blink.

In terms of broad theoretical similarity, the theory regarding transient signals described above has a much closer analogue in visual search among camouflage. Compared to an empty or visually disparate background, finding a target object becomes increasingly difficult as the environment shares more of its visual features (Neider & Zelinsky, 2006). Rather than a localized feature signal, the display presents a diffused feature signal that forces the viewer to exercise endogenous attention over portions of the display until the target is localized. Change blindness is, in this sense, change camouflage.

In a way, this camouflage analogy represents a synthesis and compromise between the misdirection and swamping theories introduced in Chapter 1, incorporating and refining their claims. First, a visual transient need not actively misdirect attention to any particular location away from a change; rather, it can obfuscate the change detection process passively by embedding the change in an environment that resembles the change signal. Although this is similar to the swamping account described in Chapter 1, the camouflage theory serves to highlight the fact that the sheer magnitude or strength of the transient signal is not enough on its own to predict difficulty of localizing a change. A zebra’s camouflage makes it difficult to visually segregate from even a small herd of other zebras, but a comparably sized herd of donkeys will do nothing to hide it. (Of course, to the swamping theory’s credit, it’s probably safe to say that we can inevitably find a herd of donkeys large enough to make finding the zebra difficult—it would simply require a lot more distractor donkeys than it would distractor zebras.) The swamping theory makes no specific hypotheses about how the qualitative nature of the transient signal interacts with its quantitative magnitude, but the camouflage theory does. This
framework also allows for broader application, such as the possibility of inducing change blindness cross-modally; the camouflage theory would predict the qualitative difference between signals coming through two different sensory modalities would require a psychophysically much larger transient signal to conceal a given target change compared to a within-modality signal.

Still, there are gaps to fill in this framework. First and foremost, the general principle must be validated empirically through the systematic manipulation of change and transient types. This is the goal of Experiment 5. Second, visual similarity, while relatively straightforward in operationalizing for visual search in camouflage, is still a bit of a mystery with respect to dynamic change signals. The association field characterization from Experiment 4 relies fairly heavily on the overlap of neural signals and receptors to explain the motion-induced change blindness effect. However, visual search and camouflage exploit attentional sets, which can differ qualitatively despite using overlapping neural hardware (for instance, forming an attentional set for one color versus another). Experiment 2 found equivalent levels of change blindness for both clockwise and counter-clockwise rotations, despite the apparent difference between the two types of rotation. Experiment 6 will examine the degree of specificity with which we can define “visual similarity” in the camouflage framework and expand evidence for the camouflage theory from one-shot change detection tasks to continuous search tasks.

3.6. Chapter 3 Figures
Figure 3.1. Experiment 1 schematic; colored shapes represent point where change occurs in each condition.

Figure 3.2. Experiment 1 results. All error bars in this paper show within-subject SEM.
Figure 3.3. Experiment 2 schematic; colored regions indicate where rotation occurred in each condition.

Figure 3.4. Experiment 2 results. Clockwise and Counter-Clockwise were both “Arc” conditions. The control condition only contained clockwise changes.
Figure 3.5. Schematic of Experiment 3 paths of motion

Figure 3.6. Experiment 3 Accuracy by Direction Traveled Past Flexion Point
Figure 3.7. Accuracy by target location and direction of motion in Experiment 3.

Figure 3.8. Experiment 4a schematic of the different motion paths the stimulus array could take
Figure 3.9. Experiment 4a results: detection accuracy for each angle of flexion.

Figure 3.10. Experiment 4a: Accuracy by target position. Locations were numbered clockwise around the array, beginning with the rightmost location (1).
Figure 3.11. Experiment 4a accuracy breakdown by target location and angle of deflection.

Angles of flexion less than 180° represent a downward movement, whereas angles above 180° were movements upward.
Figure 3.12. Accuracy as a function of angle of flexion; leftward- and rightward-moving conditions presented as separate lines

Figure 3.13. Accuracy by Array Location and Direction
Figure 3.14. Attended vs. Unattended Location Accuracies by Angle of Flexion (Exp. 4b)

Figure 3.15. Attended vs. Unattended Accuracies by Angle of Flexion (Exp. 4a)
CHAPTER 4: CAMOUFLAGE AS A MECHANISM FOR CHANGE BLINDNESS

4.1. Experiment 5

Experiment 5 takes a first step towards validating the change camouflage theory of change blindness. The task uses the same motion-induced change blindness paradigm from Experiment 1, but also introduces a color-based change detection task and transient. For the color-based change detection task, the stimulus array contains 8 roughly isoluminant colored circles, one of which changes to a different color. The “color-based” transient consists of a change in background luminance in Experiment 5a and a change in luminance levels among a set of diamond shapes surrounding the stimulus array in Experiment 5b. Half of the diamonds go from dark gray to light gray, while the other half went from light gray to dark in order to maintain a constant level of global luminance across the display.

