Research Report

THE ROLE OF FIXATION POSITION IN DETECTING SCENE CHANGES ACROSS SACCADES

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Abstract—*Target objects presented within color images of naturalistic scenes were deleted or rotated during a saccade to or from the target object or to a control region of the scene. Despite instructions to memorize the details of the scenes and to monitor for object changes, viewers frequently failed to notice the changes. However, the failure to detect change was mediated by three other important factors: First, accuracy generally increased as the distance between the changing region and the fixation immediately before or after the change decreased. Second, changes were sometimes initially missed, but subsequently noticed when the changed region was later refixated. Third, when an object disappeared from a scene, detection of that disappearance was greatly improved when the deletion occurred during the saccade toward that object. These results suggest that fixation position and saccade direction play an important role in determining whether changes will be detected. It appears that more information can be retained across views than has been suggested by previous studies.*

Subjective experience leads viewers to believe that their visual system delivers a complete and veridical representation of the scene before them—a representation akin to a relatively detailed color photograph. This phenomenology forms the basis for the majority of theoretical work in both human and machine vision. A constraint on human perception, though, is that high-acuity vision is restricted to a small foveal region surrounding the current fixation point, with acuity dropping off precipitously from that focal point (Riggs, 1965). The visual system handles this constraint by rapidly reorienting the eyes an average of three times each second via saccadic eye movements (Buswell, 1935; Henderson & Hollingworth, 1999; Rayner, 1998; Yarbus, 1967). Construction of a complete visual representation would therefore seem to require the storage of a high-resolution image across saccades, with images from consecutive fixations overlapped or spatially aligned to form the composite image (Breitmeyer, Kropfl, & Julesz, 1982; Davidson, Fox, & Dick, 1973; Duhamel, Colby, & Goldberg, 1992; Jonides, Irwin, & Yantis, 1982; McConkie & Rayner, 1976). According to this hypothesis, changes to the viewed scene from one fixation to the next should be highly detectable. Recent studies show, however, that human observers often fail to notice seemingly salient changes when the changes occur during a saccade (Grimes, 1996; Henderson, 1997; McConkie, 1990; McConkie & Currie, 1996). Similar *change blindness* is found when a change occurs to a scene during a brief blanking period (Rensink, O'Regan, & Clark, 1997) or a film cut (Levin & Simons, 1997), or even across the interposition of an opaque object in the real world (Simons & Levin, 1998).

The phenomenon of change blindness is strikingly counterintuitive and theoretically important, first because it undermines the traditional view that the visual system constructs a complete representation of the external world, and second because it calls into question the assumption that conscious perceptual experience directly reflects the underlying visual representation. Instead, it appears that humans perceive a complete and detailed world despite the fact that the underlying visual representation is abstract and incomplete (Dennett, 1991).

The conditions under which change blindness can be observed are not clear, however. Specifically, previous studies provided no direct evidence that participants were fixating, or had ever fixated, the changing region before or during the change. For example, in the saccade-contingent scene-change studies that have been reported (Grimes, 1996; McConkie, 1990; McConkie & Currie, 1996), the image change was generated during the *n*th ordinal saccade, where *n* was predefined prior to the experiment. Thus, the position of the fixation before or following the *n*th saccade was not used to constrain *n*. Acuity functions provide evidence that changes might have been missed simply because the changed region appeared only in the visual periphery. Similarly, eye movements typically have not been monitored in paradigms that have shown poor change detection across other sorts of blank periods (but see Hollingworth & Henderson, 1998, for an exception). Studies that have monitored eye movements during free scene viewing have shown that scene detail is preferentially encoded at fixation (Henderson, Weeks, & Hollingworth, 1999; Nelson & Loftus, 1980; Parker, 1978).

