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Investigating change blindness in three-dimensional dynamic stimuli.

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INVESTIGATING CHANGE BLINDNESS IN THREE-DIMENSIONAL DYNAMIC STIMULI

A Thesis Presented

by

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CHAPTER 1

INTRODUCTION

We often take for granted our ability to notice change in the environment. For most people, if asked whether they would notice a fairly sizeable change in plain view (e.g, the disappearance of a scarf from an actor's neck between two takes of a scene from a motion picture, Levin & Simons, 1997), the answer would be 'yes', and with a fair degree of confidence. That there is a body of evidence going back several decades now that shows that this intuition is wrong makes the phenomenon of change blindness all the more fascinating.

Beginning with research as early as the fifties, experiments investigating the ability of participants to correctly detect change indicated time and again that humans are surprisingly bad at detecting change in parts of a scene that they are not specifically attending to. This however was only true provided the change occurred during some sort of discontinuity in the observer's ability to view the stimulus undergoing the change. Ditchburn (1955), and later Wallach and Lewis (1966), ran experiments designed to investigate the mind's ability to maintain a coherent stable image of the world in the face of constantly changing visual input. Participants in these experiments were asked to detect changes in their environment. Participants in both experiments were unable to detect displacements of the viewed stimulus if that displacement occurred during an eye movement.

Later work in the seventies provided more detail on this phenomenon. Research showed that detection of a number of different forms of intra-saccadic change was difficult. Experiments by Mack (1970), Rayner (1975), and Bridgeman, Hendry, and

Stark (1975) showed poor detection of saccade contingent change for a number of different types of stimuli ranging from written text to simple targets. In each of these experiments, participants were presented with a visual stimulus that changed during a saccade. In each case, participants were rarely able to report detecting a change in the stimulus if that change occurred during an eye movement. As interest in change blindness began to foster, a major question arose, what information does the brain maintain between eye movements?

Some early models proposed the existence of a visual buffer that maintained information between fixations (e.g., McConkie & Rayner, 1976; Feldman, 1985). Under this type of model, the brain would take the visual information from one fixation and somehow merge it with information from the next fixation thereby forming a larger, more complete and more comprehensive image of the environment. Although at first this would seem like an intuitively appealing idea, a closer look at what it would entail to realize such a system makes it impractical.

This type of process would require the brain to dedicate a large amount of resources to a task of little potential benefit. On average, people make several fixations a second. The amount of visual information one receives from only a few minutes in a room is immense. It seems fairly inefficient to store all that information in the brain, since most of it will be of little to no use, and most of it can be reacquired by resampling one's environment. In addition, one would need to somehow integrate the visual information from all these fixations, which would be quite difficult. Saccades rarely land where intended, so one has to somehow determine where the information from a new saccade would fit into an image from a preceding fixation. These images would not be identical since the visual acuity of the region from which new information is to be added to an existing image is impoverished, making a match between the two extremely difficult. In other words, one would have to integrate parafoveal visual information with a newly acquired foveal image of the same scene. In addition, the system must be able to handle changes in lighting and/or perspective between different fixations and integrate that information in a matter of a few milliseconds.

Given these concerns, a second perspective emerged arguing for the lack of visual information integration between saccades (Rayner & Pollatsek, 1983; Jonides, Irwin, & Yantis, 1983). Given the difficulty and effort associated with the process of integrating information from one saccade to the next, the suggestion here was that no implicit visual information is maintained at all. Given the fact that one can refixate a given location fairly quickly, there seems to be little need for integrating visual information from one fixation to the next, at least in the manner described above. Obviously some information, possibly at a more abstract level, would need to be maintained in order for one to have a global sense of what is being viewed and to guide the location of future fixations. This model, however, leaves a number of questions unanswered. What, if any, visual information does the brain maintain? How does the brain determine what information may be pertinent ahead of time? What form does this information take? Is this global information merely an impoverished visual version of the integration model previously proposed, or is the information stored in a more abstract symbolic form?

It is difficult to determine a way of teasing out the format in which a fixation's information is retained, and indeed that may be a moot point. The more pertinent question is what information is retained from a fixation. It is clear that some sort of information is retained, not only from the fact that change detection is possible, but also from research into preview benefits. Let us make a distinction here before we move on. There is a difference between information that has consciously been attended to, and information that has been in the visual field, but may not have received specific attention. Research by Hollingworth and Henderson (2002) indicates that if an object is specifically fixated prior to the change occurring, participants are much more likely to detect the change than if they had not fixated it prior to the change occurring.

In addition, there is evidence to indicate that some information may be extracted during a fixation from parts of the visual field whose contents people may not consciously be aware of. Preview benefits have been observed in a number of studies that indicate that although explicit knowledge of certain areas of the visual field is absent, implicit measures are able to suggest that some information from that portion of the field has been extracted. One of the first experiments to illustrate the presence of a preview benefit comes from Rayner's (1975) paper on the effects of preview benefit on reading. In this study, participants showed significantly slower reading times when their ability to gain a preview benefit from words beyond what they were currently fixating was impaired. This was done by replacing words in the parafovea with random letters. These letters would change back to the intended word during the saccade that fixated that word. This was observed even though many participants were not able to explicitly report observing any overt change and were usually unaware that there had been a random string of letters in their periphery.

A great deal of research has gone into determining what type of information is gained from a preview in reading. For example, research indicates that the information extracted is independent of the case of the letters used (Rayner, McConkie, & Zola, 1980; McConkie & Zola, 1987). This indicates, consistent with what was argued above, that the information is not purely visual in nature. In addition, research has indicated that semantically related previews provide almost no benefit at all (Rayner, Balota, & Pollatsek, 1986; Altarriba, Kambe, Pollatsek, & Rayner, 2001). Similar experiments were run with scenes of line drawings (Pollatsek, Rayner, & Collins, 1984) that provided somewhat analogous findings. Participants were asked to name objects as quickly as possible. Facilitation was found if the preview was visually similar, as modest variations in size, by up to 10%, did not have a detrimental effect on naming performance. Objects that were not visually similar provided no preview benefit, even if they were semantically related to the object to be named.

Research in the change detection/blindness realm over the past several decades, although fruitful, has left many questions unanswered. It is still unclear what information is extracted from a visual scene. To answer these questions, a number of paradigms have been used that differ in the type of display material used, contingency of the display change, and measure of detectability of change. We have already discussed saccade contingent change paradigms, but the change blindness phenomenon has been observed in other paradigms, and a review of these may help shed some light on the nature of the phenomenon itself.

One popular paradigm, often called a flicker paradigm, places a gap between the presentation of one stimulus and its altered version. This is primarily done to control for motion detection, which allows one to detect a change in a static scene fairly quickly if no discontinuity in the observation of the scene is introduced. The gap may be a mask, or more often and just as effectively merely a blank interval (Pashler, 1988; Simons, 1996, and Rensink et al. 1997). This paradigm is popular because it is fairly simple to produce, and very effectively illustrates change blindness even in a natural scene and even when the change is fairly large.