The target change and transients are completely crossed to make a 2 x 2 blocked design. A flicker paradigm is included, as well, to provide an established change transient for comparison. Subjects are instructed to either detect the orientation change (motion) target or the color change target. The task either displays the array moving in the L-shaped motion path or while the background luminance changes. Changes always occur at the moment of the transient visual signal—when the array changes directions in the motion paradigm and when the luminance signal (background or diamonds) changes. The camouflage account predicts a crossover interaction: the luminance transient should conceal the color change more than the orientation change, and the motion-based transient should conceal the orientation change more than the color change. In essence, like should camouflage like with respect to the type of target change and visual transient, but target changes that are visually incongruous from the transient should be relatively obvious.
4.1.1. Experiment 5a Methods

Subjects

Thirteen University of Illinois undergraduates participated in Experiment 5a in exchange for psychology course credit. Eleven of the participants completed Experiment 2 prior to engaging in Experiment 5a. Like Experiment 2, participant enrollment was lower than the other studies presented here due to an end-of-semester shortage of subjects. Ten of the eleven participants reported having normal color vision, with one participant reporting “unsure.” Color change detection in the motion transient condition was near ceiling for this participant (96.9%), so his color perception was assumed to be accurate enough to successfully complete the task under ideal conditions.

Materials

Experiment 5a was carried out on the same hardware and software as Experiments 1 and 2. The Gabor stimuli and motion paradigm were identical to those in Experiment 1 with the exception that the array contained eight elements rather than six.

Unique to Experiment 4 were the color change stimuli and the background luminance transient. The color stimuli were black-outlined circles subtending approximately the same visual angle as the Gabor patches (.85°). The procedure for selecting colors was as follows: The experimenter roughly pre-defined intervals of hue in the Hue-Saturation-Value (HSV) color space for a fixed saturation and value level (50% for both) that roughly corresponded to seven hues: orange, yellow, green, cyan, blue, and magenta. The goal was simply to ensure some level of variety in the randomly chosen colors for the stimulus array. On each trial, two random hue values were chosen from each color category, and a random subset of the hues (8 of the 14 total)
were chosen to fill the stimuli. The post-change color for the target was chosen randomly from the remaining hues. The experiment was programmed to ensure the pre- and post-change colors came from two different color categories, and randomly re-selected the post-change color if it matched the color category of the pre-change target.

The background luminance transient consisted of a change from a dark gray (21.5% of the maximum luminance possible on the display) to a light gray (78.4%). Each luminance transient trial began with a 500 ms fixation cross at the center of the screen with a dark gray background. The pre-change stimulus array then appeared centered on screen for 500 ms, immediately followed by the post-change stimulus array for the same amount of time. Background luminance increased simultaneously with the occurrence of the target change.

Finally, a flicker paradigm served as a known common condition for inducing change blindness. The background was a constant medium gray, and each trial began with a 500 ms fixation cross, followed by the pre-change stimulus array for 500 ms, a 250 ms blank screen (ISI), and finally the post-change array for 500 ms.

All conditions ended with a probe in which the post-change stimulus array appeared centered on the screen, asking subjects to click on the stimulus that underwent a change during the trial. Subjects had 5 seconds to respond before the experiment moved on to the next trial; no subjects failed to answer before the time limit.

Procedure

Participants were told their task was to find changes on every trial under a variety of visual conditions. They were instructed to maintain fixation on the center fixation dot to maximize visibility of all the stimuli across all conditions. The experimenter indicated to participants that the experiment was designed to see what conditions conceal changes, so the
change would not always be obvious; in those instances, they were told to simply make their best guess.

Trials were blocked by visual transient condition, and block order was counterbalanced between participants. Within each block, participants completed the orientation and color change detection tasks in a randomly determined order. Each change detection condition consisted of 6 practice trials and 32 experimental trials (each target location appeared 4 times within that run). In total, participants completed 32 trials for each change detection task under all three visual transient conditions for a total of $(32 \times 2 \times 3)$ 192 trials.

4.1.2. Experiment 5a Results

A 3 (transient) x 2 (change type) two-way repeated-measures ANOVA found significant main effects and an interaction. The main effect of transient, $F(2,24)=46.823, p<.001$, appeared to be driven by the fact that the flicker was significantly more effective at inducing change blindness than the motion and background luminance conditions. As for the target change categories, color changes were easier to detect than orientation changes on average, $F(1,12) = 108.034, p < .001$. Most importantly, the data revealed the anticipated interaction between transient and change type, $F(2,24) = 69.79, p < .001$.

Pair-wise t-tests were carried out to analyze the nature of the interaction and compare the new means of inducing change blindness to the traditional flicker. A Bonferonni correction for multiple comparisons set alpha to $.05/7 = .007$. As expected, the luminance transient led to significantly less color change detection than orientation change detection, $t(12) = -3.982, p = .002$. The motion transient showed the opposite trend, $t(12) = 22.265, p < .001$. Comparing color change detection between the conditions, color change detection was significantly worse in the luminance transient condition than the motion transient condition, $t(12) = -7.709, p < .001$. 
Orientation change detection showed the opposite effect, $t(12) = 9.840, p < .001$. When looking to the flicker condition as a baseline, the color change detection task appeared to be easier than orientation change detection, $t(12) = 11.2, p < .001$. Interestingly, the flicker was significantly more effective than the motion transient at concealing the orientation changes, $t(12) = 3.311, p = .006$, but was not more effective than the luminance transient at concealing color changes, $t(12) = -1.036, p = .321$.