In the present study, we introduced a new methodology (object changes contingent on a saccade to or from a predefined critical scene region) to investigate the sensitivity of the visual system to scene changes when fixation position relative to the changing region is precisely controlled. In our paradigm, computer-rendered color images of naturalistic scenes were changed contingent on a saccade toward or away from a prespecified target object (see Fig. 1). In the *toward* condition, the change took place during the first saccade that brought the eyes to the target object; in the *away* condition, the change took place during the saccade that took the eyes away from the target object immediately after it had been fixated the first time. We also included a control condition in which the target object changed during the first saccade to a nontarget object that was present elsewhere in the scene. To investigate the nature of the information that is encoded and retained across a saccade, two types of object changes were compared. In the *rotation* condition, the target object instantaneously rotated 90º around its vertical axis during the saccade. In the *deletion* condition, the target object instantaneously disappeared from the scene during the saccade. Finally, no-change catch trials were included to provide an assessment of the false alarm rate in the experiment. Participants were instructed to view each of 35 scenes in preparation for a later memory test, and to press a response button if and when they noticed a change to any of the objects in the currently viewed scene.

If change detection is independent of fixation position, as has been assumed implicitly in the change-blindness literature, then detection rates would be equivalent in the three saccade conditions (toward, away, and control). If instead, as previous eye movement studies suggest, information is preferentially encoded from fixated objects in a

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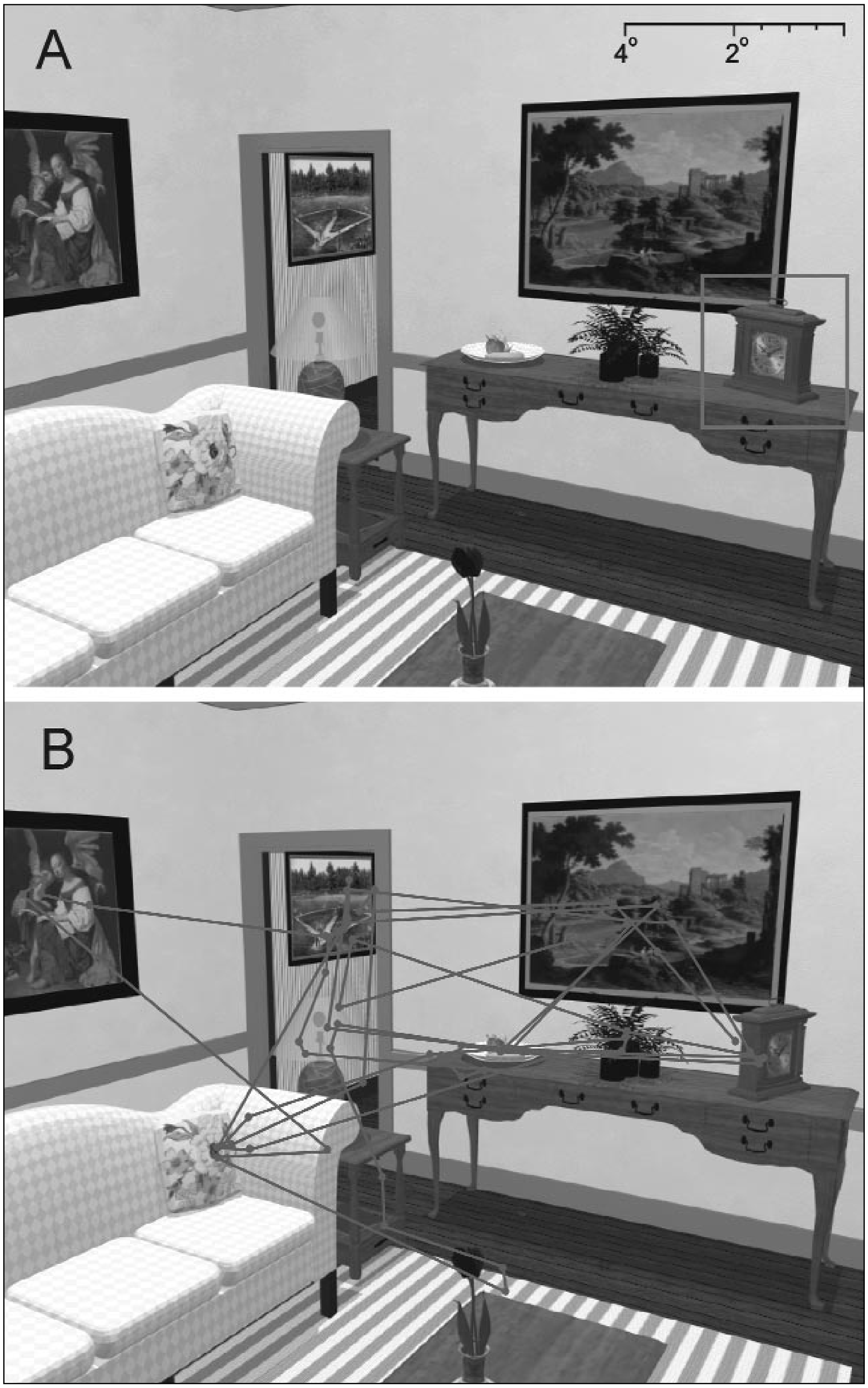