Variations on the flicker paradigm include the *splat paradigm* (Rensink et al. 2000), where a change occurs simultaneously with the appearance of a distracting "splat" (i.e., blob) on the screen, and the *occlusion contingent* paradigm (Simons & Levin, 1998; Rich & Gillam, 2000) in which the change occurs while the relevant part of the visual field is being occluded. Two paradigms that operate on a principal similar to that of the flicker paradigm are blink contingent changes (O'Reagan et al. 2000), in which the change occurs during a blink, and cut contingent changes (Levin & Simons 1997, 2000), in which the change occurs during a cut from one scene to the next, or from one perspective view to another.

A paradigm similar to the saccade contingent paradigm shifts the entire display in an attempt to induce a saccade without the need for the use of eye-tracking equipment (Sperling, 1990; Blackmore et al. 1995). Change blindness is observed in this paradigm even when a saccade is not induced, since the scene shift is enough to disrupt the continuity of the display.

There is one final paradigm that is somewhat different, the gradual change paradigm (Simons et al. 2000). In this paradigm the change occurs gradually over several seconds; there is no large disruption of the visual scene at any point in time, yet participants still have a very difficult time detecting a change in the scene.

The key to hindering the detection of change in a visual scene seems to be a disruption of either the spatial or temporal continuity of one's experience of that scene. It seems as though motion detectors are primarily responsible for the detection of change in our environment, and making them irrelevant to the task is critical to the induction of change blindness. The introduction of a gap, a change in perspective, or the gradual introduction of a change to a scene all serve to disrupt the brain's ability to detect the relevant motion in that scene and severely hinder one's ability to detect the relevant change.

A wide range of stimuli can be used for any of these paradigms. These range from the words and sentences used in the reading experiments mentioned earlier, to line drawings, pictures of natural scenes, dynamic stimuli, film footage, or even real life actors. Although some evidence has been found for some retention of information from parts of a visual scene that have not been explicitly attended to, the vast majority of research has been unable to find overt reports of change detection in most of these paradigms. The exception has been in a number of studies that have found relatively good detection of saccade contingent change in moving stimuli. The fact that the use of moving stimuli seems to improve change detection well above that of the level found for experiments using static stimuli has given rise to two questions: (a) Do people encode dynamic stimuli in a manner different from that of static stimuli? (b) If not, what is it about a dynamic stimulus that makes it more memorable than a static stimulus?

In a series of experiments (Verfaillie, De Troy, & Van Rensbergen, 1994; Verfaillie, 1997; Verfaillie & De Graef, 2000), Verfaillie and colleagues investigated participants' ability to detect change in dynamic stimuli. Participants in these experiments saw a number of moving dots on a computer screen. These dots were positioned in such a way as to mimic the locations of major joints on the human body, and move in such a manner as to give the illusion of a walking man. Participants in these experiments had no problem seeing this simple collection of moving dots as a walking man.

The experiments investigated the ability of participants to detect saccade contingent changes in this stimulus. Participants saw the aforementioned walking man on the screen. During a critical saccade, a change was induced in the walking man. The original experiment changed the position in the walking sequence that the man would have been in at the end of the saccade by rearranging the dots into a position at some interval of time before or after the position they would have maintained had no change occurred, the sequence then continued normally from that point onwards. Although performance was not perfect, participants were much better at this task than many of the other change detection tasks previously mentioned and just as good at detecting the change as when it occurred within a fixation.

Later experiments by Verfaillie and his colleagues revealed that this type of moving stimulus facilitated the detection of a wide range of different types of change – however, to varying degrees. The same paradigm was used to detect changes that ranged from displacements of the walking figure to in depth rotations. Although it is difficult to compare performance of one type of change to another, the evidence from these experiments has indicated that change detection for a dynamic stimulus is better than change detection on tasks that utilize static stimuli. They also indicated that changes directly pertaining to the motion itself were more salient than other types of change. For example, changes in the position of the dots as described above were better detected than changes that displaced the figure as a whole. The results of experiments using the walking man paradigm suggest that this improvement in performance might due to a higher retention of visual information for moving stimuli. What type of visual information is retained and what form it takes remain unclear.

Similar experiments by Pollatsek and Rayner (2002) obtained comparable findings using a fairly different stimulus. The experiments using the walking man thought that perhaps there was a special significance to biological motion detection as being a possible important factor in the detection of change in that stimulus. Pollatsek and Rayner's experiment used a dynamic stimulus of a completely different sort, their stimulus consisted of a simple rotating line. The line rotated about a fixed point in the center of the display. Change in this experiment was again saccade contingent. The appearance of a cross induced participants to perform a saccade during which a change to the display occurred on half the trials. This change consisted of a "jump" in the location of the line to a position ahead or behind that of the current location. Although not as good as within fixation trials, detection of the change in the between fixation condition was well above that of the false alarm rate and again surprisingly good in comparison to the vast majority of change blindness experiments. Replication of this experiment with stricter controls designed to control against motion detection provided further evidence that this finding was not spurious and that detection of change in a dynamic stimulus was as good between fixations as it was within fixations. Of course, other than the fact that the stimuli were moving, and that the type of change was directly related to that motion, it is still unclear what it is that is in common between the walking man experiments and the rotating line experiments that allows for the improved performance. Although the evidence for some sort of visual information retention is strong, it is still possible to use some possible motion tracking mechanisms to solve these tasks. And if visual information is being retained we still know very little about the nature and extent of that information.

CHAPTER 2

PROPOSED PARADIGM

The following experiments were designed in an effort to resolve the numerous issues presented above or to at least shed some light on the nature of change detection for moving stimuli. The experiments centered on a single basic stimulus in a paradigm similar to that employed in the walking man and rotating line experiments. The stimulus consisted of a computer rendering of a three-dimensional cube rotating about an axis.

Although the cube is still a fairly simple figure, it does pose a sizeable departure from the types of stimuli that have been used thus far. The "walking man" stimulus is a two-dimensional representation of apparent biological motion. The rotating line is a very simple two-dimensional shape providing a minimal amount of visual information. The fully rendered cube, however, does represent a potential real life shape that one is likely to observe in the environment. In addition, the lighting and the texture effects of the rendered cube provide a richer, and possibly harder to process, wealth of visual information than did the rotating line or the "walking man" dots.

Participants in the experiments were asked to wear an Eyelink II SR Eyetracker. The stimuli were presented on a 19-inch monitor at a resolution of 800 by 600 pixels using 16-bit color coding and refreshing every 6 ms. The eye position was sampled every 2 ms. Viewing was binocular, but eye movements were recorded using the right eye.

Once participants were calibrated, they went through ten practice trials in order to familiarize themselves with the apparatus and the task. The beginning of each trial consisted of a fixation point in the center of the screen. Once the trial was initiated, the fixation point disappeared, and the stimulus appeared in its place. In addition, a fixation cross appeared to the left of the stimulus. Participants were instructed to fixate the cross as soon as it appeared on the screen. The eye tracker was used to determine whether or not fixation of the cross was maintained.

After a variable predetermined interval, the fixation to the left of the cube disappeared and a new fixation cross appeared to the right of the stimulus. For conditions where the change happened within a fixation, the change occurred 100 ms prior to the fixation cross “jump”. Saccade contingent changes were initiated as soon as the eye tracker detected a saccade across the stimulus to the new fixation cross. Participants then indicated whether or not they believed a change had occurred by pressing one of two buttons. Response times and eye movements were recorded.