Overall, Experiment 5a appears to support the change camouflage hypothesis; like conceals like when it comes to changes and visual transients. However, there are some flaws in the design that must be addressed. First, there is a possibility that the transients did not disrupt change detection in the same way. In the case of the rotation targets, the global luminance change may affect the stimuli in contrast and perceived brightness, but does not affect the dimension which defines the target: orientation. The color stimuli, on the other hand, all change in perceptual brightness, which is one dimension that contributes to signaling the target change. Furthermore, the changes themselves were not always consistent. Target color changes jumped from one color category to another at random, which could be perceptually separated in color space to varying degrees. This differed from the rotations, which were always fixed in size.

4.1.3. Experiment 5b Methods

As described above, the background luminance change condition had a critical flaw in that the surrounding luminance of the color stimuli influenced color perception due to lightness constancy mechanisms. Experiment 5b serves to rectify this problem by instead localizing the non-target luminance change to diamond shapes in the periphery. To the same end, half of the diamonds changed from light to dark while the other half changed from dark to light. This preserved the overall luminance of the image while creating a luminance-based transient signal.
that did not alter color perception of the stimulus array as a whole. The color stimuli themselves were refined, as well. First, rather than subjectively defining the set of colors used in the stimuli (as in Experiment 5a), the colors were now evenly distributed across the HSV space. Second, targets always changed to their immediate neighbor in the set of target colors rather than a random color in order to equalize color change size across trials.

**Subjects**

Twenty-four University of Illinois undergraduates participated in Experiment 5b in exchange for psychology course credit. Two participants’ data were discarded because they did not report having normal color vision. All participants also completed Experiment 6b prior to Experiment 5b.

**Materials**

Experiment 5b was carried out on the same software and hardware as Experiment 3b. The Gabor patch stimulus array was generated in an identical manner. The parameters and conditions of the experiment were identical unless otherwise noted below.

The color stimuli were once again 1-pixel black-outlined circles subtending approximately the same visual angle as the Gabor patches (86 pixels, 1.79°). A set of nine colors used for the color-change stimuli were pre-defined in HSV color space by fixing the saturation and value at 40%, then taking nine equally-spaced points along the hue dimension. The target’s pre-change color was determined randomly on each trial but always changed to one of its two neighboring colors in the HSV space in order to make the changes roughly comparable in size. The remaining seven colors in the set of pre-designed hues were then distributed randomly throughout the array.
The background luminance change condition presented either the Gabor or colored circle stimuli at the center of the screen surrounded by 12 light and dark gray diamonds. The diamonds were not outlined and their shape chosen to make them dissimilar to (and therefore easier to segment from) the colored circle stimuli. The target stimuli were presented at 2.24° eccentricity (108 pixels from the center of the screen to the center of the stimuli), while the diamonds were presented at 4.03° (194 pixels). Light gray was set at a value of 60 out of 255, while dark gray was 200 out of 255. The diamonds were all 1.79° (86 pixels) in height and width. The pre-change and post-change stimuli were each on screen for 250 ms followed by a 100 ms ISI and probe screen asking subjects to respond.

The physical characteristics of the motion condition also differed from Experiment 4a due to the different equipment. The stimulus array began each trial centered at 6.83° (329 pixels) to the left of and 5.27° (254 pixels) above the center of the screen. At a constant velocity of 12.46°/sec (6 pixels per refresh), the array moved downwards by 7.23° (348 pixels), then change directions to move rightward for 13.66° (658 pixels). As before, the change always occurred at the point of flexion.

4.1.4. Experiment 5b Results

A 2 (target behavior) x 3 (transient type) repeated-measures ANOVA of accuracy found a significant main effect of transient type, \( F(2,40) = 296.996, p < .001 \), and a significant interaction, \( F(2,40) = 80.769, p < .001 \). There was no main effect of target type, \( F(1,20) = .713, p = .409 \). The results of Experiment 5b show that, even after refining the design of Experiment 5a, transients effectively conceal visually similar change signals better than dissimilar change signals.
4.1.5. **Experiment 5a & 5b discussion**

Experiments 5a & 5b validate the theorized camouflage mechanism for change blindness. Both paradigms, despite some methodological differences, demonstrated a crossover interaction between change and transient signal types. Cases of change blindness in which the target change remains visible credibly represent a form of dynamic camouflage, concealing a target change’s signal with similar changes in its surrounding visual environment. A motion-based transient concealed a motion-based target change in the experiments thus far, but it could not conceal a color-based change as effectively. These results also validate the refinements to the swamping-out hypothesis outlined previously, as it demonstrates there is more to inducing change blindness than one signal simply overwhelming another in terms of physical energy or level of neural activation. The luminance change signal swamped out the color change signal more than the orientation change signal, but the deflection in motion swamped out the orientation change more than the color change. Extending this camouflage account potentially explains change blindness findings not only in the past four experiments, but also change blindness findings up to this point in the literature.