Fig. 1. Sample scene before (a) and after (b) the object change in a rotation trial. In (a), the boundary region defined around the target object is marked in blue. A change was made to the scene either during the first saccade entering this region (toward condition) or the first saccade exiting this region (away condition). The picture in (b) shows the scan pattern of 1 viewer in the toward condition. Dots represent fixations and lines connecting dots represent saccades. Eye movements before the change are marked in light green and after the change are marked in red. This participant did not detect the change.

scene, then detection would be better when the eyes fixated an object prior to its change (away condition) than when they did not (toward and control conditions). This hypothesis also predicted a detection gradient, with detection rate declining as a function of the distance of the nearest fixation to the changed object. Finally, according to the saccade-target theory of visual stability (Irwin, McConkie, Carlson-Radvansky, & Currie, 1994; McConkie & Currie, 1996), an object that is about to be fixated is preferentially encoded, retained, and compared across a saccade. Thus, this theory predicted that participants would be particularly sensitive to scene changes in the toward condition.

METHOD

Eye movements were monitored with a Generation 5.5 Fourward Technologies dual Purkinje-image eyetracker (1000-Hz sampling rate, 1' arc accuracy) while 21 naive participants examined 35 images of scenes of common environments for 20 s each. Images were computer rendered (800 × 600 pixels × 256 colors) from three-dimensional wire-frame models and subtended 15.8º × 11.9º of visual angle at a viewing distance of 1.13 m. Target objects subtended 2.43º on average along the longest axis.[1] Critical regions for triggering changes were 0.36º larger on each side than the smallest rectangle enclosing the target object. Changes were triggered when the eyes crossed the boundary of the critical region. The vertical refresh rate was 143.3 Hz; the change could be started beginning at any point in the vertical refresh cycle, so complete region changes were effected in a maximum of 6.96 ms.[2]

Participants were instructed to view the scenes to prepare for a later memory test. The test was described as one in which a small detail of a single object might be different. Participants were also instructed to monitor for object changes during initial viewing. They were told to press a response button as soon as such a change was detected. Possible changes were described using a sample scene. Each participant saw all 35 scenes, 5 in each of the 6 conditions created by the 3 × 2 factorial combination of eye movement condition (toward, away, control) and change type (deletion, rotation), and 5 in the catch-trial condition. Across participants, each scene appeared in each condition an equal number of times. The order of scene presentation was determined randomly for each participant.

RESULTS AND DISCUSSION

Overall, 11.6% of the trials were eliminated because of track losses. In the toward condition, landing positions of 17.3% of the fixations immediately after the change were just beyond the target object region. Elimination of these latter trials did not change the pattern of results, so they were retained in the analyses reported here.