CHAPTER 3

EXPERIMENT 1

The aim of the first experiment was to investigate participants' ability to detect saccade contingent changes in the rotating cube paradigm outlined above. By comparing performance on the task in the within fixation change condition versus the saccade contingent change condition, we were able to compare the performance of participants on this task with the performance of participants in Verfaillie's "walking man" paradigm, and Pollatsek and Rayner's rotating line paradigm. My prediction coming into this experiment was that detection of change in this task would prove to be difficult in general, but that detection levels would be significantly above chance both when the change occurred during a saccade and when it occurred during a fixation.

Participants. Eight participants were recruited from the University of Massachusetts community to participate in this experiment. They all had normal, or corrected to normal vision, and were offered either pay or course credit for their participation.

Apparatus. Each participant viewed the stimuli on a 19 inch NEC Trinitron monitor connected to a 2.4 Gigahertz Pentium 4 PC. The refresh rate of the monitor was 160 Hertz. Participants were required to wear a lightweight helmet that is part of the Eyelink II SR eyetracking system. The eyetracking system samples at the rate of 500 Hertz and provides eye movement data both for data analysis, and to the display PC for the purposes of conducting display contingent changes. No head restraint was used since the Eyelink II system is able to compensate for head movements. Eye movement data was collected from the right eye.

Stimuli and Design. The stimuli used in this experiment were the cubes described above. The overall screen resolution was set at 800 by 600 pixels, and each stimulus was presented at the center of that display. The stimulus in each case was a blue rotating cube that was fully rendered and set against a black background. The cube rotated at the rate of 3 degrees every 12 ms (i.e. the frame changed every other refresh period). During each trial in Experiment 1, the cube rotated about the axis that ran through the topmost and bottommost corners of that cube. The cube appeared in one of two different orientations (see Figure 1) an equal number of times randomly distributed across all trials. Orientation A allowed the cube to rotate about the vertical axis with its topmost and bottommost corners on the axis of rotation. Orientation B was achieved by rotating the cube described in the first condition by 30-degrees in the z-plane.

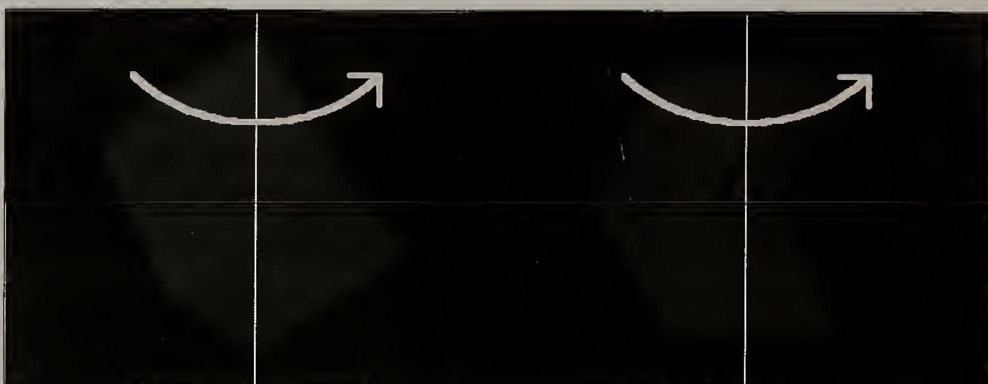

Figure 1. Rotation Axis for Orientaion A (left) and Orientation B (right)

A change in the motion of the stimulus occurred on three quarters of the trials. The change consisted of a jump in the sequence of rotation of the cube. That is, instead of moving ahead at the same rate of rotation, the cube performed a one-time jump of plus or minus 12, 24, or 48 degrees, and continued its rotation from its new location at the same rate of rotation it had before the jump. A control for low-level motion detection was introduced during the 12 ms interval directly preceding the jump in trials when a change occurred, and at a corresponding point in time in trials where no change occurred. Note that although frames were incremented every other refresh period during the cube's normal motion, the change was initiated at the beginning of the first possible refresh period.

On each trial, one of two possible controls was used. Control A consisted of a 135-degree jump ahead in the cube's rotation that was followed by a return to its original trajectory in the case of the no change condition, or to a new location in the case of the change conditions. Control B consisted of a jump ahead in the cube's rotation of a magnitude that would allow the jump in the following frame to be of a magnitude of 135-degrees. To give an example of a type B control, consider a 24-degree forward change condition. The control jump ahead would be of a magnitude of 162-degrees (note that this includes an extra 3-degrees to compensate for the frame that is taken up by the control). Given a 12-degree backward jump change condition, the control jump backwards would have been of a magnitude of 126-degrees. As indicated above, the purpose of both controls was to eliminate the use of low level motion detection to determine whether there was a change (especially when the change was within a fixation).

On half the trials, the change occurred during an induced saccade while on the other half of the trials, the change occurred 100 ms prior to the induction of the saccade. The saccade was induced in the following manner on each trial. Participants were required to fixate a cross to the left of the rotating cube. After a varying predetermined period of time and after the cross had been fixated for at least 100 ms, the cross jumped to the right side of the rotating cube. Participants were instructed to make a saccade to the new cross location as soon as possible. Saccade contingent changes were introduced only after the eyetracker had determined that the saccade had indeed begun. For the within fixation condition, changes that occurred during a fixation occurred 100 ms prior to the induction of the saccade. At the end of each trial, participants indicated whether there was a change in the motion of the stimulus during the trial (they were asked to ignore the control) using a response box.

To summarize, each participant saw the cube in: (a) two orientation conditions, each rotating about the axis running through its topmost and bottommost corners, (b) two jump directions, either forwards or backwards, (c) two control conditions, and (d) four angles of rotation, one of which being the "no change" condition. Each of these appeared in either the within fixation condition or the within saccade condition five times for a total of 320 experimental trials. A break was introduced in the middle of the experiment to give participants a chance to rest. There were also ten practice trials at the beginning of the experiment in order to familiarize participants with the task, the equipment, and the stimulus. These practice trials were preceded by a demonstration in which participants were shown what the cube would look like, and what change and control conditions would look like.

Results. Contrary to my original prediction, the data from Experiment 1 indicated that participants were almost at chance at detecting the presence of a change in the within saccade condition. The false alarm rate was 5.3%, and the hit rates were 4.7%, 5.6%, and

11.6% in the 12-, 24-, and 48-degree jump conditions respectively, $F(3, 21) = 1.185$, $p > .3$. Even the comparison of the hit rate in the 48-degree jump condition to the false alarm rate failed to reach significance, $F(1, 7) = 1.054$, $p > .3$. Participants, however, were able to detect change in the within fixation condition. The false alarm rate was 45.3%, and the hit rates were 63.8%, 72.2%, and 89.4% in the 12-, 24-, and 48-degree jump conditions respectively, $F(3, 21) = 22.989$, $p < .001$.

The majority of the other variables did not significantly affect participants' ability to detect change in either the within saccade or within fixation conditions. The cube was presented in one of two different orientations in Experiment 1. As can be seen in Table 1, cube orientation had no effect on participants' ability to detect change in the cube's motion whether that change occurred during a saccade or during a fixation.

Within	Orient.	False Alarms	Hits			F(3, 21)	p
			12-degree	24-degree	48-degree		
Fixation	A	42.5%	64.4%	73.1%	90.6%	< 1	> .5
	B	48.1%	63.1%	71.2%	88.1%		
Saccade	A	5.6%	3.8%	5.6%	11.3%	< 1	> .5
	B	5.0%	5.6%	5.6%	11.9%		

Table 1. Interaction of orientation with ability to detect change in the within fixation and within saccade conditions.