Arrington and colleagues (2006) found varying degrees of change blindness for their different transients, but also used a variety of natural scene-based changes. Certain changes—particularly the changes involving surface patterns, addition/deletion of objects, and exemplar substitutions—could conceivably entail luminance changes or the onset/offset of colors, which were the very transient signals being used to induce change blindness. The camouflage account therefore predicts that the difficulty of change detection in their paradigm depends on the degree to which the target change signals themselves resemble the transient signals used to induce change blindness. The camouflage theory may likewise account for change blindness as a result
of contrast polarity reversals (Turatto et al., 2003) and even the classic mudsplashes. Contrast polarity reversals drastically change local luminance signals across the image, as a change might be expected to do to the image. Similarly, a target change might involve the onset or offset of part or all of an object. This object onset or offset should blend in with the onsets and offsets of the mudsplashes.

**4.2. Experiment 6**

Experiment 6 sets out to generalize the change camouflage theory to more closely resemble other change blindness paradigms in the literature. Whereas the experiments up to this point have all used some form of one-shot paradigm, many means of inducing change blindness involve searching for a change that cycles between two states repeatedly on screen. The classic Flicker and Mudsplash paradigms serve as prototypical examples; although a seemingly obvious change is occurring continuously in a scene, it fails to reach the viewer’s awareness until attention is focused upon it.

Given the onerousness of finding and properly altering natural scenes to contain changes matching particular transient signals, Experiment 6 simulates the experience of searching a natural scene by having participants detect changes among a set of eight objects distributed across the display. Object photographs were chosen to increase the ecological validity of the task past the simple shapes used in the preceding experiments. They also served as stimuli that could be segregated relatively easily from a background of Gabor patches, which served as the delivery medium for creating a non-target transient signal.

In Experiments 6a and 6b, participants search for a change that is either visually similar or dissimilar in nature from the transient signal created by the Gabors. The camouflage theory predicts that transients should increase search time when they generate a signal that resembles
the change compared to when they generate a qualitatively different signal. Experiment 6a asked participants to find either a color or orientation change among a background of Gabor patches changing in either color or orientation.

While Experiment 6a tested the generalizability of change camouflage among types of visual signals, Experiment 6b tests the degree of specificity with which camouflage can operate. Both types of visual signal generated by the target changes and Gabors were motion-based in nature, but consisted of different types of motion: rotation and looming/receding. Although qualitatively different to observers, the different types of motion involve more closely overlapping neural correlates than a rotation and a color change. Visual search of a static display involves the use of relatively fine-grained attentional sets that can separate subordinate categories of signals like these (such as differently oriented or colored lines). If visual search for a change functions similarly to visual search for a static target, Experiment 6b should show a crossover interaction similar to Experiment 5.

In addition to manipulating the type of signals involved, the following experiments also varied the intensity of the transient signal via the size of the changes to the Gabors. This manipulation incorporates the signal-swamping theory of change blindness by observing the interaction between transient signal type and magnitude. It will serve to explain how a seemingly dissimilar visual signal (such as a flicker) can conceal a wide variety of change signal types within the camouflage theory framework.

4.2.1. Experiment 6a Methods

Subjects

Twenty University of Illinois undergraduates participated in Experiment 6a for course credit. One participant was discarded from the analyses for reporting non-normal color vision.
Procedure

Participants completed a visual search task in which they needed to locate an object undergoing a change in orientation or color among a set of eight object images scattered across the screen among Gabor patches that were all changing in either orientation or color. As soon as subjects identified the target object, they pressed the spacebar to record their total search time and clicked on the target object to verify they had found it. The computer displayed accuracy feedback for 500 ms and then immediately began the next trial.

Materials

Experiment 6a was carried out on the same software and hardware as Experiment 4b and 5b. All stimuli were presented on a medium gray background. Stimulus locations were determined by invisibly dividing the screen evenly into eight rows and ten columns with a 52-pixel (1.08˚) space between each of the resulting cells in which no stimuli could appear. One stimulus (either an object image or Gabor patch) was placed at a random location within each cell to prevent the stimuli from forming clearly visible rows and columns. In order to prevent the eight object stimuli from clustering in one area of the display, the screen was divided into four quadrants, which each received two randomly placed object images on every trial. A Gabor patch occupied all other cells in the display not already containing an object image.

Each search display contained eight object images taken randomly from a stimulus set compiled by Brady et al. (2008; available at http://cvcl.mit.edu/MM/download.html). Before use in the experiment, the image set was processed algorithmically in Matlab to automatically replace opaque white pixels with transparent ones in order to superimpose the objects on a medium gray background. The experimenter then selected images for use in the task based on which objects remained intact after the pixel replacement process (i.e., the object was completely
separated from its original background, and no pixels belonging to the object itself were removed). Images containing faces or visually similar objects (e.g., human face masks) were excluded to prevent them from attracting attention during the task. The selection process resulted in a set of 408 object images belonging to a variety of categories (e.g., food, tools, clothing, animals) in the final experiment. Images were scaled down from an original 256x256 pixels to 98x98 pixels (2° square) in the search display. Different objects took up varying amounts of this space, as they varied in size, shape, and aspect ratio.

Targets could be defined by either a change in orientation or color and alternated between changed and unchanged states every 250 ms. Orientation targets rotated back and forth by 20°, whereas color-based targets alternated between the original object image and a color-modulated version. The color modulation was carried out by first determining the “dominant” color channel in the target image by summing the red, green, and blue color channels separately across the entire image and selecting the channel with the highest sum. The other two color channels were then attenuated by 50% to create the color-modulated version of the image.

In order to prevent finding the target based on abnormal coloring on a single frame, the exact same color modulation described above was applied to three of the non-target objects on each trial. Similarly, the object images were each given a random orientation (from 0° to 360°) to prevent finding an orientation target by spotting an askew object. The color and orientation transformations were applied to all non-target object stimuli on every trial, regardless of the nature of the target.

Gabor patches distributed across the screen served to induce change blindness. All Gabor patches were generated with the same visual parameters as Experiment 4b and 5b and had a random orientation, phase shift, and color modulation (described below) applied to them.
Simultaneous with the target object’s 250 ms alternations, the Gabor patches underwent a similar change in either orientation or color. In the orientation condition, they rotated back and forth (similar to the target) by $0^\circ$, $5^\circ$, $10^\circ$, or $15^\circ$. In the color condition, one color channel (chosen randomly for each trial) attenuated by 0%, 25%, 50%, or 100% and returned to normal with each alternation. Color modulation and orientation changes were applied to a random selection of half of the Gabor patches on each alternation. On any given frame, exactly half were color-modulated on every trial, including trials in which the Gabors were rotating; in that case, the color modulation was applied to a random channel by one of the three possible color modulation levels (0%, 25%, 50%, or 100%) for all Gabors. For the orientation condition, half of the patches rotated clockwise across the alternation while the other half returned to their original orientation. Pressing spacebar stopped the alternations.

The trials evenly represented the four levels of each of the two Gabor conditions crossed with the two types of target changes. The target could appear in each of the four quadrants a total of five times across the experiment, bringing the total number of trials to 320. The experiment began with 10 randomly generated practice trials and encouraged subjects to take a break every 60 trials.

4.2.2. Experiment 6a Results

Trials on which the participants’ responded incorrectly were discarded. Average overall accuracy for the task was 97.65% (SD = 1.42%), and so 143 of 6080 trials were removed from the data. Response times (RT) were analyzed over three variables. The target’s behavior (changing color or orientation), the Gabor patches’ behavior (changing color or orientation), and the “intensity” of the Gabor patches’ behavior. The experiment had four levels of intensity: zero (the control condition where no changes occurred in the Gabor patches), low ($5^\circ$ rotations or 25%)
color channel attenuation), medium (10° rotation or 50% color channel attenuation), and high (15° rotation or 100% color attenuation).

A 2 (target behavior) x 2 (Gabor behavior) x 4 (Gabor behavior intensity) repeated-measures ANOVA of RT found significant effects for all three variables: target behavior, $F(1,18) = 17.007, p = .001$; Gabor behavior, $F(1,18) = 30.352, p < .001$; and Gabor behavior intensity, $F(3,54) = 127.801, p < .001$. Across the entire experiment, orientation change targets took longer to find on average than color change targets, 973 ms vs 892 ms, respectively. Target detection took longer when the Gabors were changing orientation (987 ms) than when they were changing color (877 ms). Finally, search took significantly longer with every increment of stimulus intensity (772 ms at zero, 827 ms at low, 950 ms at medium, and 1,180 ms at high).

All interaction terms were significant, as well: intensity with target behavior, $F(3,54) = 5.780, p = .002$; intensity with Gabor behavior $F(3,54) = 13.341, p < .001$; target behavior with Gabor behavior $F(1,18) = 53.318, p < .001$; and the three way interaction among intensity, target behavior, and Gabor behavior, $F(3,54) = 11.576, p < .001$. The interactions are best understood starting with the interaction between Gabor behavior and intensity. Whereas RTs increased incrementally with the size of the orientation change in the Gabors, changes in the color modulation did not appear to increase RT until the high-intensity condition. This suggests that the low and medium color modulation conditions were equivalently ineffective in interfering with finding the change, whereas the high-intensity modulation condition crossed some threshold that significantly increased interference for participants.

The lack of effective interference in the low- and medium-intensity color modulation conditions further explains the three-way interaction. A 2 (Gabor behavior) x 2 (Target behavior) ANOVA run separately for the low, medium, and high intensity levels revealed a
significant interaction in the medium-intensity \( F(1,18) = 18.380, p < .001 \) and high-intensity \( F(1,18) = 33.704, p < .001 \) conditions, but not in the low-intensity condition, \( F(1,18) = .057, p = .813 \). The significant cross-over interaction in the high-intensity condition is particularly crucial to the current hypothesis, as it shows that irrelevant motion signals interfered with finding color-change targets more than motion-based targets, and irrelevant motion signals interfered with finding motion-based targets more than color-change targets.