Previous research, as well as pilot data using this paradigm, had indicated that there was no significant difference in participants' ability to detect change between when that change took the form of a jump forwards or a jump backwards. In some cases, there was a trend favoring the detectability of backward jumps, and therefore jump direction was included as a variable in Experiment 1. The data from Experiment 1 (see Table 2) indicated that the detection of change in the rotation of a cube is marginally better if that change takes on the form of a backwards jump than a forwards jump; however, the effect was far from significant in both the within fixation and within saccade conditions.

Within	Jump	False Alarms	Hits			F(3, 21)	p
			12-degree	24-degree	48-degree		
Fixation	Back	46.9%	56.9%	64.4%	86.9%	1.168	> .3
	Forwards	43.8%	70.6%	80.0%	91.9%		
Saccade	Back	4.4%	3.1%	6.3%	12.5%	< 1	> .45
	Forwards	6.3%	6.3%	5.0%	10.6%		

Table 2. Interaction of jump direction with ability to detect change in the within fixation and within saccade conditions.

As for the two different types of control used; control A kept the initial jump ahead constant, whereas control B kept the return to the trajectory constant. There was no reason to believe that there would be a significant difference between these two different types of control, especially considering the brevity of the period of time during which they occurred. They however were included to detect any kind of low-level ability one might have to garner information from the magnitude of the jump to the control frame, or the magnitude of the jump back from the control frame. Results from Experiment 1 showed no significant effect across the two types of control on the detectability of changes that occurred during a saccade. The effect the two types of control had on the detectability of change within a fixation was not significant either as can be seen in Table 3. However, participants seemed to perform slightly better when Control B was used.

Within	Control	False Alarms	Hits			F(3, 21)	p
			12-degree	24-degree	48-degree		
Fixation	A	47.5%	58.8%	68.1%	88.1%	1.704	> .15
	B	43.1%	68.7%	76.3%	90.6%		
Saccade	A	6.3%	5.6%	8.1%	11.9%	< 1	> .6
	B	4.4%	3.8%	3.1%	11.3%		

Table 3. Interaction of control type with ability to detect change in the within fixation and within saccade conditions.

The initial prediction coming into this experiment was that only the presence or absence of the jump would have any effect on change detection. As revealed above, this was true of the within fixation condition, but not quite so for the within saccade condition. Another prediction was that the detection of change would increase as the magnitude of the change increased. As can be seen in Figure 2, this again was true of the within fixation condition, but not the within saccade condition. One however can see that a slight trend did indeed exist for the within saccade condition. This prompted a closer investigation of the performance of each participant individually, and as can be seen in Figure 3, Participant 2 was able to perform significantly above chance in both the within fixation condition, $F(3, 128) = 6.926$, $p < .001$, and the within saccade condition, $F(3, 128) = 9.490$, $p < .001$. As illustrated in Figure 4, once Participant 2 was removed from the analysis, the slight trend disappears completely. The false alarm rate became 2.9%, and the hit rates became 2.1%, 1.4%, and 3.2% in the 12-, 24-, and 48-degree jump conditions respectively, $F < 1$, $p > .7$.

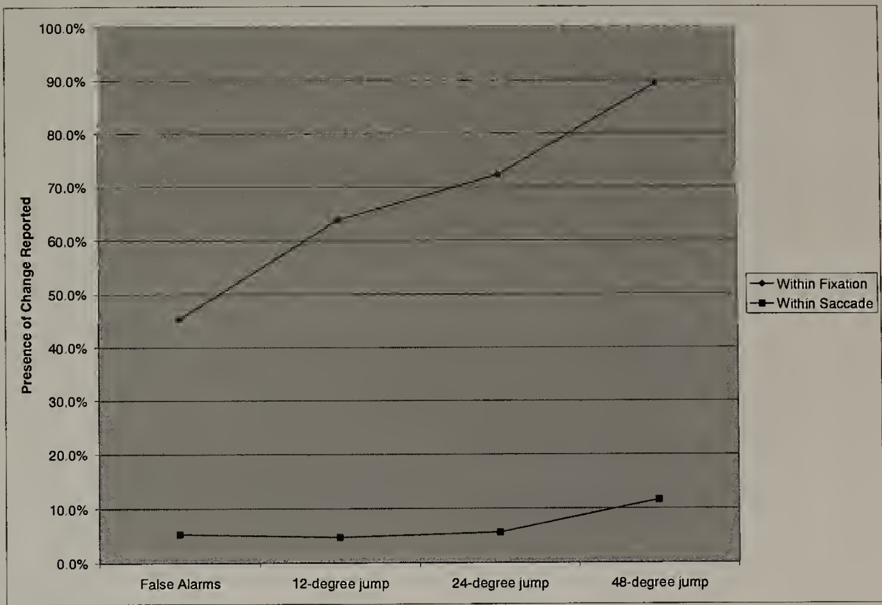

Figure 2. Change detection in the within fixation and within saccade conditions.

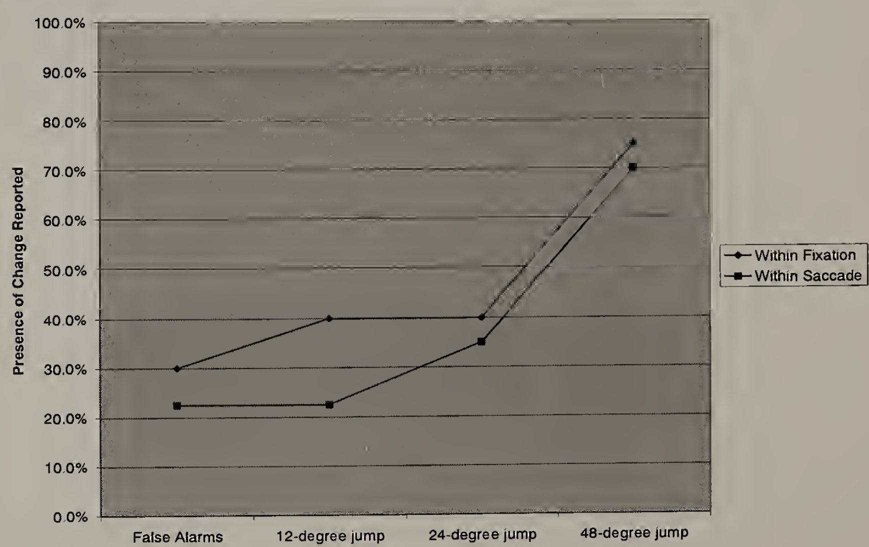

Figure 3. Change detection in the within fixation and within saccade conditions for Participant 2.