The relative inability of the color signal transient to interfere with color-based target detection at the low and medium intensity levels may also explain some of the main effects. Orientation-change targets took longer to find on average, but most likely because the orientation-change transients interfered with their localization in a way the color-change transients did not interfere with color-change targets. The main effect for transient type also indicates that the orientation-change transient interfered with search more effectively, but primarily for the orientation-change targets. The average search time for the orientation-change targets amidst the similarly changing Gabors increased from 899 ms to 1231 ms (332 ms increase) to 1388 ms (157 ms increase); search time for the color-change targets, on the other hand, only increased from 871 ms to 939 ms (68 ms increase) to 1056 ms (117 ms increase).

These results all point to the fact that even in a continuous change detection paradigm, motion transients conceal motion changes, color transients conceal color changes, and each are less effective at concealing the other. The increase in search time with transient intensity level also lends support to the signal-swamping account of change blindness, and puts us on the road to more precisely defining its parameters. In this case, increasing the size of the transient signal did lead to slower search times in the opposite type of change signal, but not to the same degree it affected search for change signals of its own type. This could explain how certain transient
signals (e.g., flickers, mudsplashes, polarity reversals) can induce varying degrees of change blindness for a variety of target change types in natural scenes.

4.2.3. Experiment 6b Methods

Experiment 6b serves two primary purposes. First, it tests if a transient motion signal of one type conceals a change signal of the same type of motion but not a different one. Second, it further elaborates on the relationship between the size of the transient signal and the size of the change signal. Whereas Experiment 6a had target changes of a physically larger size than the transient signal changes, Experiment 6b sets the target change signals equal to the medium-intensity level of the transients.

Subjects

Twenty-four University of Illinois undergraduates participated in Experiment 6b for course credit.

Materials

Experiment 6b was identical to experiment 6a with the following exceptions. In cases where the stimuli changed in color for Experiment 6a, they now changed in size. The target stimuli alternated between 100% and 80% of its normal surface area; the 98x98-pixel square object images alternated with an 88x88-pixel (1.82”) scaled-down version. Similarly, the Gabor stimuli alternated between 100% and a reduced percentage of their normal size. The three levels of the size-change condition for the Gabors were 100% (no size change), 90%, 80%, and 60%. All stimuli maintained their center point when changing in size, giving the appearance of expanding/contracting or looming/receding. Changes in orientation were different in size from Experiment 6a, as well. Target changes were now a 10° rotation, and the Gabors rotated 0°, 5°, 10°, or 20°.
4.2.4. Experiment 6b Results

Like Experiment 6b the analyses only used trials on which participants answered correctly. Accuracy was at 97.07% on average, meaning 225 of 7680 trials were discarded from the analyses. A 2 (target change signal) x 2 (transient signal) x 4 (intensity) repeated-measures ANOVA of RTs found a significant main effect of intensity, $F(3,66) = 170.320, p < .001$, and transient type, $F(1,22) = 42.909, p < .001$. There was no main effect of target change type, $F(1,22) = 1.358, p = .256$. Bonferroni-adjusted pairwise comparisons found that all intensity levels were significantly different from one another ($ps < .016$), and orientation-change transients led to slower response times than size-change transients overall, $p < .001$.

Most interaction terms did not reach statistical significance: intensity and change signal type, $F(3,66) = .532, p = .662$; change signal type and transient type (in contradiction to the camouflage hypothesis), $F(1,22) = .729, p = .402$; or the three-way interaction among intensity, change signal type, and transient signal, $F(3,66) = .823, p = .486$. There was, however, a significant interaction between intensity and transient type, $F(3,66) = 6.600, p = .001$. Whereas increases in the degree of size-change transient signals led to incremental increases in response time with each step up, the orientation-change transients reached maximal interference with search by the medium intensity level.

Collectively, the results of Experiment 6b suggest that any motion-based signal will hide another motion-based signal, regardless of the types of motion involved. Indeed, the data lacked the characteristic crossover interaction of change signal and transient signal types predicted by the camouflage theory of change blindness. The interaction between intensity and target type, however, is somewhat telling. In the case of orientation change, it appears that maximum interference occurs when the transient signal is at least equal in size to the change signal. A size-
change transient, on the other hand, can exceed the degree of size change in the target signal before it becomes maximally effective in inducing change blindness. Although this trend suggests an interaction between transient type and intensity, it may only hold for the current intensity manipulation. The current experiment does not tell us if the same patterns would appear in displays that manipulated stimulus intensity by other parameters, such as the ratio of objects to Gabors.

4.2.5. Experiment 6a & 6b Discussion

Experiments 6a & 6b extended the motion-induced change blindness paradigm’s theoretical underpinnings to continuous change detection tasks. Although the transient signal was not as closely tied to the changing stimulus itself, as it was in the Chapter 2 experiments, the tasks demonstrated that embedding a target change within an environment that generates a similar visual signal is sufficient to induce change blindness. The data also show that the camouflage principle applies only to broad categories of dynamic signals—in this case, motion versus color change—rather than the finer grained distinctions that can be made in the attentional sets of a static visual search task. Furthermore, the results also incorporate predictions of the signal swamping account of change blindness; as the transient signal increased in intensity, search times increased, indicating greater difficulty in localizing the change. This finding is also crucial for explaining how transients can still induce change blindness for dissimilar target changes.

Still, we must be wary of some limitations of the current experiment. First, it is not clear what necessarily separates motion and color but not rotation and looming/receding. Although separate neural systems have been posited as one potential mechanism, color and motion are not completely separate in the brain. In fact, changes in color and luminance can activate motion
sensitive cells in MT the same as rotation (Ramachandran & Gregory, 1978; Thiele, Dobkins, & Albright, 2001). Conversely, looming motion activates receptors that are distinct from motion sensors for rotation (Tanaka, Fukada, & Saito, 1989). Ultimately, a wider variety of change and transient signals must be tested against each other at different stimulus intensities to determine where the categorical boundaries lie for defining similarity and dissimilarity among these dynamic visual signals.

Second, Experiments 6a & 6b only scratch the surface of operationalizing signal intensity for the sake of studying the signal-swamping theory of change blindness. The term “intensity” has been thrown around admittedly vaguely thus far; although the current task manipulated the physical size of the difference from one frame to another, numerous other characteristics of the displays could also modulate search times. The discussion of Experiment 6b above mentioned the ratio of Gabors to objects as one potential alternative means of modulating stimulus intensity, but numerous other possibilities exist, as well: surface area, contrast, speed, stimulus onset asynchrony, and stimulus density are just a few examples of parameters that could plausibly manipulate the effectiveness of the transient signals used in these experiments to conceal a change. Different parameters may interact with different types of transients, as well, and introduce new manipulations to modulate intensity. Furthermore, these intensity manipulations to the transient stimuli’s physical appearance may simplify to a completely different underlying factor, such as physical energy or neural response. The question of stimulus intensity is far from answered, but the data here provide a piece—albeit small—to the larger puzzle.

The nature of these experiments bring to mind to a recent finding by Suchow and Alvarez (2011) in which motion “silences awareness” of color change. In their paradigm, a ring of randomly colored circles cycled gradually through the hue dimension of HSV color space with
fixed saturation and value. When the ring of colored circles rotated, participants perceived the gradual color changes in the ring as happening more slowly than when the ring was still. In contrast to the conclusions drawn from this chapter, a motion signal concealed a color-change signal. Still, the data presented here highlight the interaction between change and transient signal types based on two types of signals. Suchow and Alvarez’s findings are compatible with the data in Experiment 5b, which found similar detection accuracy for color change in both the motion and color transient conditions.

Neither these experiment nor theirs, however, controlled for isoluminance across the color changes, and the visual system may treat the change in luminance as a motion signal itself. There is still a possibility that motion suppressed the color change signal in all these experiments only insofar as it suppressed the motion signal created by a change in luminance. This theory would predict that equating the luminance of all the colors used in a given paradigm should prevent motion from having any effect on the perception of color change. Such a control may be intractably difficult to execute with the Suchow and Alvarez (2011) paradigm, but would predict an attenuation of their “silencing” effect. Adjusting the color-based changes to be isoluminant (i.e., changes affect hue but not luminance level of the target) should also increase the size of the crossover interaction between color and motion signals seen in this chapter.
4.3. Chapter 4 figures

Figure 4.1. Experiment 5a design schematic.

Figure 4.2. Experiment 5a results.
Figure 4.3. Experiment 5b luminance transient condition

Figure 4.4. Accuracy by Change Signal and Transient Type
Figure 4.5. Experiment 5a example display. Color modulation created red-tinted objects and pink/green Gabor patches. Gabors and objects could either rotate back and forth or flash between color-modulated and normally colored states.

Figure 4.6. Experiment 6a RT for each change type by transient signal (horizontal axis) separated by stimulus intensity levels.
Figure 4.7. Response times for each change type by transient intensity (color transient only)

Figure 4.8. Response times for each change type by transient intensity (rotation transient only)
Figure 4.9. Experiment 6b example display. Gabor patches and object images alternated between two orientations or sizes until subject froze the display and responded.

Figure 4.10. Experiment 6b RT for each change type by transient signal (horizontal axis) separated by stimulus intensity levels
CHAPTER 5: CONCLUSION

Over the course of six paradigms and nine data sets, we have established the foundations of a new, motion-based change blindness paradigm; put forward a potential mechanism of motion-sensitive association fields to explain it; and by synthesizing it with the existing change blindness literature, proposed a theory for a common mechanism underlying the disparate variety of established change blindness paradigms. The camouflage theory of change blindness proposes that a transient signal induces change blindness to a degree proportional to both its visual similarity to the target change’s signal and the ratio of the transient to change signal’s physical intensity. This theory accounts for the whole of the data presented here in ways the theories of attentional misdirection and signal swamping cannot adequately do alone.