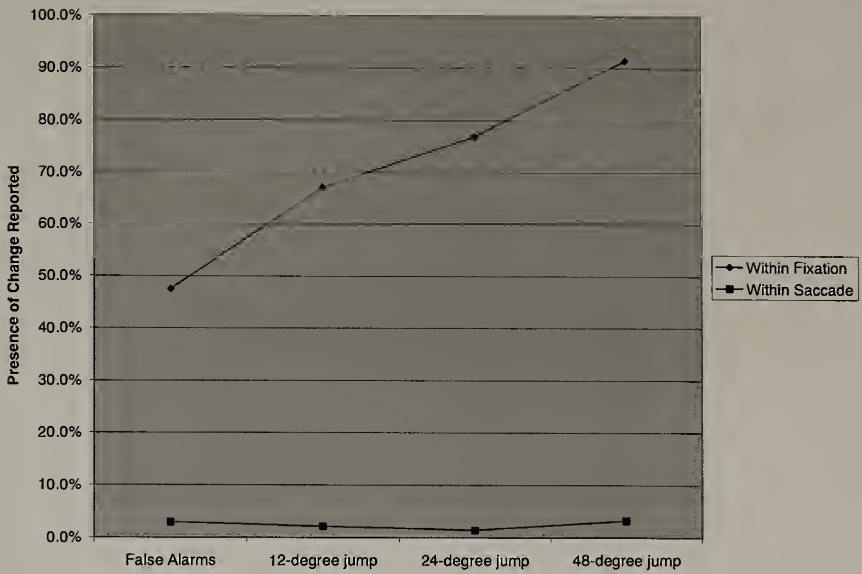

Figure 4. Change detection in the within fixation and within saccade conditions excluding Participant 2.

Given the high level of performance Participant 2 was able to achieve even in the within saccade condition, a follow-up interview was conducted to ascertain how he was able to perform so well. He articulated a strategy that allowed for the detection of change without the need for the maintenance of any visual information. Given the fact that the cube in Experiment 1 was rendered and had lighting and texture effects, Participant 2 was able to detect a peak in the reflection of the light off of one of the cube's faces at uniform intervals. This allowed him to construct a "rhythm" of light reflection peaks at uniform intervals. He was able to maintain this "rhythm" as a mental beat, which helped him determine whether or not the cube had undergone a change by comparing the "rhythm" maintained mentally with the pattern of light reflection peaks the cube exhibited after the saccade. This enabled him to detect change in the within saccade condition just about as well as in the within fixation condition (see Figure 3). Subsequently, Participant 2 was asked to participate in Experiment 2 to determine whether or not he would be able to obtain similar results with the cube rotating about an axis that may not allow use of similar light cues.

CHAPTER 4

EXPERIMENT 2

Unlike the results of the "walking man" and rotating stick experiments, detection of change for our stimulus in Experiment 1 proved to be essentially impossible for all but one of the participants when the change occurred during a saccade. In Experiment 2, our purpose was to investigate whether it was some aspect of the nature of the change with respect to the motion of the stimulus in Experiment 1 that hindered change detection, or whether detectability of change in this paradigm, unlike performance on earlier paradigms involving moving stimuli, is close to impossible without the aid of a conscious strategy specifically designed to detect that change.

Experiment 2 tested the effects of (a) the speed of the rotation and (b) the plane of the rotation had on the detectability of change in the rotation of a rendered cube. A concern we had after viewing the results of Experiment 1 was that the speed of the rotation of the cube was too rapid and may have been a major contributor to poor change detection performance. A planar rotation of the cube served two purposes: the first was that it provided a close analog to Pollatsek and Rayner's rotating stick experiments; the second was that it provided us with a means of testing Participant 2's strategy with a rotation that did not provide the same light reflection patterns seen in Experiment 1.

Participants. Eight participants were recruited from the University of Massachusetts community to participate in this experiment. Participant 2 from Experiment 1 was invited to participate in Experiment 2 and is designated as Participant 2 in this Experiment. All participants had normal, or corrected to normal vision, and were offered either payment or given course credit for their participation.

Apparatus. Each participant viewed the stimuli on a 19 inch NEC Trinitron monitor connected to a 2.4 Gigahertz Pentium 4 PC. The refresh rate of the monitor was 160 Hertz. Participants were required to wear a lightweight helmet that is part of the Eyelink II SR eyetracking system. The eyetracking system samples at the rate of 500 Hertz and provides eye movement data both for data analysis, and to the display PC for the purpose of conducting display contingent changes. No head restraint was used since the Eyelink II system is able to compensate for head movements. Eye movement data was collected from the right eye.

Stimuli and Design. Experiment 2 used stimuli that were very similar to those used in Experiment 1. The overall screen resolution was set at 800 by 600 pixels, and the stimulus was presented at the center of that display. The stimulus in each case was a blue rotating cube that was fully rendered and set against a black background. In Experiment 2, the cube rotated about two different axes (see Figure 5), one along the y-axis using the orientation referred to as orientation A in Experiment 1, and one along the z-axis allowing for a rotation in one's visual plane in an orientation allowing the cube to rotate with one of its corners in the center of the display. Both these rotations appeared in two different speed conditions, either at the 'fast' rate of 3 degrees every 12 ms, or at the 'slow' rate of 1.5 degrees every 12 ms.

Figure 5. The y-axis of rotation (left) and the z-axis of rotation (right)

A change in the rotation path of the stimuli in Experiment 2 occurred on half of the trials. The change consisted of a jump in the sequence of rotation of the cube. That is, instead of moving ahead at the same rate of rotation, the cube performed a one-time jump of 48-degrees, and continued its rotation from its new location at the same rate of rotation it had prior to the jump. A control for low-level motion detection was introduced during the 12 ms interval directly preceding the jump in change trials, and at a corresponding period in time on no change trials. Note that although frames were incremented every other refresh period, the control was initiated at the beginning of the first available refresh period.

In Experiment 2, only one control was used since no significant difference was found between the two different types of control used in Experiment 1. To err on the side of caution, the control referred to as control A in Experiment 1 was used exclusively in Experiment 2 since it elicited marginally worse performance on the within fixation condition than did control B. This control consisted of a 135-degree jump ahead in the cube's path of rotation followed by a return to the location the cube would have been at had no jump occurred in the no change condition, or returning to a location 48-degrees ahead of where the cube would have been in the change condition. The purpose of the control, once again, was to eliminate the use of low-level motion detection in determining whether or not a change in the motion of the cube had occurred. In Experiment 2, the change condition consisted of jumps ahead in the cube's rotation. No backward jumps were included because the direction of the jump had no significant effect on the results of Experiment 1.

Due to hardware constraints, our computer system was unable to hold enough frames in memory to display rotations across both the y- and z-axis without reloading. Therefore, in the first 160 trials, some participants saw the cube rotating about the y-axis with both its topmost and bottommost corners lying on that axis in a display similar to that of orientation A in Experiment 1. In the remaining 160 trials, those same participants saw the cube rotate about the z-axis, a rotation in those participants' fields of vision, with one of that cube's corners being closest to the viewer and one furthest away (the later would of course be hidden from view). An equal number of participants saw the z-axis rotations during the first 160 trials, and the y-axis rotations in the remaining 160 trials.

Experiment 2 manipulated the speed of the rotation to investigate its effect on the detectability of change. One possible concern we had with Experiment 1 was that the cube was rotating at a fairly brisk pace. To address the concern that the cube in Experiment 1 was moving too quickly for participants to be able to detect the presence of a change in the within saccade condition, we included speed as a manipulation in Experiment 2. To that end, each axis of rotation appeared in one of two speed conditions, either rotating at the 'fast' rate of 3 degrees every 12 ms, the speed the cube had rotated at in Experiment 1, or at the 'slow' rate of 1.5 degrees every 12 ms. Rotations about the y-axis and about the z-axis each appeared in both the 'slow' and 'fast' speed conditions an equal number of times. All participants saw 'fast' and 'slow' blocks of y-axis and z-axis rotations. Those blocks were counterbalanced across participants.

On half the trials, the change occurred during an induced saccade while on the other half of the trials, the change occurred 100 ms prior to the induced saccade. The saccade was induced in the following manner on each trial. Participants were required to fixate a cross to the left of the rotating cube. After a predetermined period of time and after the cross had been fixated for at least 100 ms, the cross jumped to the right side of the rotating cube. Participants were instructed to make a saccade to the new cross location as soon as possible. Saccade contingent changes were introduced only after the eyetracker had determined that the saccade had indeed begun. At the end of each trial, participants indicated whether or not they were able to detect a change in the stimulus during the trial using a response box.

At the end of each block of the experiment (i.e. after every 80 trials), participants were given a break. Each part was fairly similar to the last in all respects with the exception of either the axis of rotation, the speed of the rotation, or both as was described above. All other variables remained the same.

To summarize, each participant saw the cube in: (a) Two rotation conditions, one about the y-axis, and one about the z-axis, (b) each underwent either a 0 or 48 degree jump, (c) half the trials rotated at a 'slow' rate of 1.5 degrees every 12 ms, while the other half rotated at the 'fast' rate of 3 degrees every 12 ms, (d) each change occurred in either the within fixation condition or the within saccade condition. Each of these types of stimuli was presented twenty times for a total of 320 experimental trials. Every participant saw the trials in four blocks of 80 trials each, one block for each of the four conditions defined by rotation axis and speed. The order in which these blocks were presented was counterbalanced across participants. Each block of 80 contained an equal number of jump trials, and an equal number of within saccade changes. The order in which these appeared within a block was random. A break was introduced after each block to give participants a chance to rest. There were also ten practice trials at the beginning of the experiment in order to familiarize participants with the task, the equipment, and the stimulus. These practice trials were preceded by a demonstration in which participants were shown what the cube would look like, and what change and control conditions would look like.

Results. As was the case in Experiment 1, participants were able to reliably detect the presence of a change in the motion of the cube in the within fixation condition (18.9% false alarm rate, 86.9% hit rate), $F(1, 7) = 104.536$, $p < .001$. However in the within saccade condition, they were only slightly more likely to say that a change had occurred in the no change condition than when a change had indeed occurred (4.7% false alarm rate, 11.7% hit rate), $F < 1$.

The inclusion of a new axis of rotation in this experiment (i.e. rotation about the visual plane) did not seem to significantly affect participants' performance. Participants fared equally well at detecting the presence of a change in the cube's motion whether that change occurred during a rotation about the z-axis or a rotation about the y-axis (see Table 4). However, participants exhibited slightly higher false alarm rates in the within fixation condition when the change occurred during a planar (z-axis) rotation.

Within	Axis	False Alarms	Hits	F(1, 7)	p
Fixation	Y	15.0%	86.6%	3.537	> .1
	Z	22.8%	87.2%		
Saccade	Y	4.7%	14.4%	< 1	> .4
	Z	4.7%	9.1%		

Table 4. Interaction of axis of rotation with ability to detect change in the within fixation and within saccade conditions.

In Experiment 1, we examined the effect that the magnitude of a change in the cube's rotation had on one's ability to detect that change. The inclusion of a 'slow' and a 'fast' condition in Experiment 2 gave us the ability to determine whether the magnitude of the change in a cube's rotation affects the detectability of that change independent of the speed at which the cube is rotating, or whether the magnitude of a change in a cube's rotation must be considered relative to the speed at which that cube was rotating. Slowing down the speed of the rotation of the cube seemed to improve performance overall; however, the effect was reliable only in the within fixation condition (see Table 5).

Within	Speed	False Alarms	Hits	F(1, 7)	p
Fixation	Slow	11.3%	90.6%	6.380	< .05
	Fast	26.6%	83.1%		
Saccade	Slow	2.5%	13.4%	1.459	> .25
	Fast	6.9%	10.0%		

Table 5. Interaction of speed of rotation with ability to detect change in the within fixation and within saccade conditions.

Given Participant 2's performance in Experiment 1, we decided to look at his performance more closely in Experiment 2. As can be seen in Figure 6, although we have reported earlier that participants were unable to reliably detect the presence of a change in a cube's rotation in the within saccade condition, a weak trend was apparent. Participant 2 (see Figure 7) was able to detect the presence of a change in the cube's rotation reliably in both the within fixation condition, $F(1, 152) = 81.022$, $p < .001$, and the within saccade condition, $F(1, 152) = 98.402$, $p < .001$. When Participant 2 was removed from our analysis (see Figure 8), the small trend in the within saccade condition disappeared completely, $F = 0$.

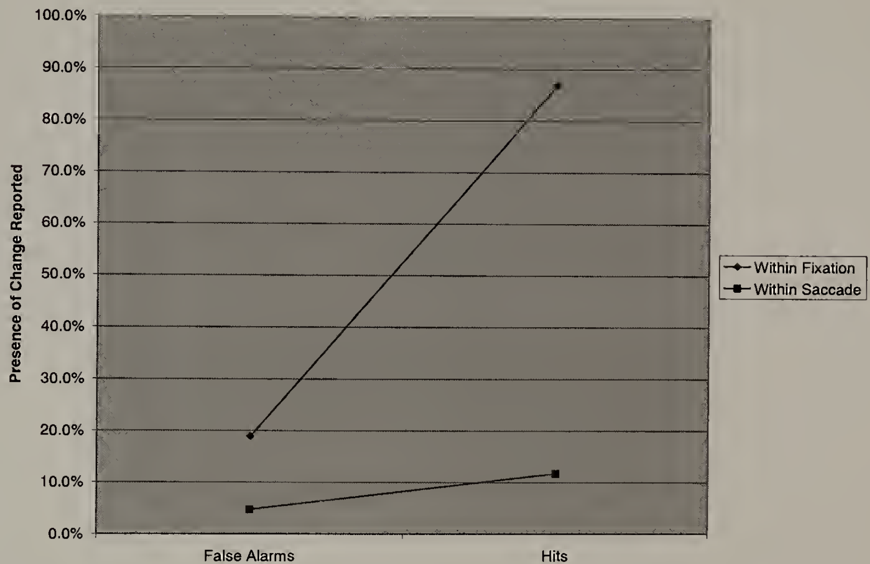

Figure 6. Change detection in the within fixation and within saccade conditions.