Still, this research leaves some questions unanswered. First, as much as the intensity of the transient signal seems to play a role in change blindness, there is no straightforward operational definition for it. Although “swamping” out a change signal with another happened incrementally with the manipulations of Experiment 6, it is still not clear what exactly is swamping what. Changes in the physical light energy in the stimulus or the evoked neural activity may serve as potential means of parameterizing the magnitude of the visual signal to predict change blindness, but magnitude alone does not adequately explain the motion-induced change blindness effect of Chapter 2 and its selective effect on rotation over color in Chapter 3. Although research up to this point has examined a multitude of transient signals and their effect on detecting changes, no one has previously considered how those two signals interact. That alone opens new avenues for analysis of past paradigms and the development of new means of inducing change blindness on the basis of finding transient signals that match key change signal characteristics.
The interaction between characteristics of the change and transient signals raises an important new question to the change blindness literature: what makes a transient and a change similar or dissimilar? Although these studies demonstrate that changes are better hidden among apparently similar transients than dissimilar ones, it is not entirely clear what makes rotation, expansion/contraction, and trajectory changes all similar, but separates them from chromatic and luminance-based motion signals. Future research will need to systematically measure the degree of change blindness for specific types of changes in response to different transient signals to find the boundary lines of how the visual system categorizes these dynamic signals. Those which interfere with one another, according to the camouflage theory, are functionally similar to the visual system for the purposes of change detection.

This further raises questions as to how attention functions during the tasks in Experiments 5 and 6. First, the current data do not indicate to what degree top-down control of attention might impact performance on the task. First off, we cannot be certain that is true for all the tasks described in this project. The experiments of Chapter 3 put forward a low-level mechanism for the experience of change blindness, with the potential for attention to simply modulate change detection performance by adjusting the gain of the motion signal coming from a particular stimulus. In that regard, the motion-induced change blindness paradigm may depend on a different set of cognitive processes than the experiments of Chapter 4. Experiments 6a and 6b require visual search rather than simple detection of a change signal, and therefore invoke attention in a different way. As mentioned in the introduction, theories of object recognition posit that a given object requires attention to combine the set of low-level feature signals that make it up into a coherent mental representation. Detection of a localized change signal may not necessarily require the formation of a complete object representation in cases where a change is
directly observable as a motion signal (as it is here, but not in paradigms involving an ISI).

Although spatial attention may modulate performance in Experiments 1-5, it is not clear to what degree attention is required for change detection.

Experiment 6, on the other hand, very much resembles a traditional visual search task, and applying the framework of that literature inevitably raises myriad questions. For instance, is the change signal a feature of an object the same way color or orientation is? The evidence presented here would suggest so. In a static conjunction search, objects in the search space all share multiple features, and the target is defined as the one object that has a particular combination of those features. In the case of Experiment 6, all the objects in the search display share the change signal, and the participant must direct endogenous attention around the search space in order to determine which object has the desired combination of features and change signal. In a sense, the participant is using attention to bind the change signal to the objects at the same spatial locations in order to determine whether the change signal is coming from a distractor Gabor or an object photograph.

If the change signal truly is just another feature to the visual system, this raises further questions as to how attention behaves in the visual search task. For instance, attention might filter a particular type of change signal upon observation of the behavior of the Gabors in Experiment 6; the slower RTs in the condition where target and distractor change signals are consistent would reflect attention inadvertently filtering out the target object during the search task. Alternatively, attention may engage in a purely selective process, such that the spotlight of attention is guided towards any change signals. When the target change signal is inconsistent with its environment, it may draws attention towards it, whereas a single type of change signal across the search space forces attention to move through more objects on the basis of which ones
exhibit the change signal. Finally, some combination of the two accounts may (and likely does) occur, where attention filters certain objects on the basis of one type of feature (e.g., those consistent with simple Gabor gratings), but selects on the basis of another (e.g., the change signal). Future experiments can disentangle these different accounts by simply manipulating the number of objects and distractor Gabors present in the displays and seeing how it affects measures of visual search (e.g., search slope, efficiency).

This change-as-feature theory also raises interesting possibilities for how top-down attention may further modulate performance, perhaps through a mechanism similar to attentional sets. For instance, participants may be able to enhance change detection based on how prepared they are to select or filter a particular type of change signal. Although the degree of precision of this possibility is another unknown, performance may improve if the participant knows, for example, what colors will be involved in the target change. Experiment 5 was blocked by target change and transient type, but the relatively low number of trials (40 per condition) makes meaningful analysis difficult. With more trials and stronger means of establishing an attentional set for the participant—perhaps by giving a preview of the target change without its spatial context or looking at inter-trial effects when color or orientation changes were the same from one trial to the next—future experiments can explore the degree to which attentional control plays a role in these paradigms.

Understanding the elemental components to these change blindness phenomena stands to benefit applications in which a person must find change-related signals in a dynamic environment. Instrument panels and information displays in airplanes, power facilities, factory consoles, and other complex mechanical systems present humans with constantly changing visual information. Designing those changes to be easily segregated by the visual system can
potentially help operators notice safety-critical fluctuations sooner. Conversely, understanding what types of visual signals conceal each other can serve to camouflage dynamic signals we do not want found. This area of research can benefit the magicians that originally inspired it by guiding the development of new ways to conceal maneuvers. To much more militaristic ends, change camouflage can also inform methods for hiding the movement of persons, vehicles, or machinery in dynamic environments beyond forms of camouflage based on static visual features.

In sum, this project presents us with a novel visual phenomenon and opens new avenues for inquiry through a revised framework for analyzing change detection. As effective as a door to the face or a splash of mud in the eyes can be in blinding our perception, this work reminds us that sometimes a flick of the wrist or a wave of the wand can just as easily make things disappear right before our eyes.
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