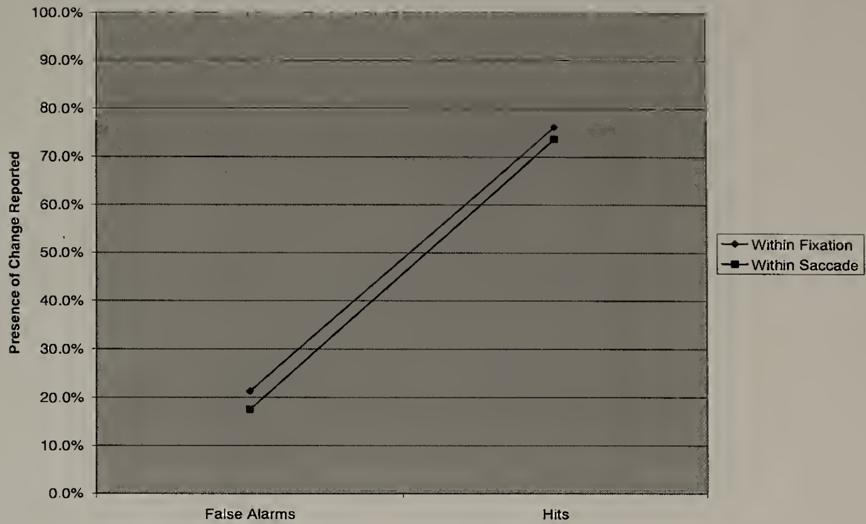

Figure 7. Change detection in the within fixation and within saccade conditions for Participant 2.

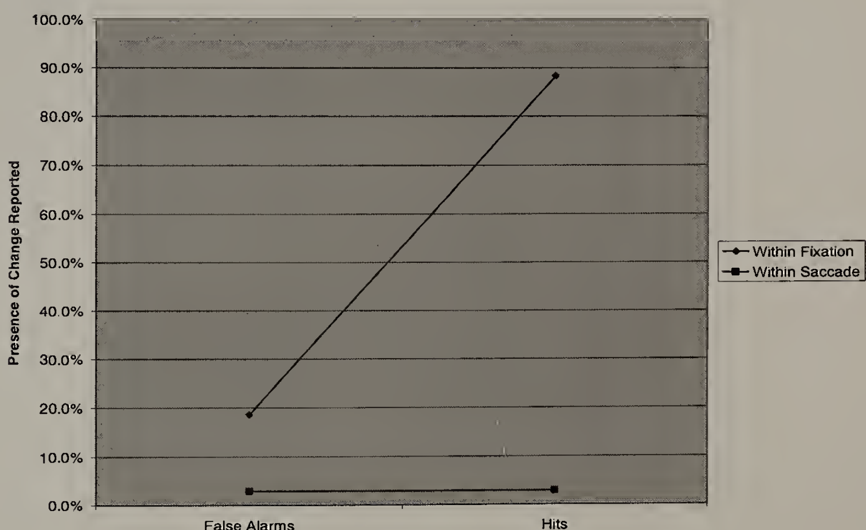

Figure 8. Change detection in the within fixation and within saccade conditions excluding Participant 2.

The fact that Participant 2 was able to perform well in Experiment 2 was not surprising. Of greater interest was whether or not he was able to perform equally well across the different speed and axis conditions. Figures 9-12 show that he was able to detect the presence of a change in the cube's rotation in most conditions, and that he was able to do so as well (and possibly better) when that change occurred across a saccade rather than during a fixation. Participant 2 however had a difficult time with the 'fast' planar (along the z-axis) rotation condition illustrated in Figure 12. In fact, he was unable to reliably detect the presence of a change in the within saccade condition, $F < 1$, $p > .5$, nor the within fixation condition, $F < 1$, $p > .3$.

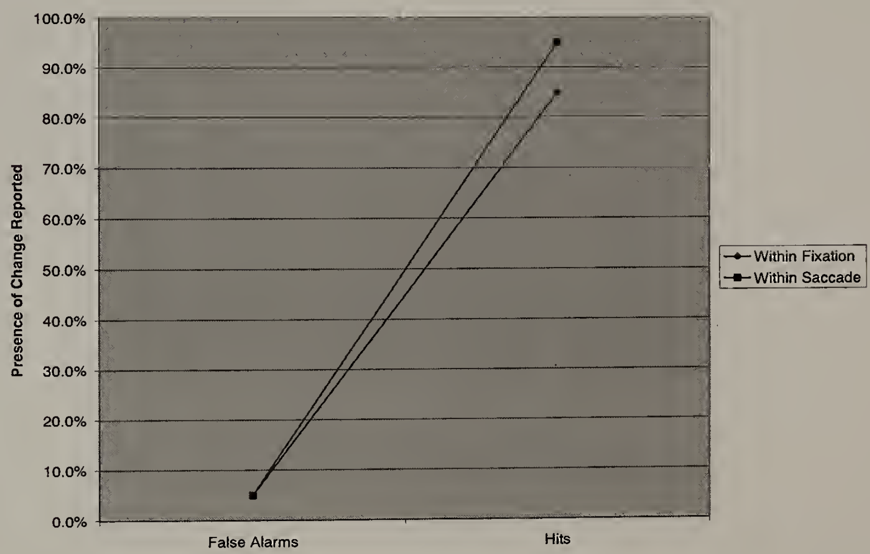

Figure 9. Participant 2's ability to detect change in 'slow' y-axis rotations both in the within fixation and within saccade conditions.

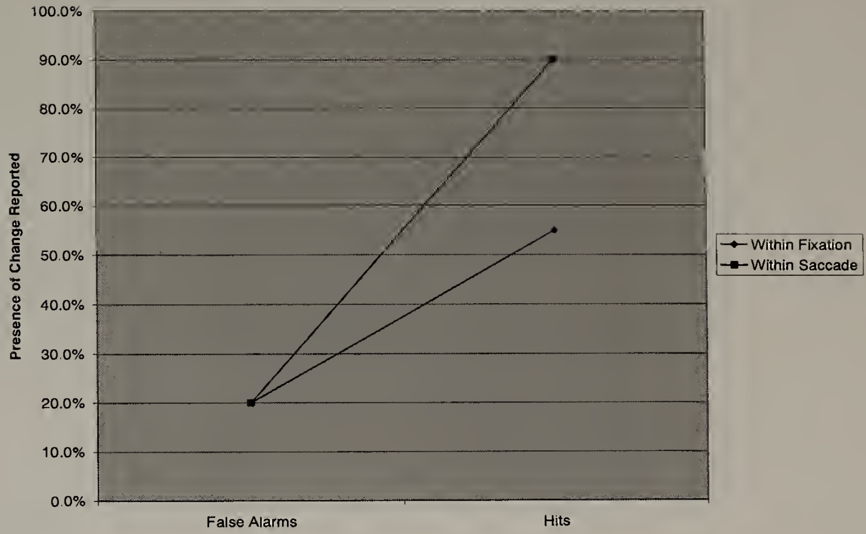

Figure 10. Participant 2's ability to detect change in 'fast' y-axis rotations both in the within fixation and within saccade conditions.

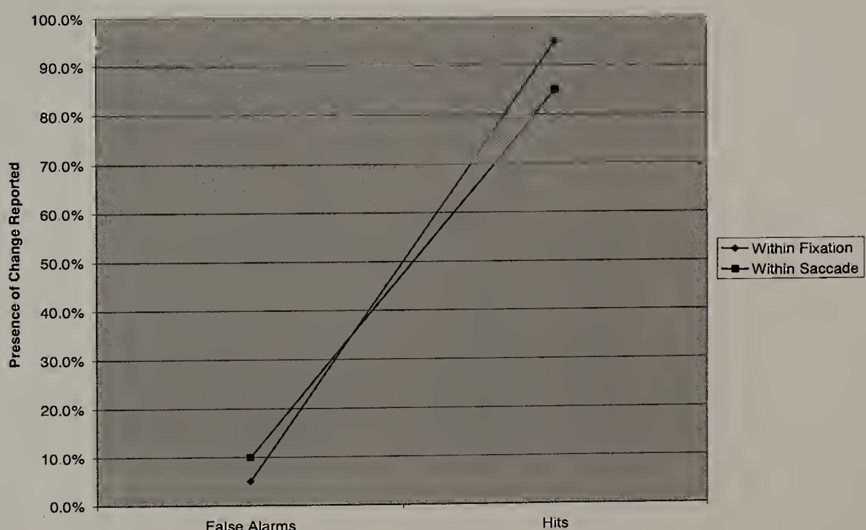

Figure 11. Participant 2's ability to detect change in 'slow' z-axis rotations both in the within fixation and within saccade conditions.

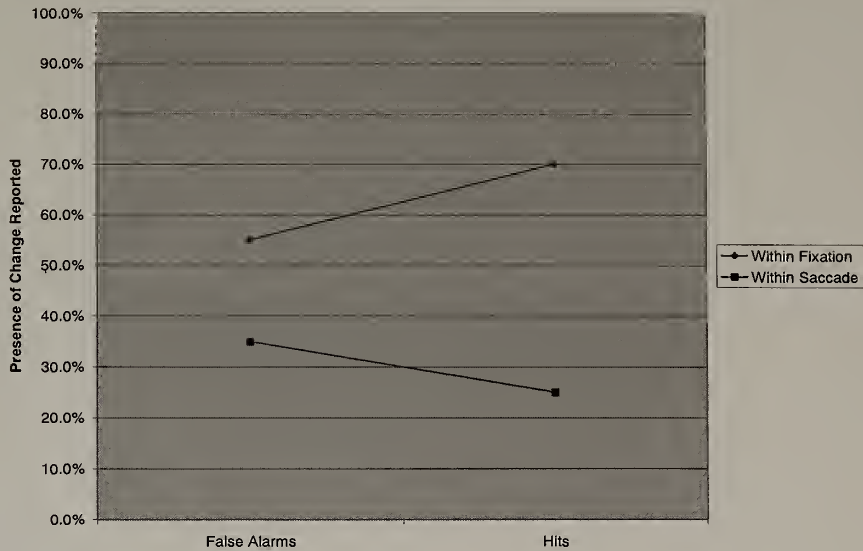

Figure 12. Participant 2's ability to detect change in 'fast' z-axis rotations both in the within fixation and within saccade conditions.

In a follow-up interview, Participant 2 reported the use of the same strategy he reported using in Experiment 1 for both of the y-axis rotation conditions. He however attempted the use of a different yet analogous strategy in the z-axis conditions. The strategy consisted of the establishment of a reference point along the cube's perimeter of rotation. As each corner of the cube crossed that reference point he was able to establish a beat and maintain that beat as a mental "rhythm". He then compared this mental "rhythm" with the beat exhibited by the cube's rotation following the saccade to determine whether or not a change had occurred. Participant 2 reported more difficulty with this strategy than the strategy employed with the y-axis rotations, and found it very difficult to apply to the ‘fast’ planar rotation condition, the condition he performed poorly in.

CHAPTER 5

GENERAL DISCUSSION

In the introduction, I had identified two major questions driving research in change blindness paradigms involving moving stimuli: (a) Do people encode dynamic stimuli in a manner different from that of static stimuli? (b) If not, what is it about a dynamic stimulus that makes it more memorable than a static stimulus? Before these questions could be addressed, we needed to confirm that participants could reliably detect a change in our dynamic stimulus. As was reported in the result sections of both Experiment 1 and Experiment 2, most participants were unable to reliably detect the presence of an intrasaccadic change.

This finding was puzzling given the results of Verfaillie's et al's "walking man" experiments and Pollatsek and Rayner's rotating line experiments. Both these paradigms were able to report that participants could detect the occurrence of an intrasaccadic change for types of motion that are analogous to the change in motion of the cube in our experiments. Setting aside for the moment the potential control improvements that might exist in our experiments as a result of faster hardware, let us take a close look at the three different paradigms and identify the distinctions.

The first difference one sees between the three paradigms is that the rotating cube paradigm provides a richer wealth of visual information. Both the "walking man" and the rotating line paradigms have stimuli that are monochromatic and simple. The cube has color, depth cues, texture and light rendering. Participant 2 in both our Experiments was able to detect the presence of a change reliably in most conditions. He was able to do so by employing a strategy that required a point of focus or a cue. Given their simplicity, both the rotating line (the moving end of the line) and the "walking man" (any of the dots) paradigms provide ready points of focus that may elicit a greater number of participants to use conscious strategies to help in the detection of change.

If this assumption is correct, then one would expect that some participants in the "walking man" and rotating line experiments could employ such a strategy and hence be able to achieve a high level of intrasaccadic change detection, while others would not employee any strategy and may not exhibit an ability to detect the presence of a change across saccades at all. This would produce a data set that would show a high ability to detect the presence of a change within a fixation in the overall data, and a lower yet potentially significant level of change detection across saccades. This overall pattern of data is true of the results of experiments using both the "walking man" and rotating line paradigms.

There are potentially two ways of testing this theory. The first would involve running an experiment using either the "walking man" or rotating line paradigms, and analyzing the data of each participant individually. We would expect to see some individuals perform very well at detecting intrasaccadic change, while we would expect others to perform poorly. The second, and more powerful test, would involve a modification of the rotating line paradigm that would involve the use of two rotating lines rather than one. Participants would presumably have a difficult time focusing on both lines simultaneously and would therefore have to either concentrate on apply a strategy to one of the two lines or abandon the use of conscious strategies altogether. One would probably want the two lines to rotate at different speeds to control for any strategy involving synchrony between the two lines.

The possible use of conscious strategies is one possible explanation for the difference in performance between participants in experiments using the rotating cube paradigm, and those utilizing the "walking man" and rotating line paradigms. Verfaillie et al have posited that one potential explanation for the high level of performance exhibited by participants in their experiments is that humans are sensitive to biological motion. To test this theory, it would be interesting to run participants in an experiment that used either computer generated human figures or video footage of humans or animals in motion. Such a stimulus would probably not provide as easy a focus for the use of a conscious strategy. Strong performance by participants on such a task would reveal a possible privileged position for biological motion in human perception.

Of all the stimuli used in our experiments, stimuli using a planar (z-axis) rotation provided the closest comparison the cube paradigm has to the rotating line paradigm. At its simplest, the planar rotation of the cube can be likened to a rotation involving three equidistant lines rotating about the same point. If participants performed as poorly in a three line paradigm as they did in the cube paradigm, and if participants showed an ability to detect intrasaccadic changes in the original rotating line paradigm even when analyzed individually, then one could speculate that participants may be maintaining some error tolerant expectation of the post saccadic visual input. Such a system may be able to detect change in the rotation of a single line but may confuse the position of any one of the lines in a three line stimulus with another.

Although further research is needed to determine whether the detection of change in a moving stimulus across a saccade is possible without the aid of a conscious strategy, our research shows that the assumption that that is true for all moving stimuli is false.

Research at this point must examine whether or not good performance in the "walking man" and rotating line paradigms is due to the use of conscious strategies. If we can establish an ability to detect an intrasaccadic change in at least some types of moving stimuli without the aid of any conscious strategies, then we can proceed to determine what unique aspects of those stimuli are preserved across saccades.

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