As in previous studies that have been reported, participants generally failed to notice what would seem to be obvious changes to the scenes they were viewing. It is also clear that change detection was mediated both by the direction of the saccade that generated the change and by the nature of the change itself (see Fig. 2). An analysis of variance conducted on percentage of detections confirmed the main trends shown in Figure 2: There were reliable effects of eye movement condition, $F(2, 40) = 147$, $p < .001$, and change type, $F(1, 40) = 26.8$, $p < .001$; in addition, there was a reliable interaction between these factors, $F(2, 40) = 8.99$, $p < .001$.

Failure to detect changes was most apparent in the rotation condition. When an object rotated by 90º during the saccade toward that object (rotation-toward), viewers failed to notice the change on 76% of the trials. Similarly, when an object rotated immediately after it had been fixated (rotation-away), the change was missed on 71% of the

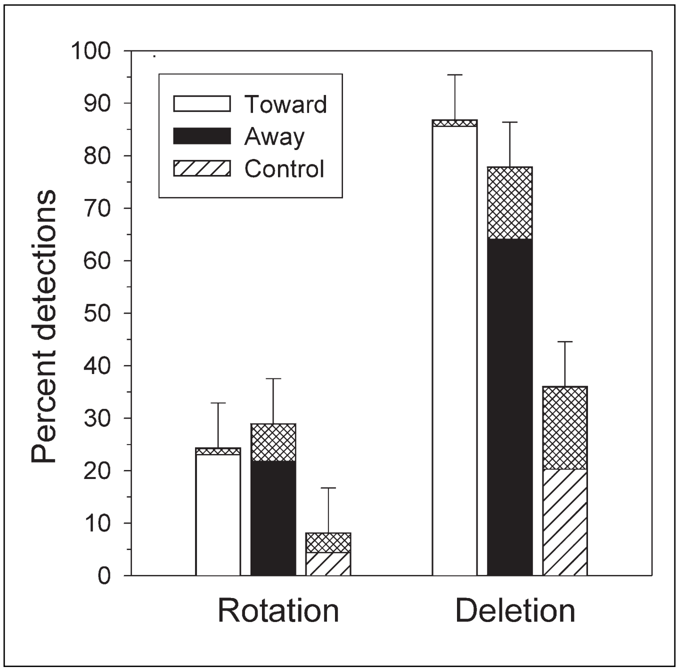

Fig. 2. Percentage of detections as a function of change type (rotation, deletion) and fixation position (toward, away, or control). The complete bars show all detections for each condition; the lower section of each bar represents immediate detections (≤1,500 ms after change), and the upper crosshatched sections represent delayed detections (>1,500 ms after change). Error bars are 95% confidence intervals for all detections based on the error term from the change-type-by-fixation-position interaction.

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[1] A control experiment demonstrated that the object changes were salient and detectable when they occurred within a fixation: All changes were presented to 2 participants while they fixated the center of the control region of each scene (an average of 10° from the target object). The changes occurred over two immediately successive presentations of each scene. One participant detected 34 and the other 35 of the 35 changes presented; neither participant made any false alarms in five trials in which no change occurred. Thus, the changes were salient enough to detect within a fixation.

[2] Phosphor persistence is a potential confound in saccade-contingent change experiments. However, such persistence is much less a problem when changes are made to full-color scenes because pixels are not simply turned off when a change occurs; instead, some pixels are brightened, some are dimmed, and some simply change color. Using a shutter test and a P22 phosphor like that used here, McConkie and Currie (1996) showed that effects of phosphor persistence were eliminated 12 ms after a change had taken place in a scene (earlier points in time were not tested). We conducted a similar shutter test using our images and viewing conditions. In this test, 2 naive viewers were presented with 105 trials in which the entire scene changed (i.e., the image changed from one scene to another) and 35 no-change catch trials. The shutter opened with a delay of 0, 7, or 12 ms following an image change. Accuracy feedback was presented after each trial. Change detection for all delays and for both participants was at chance. Thus, phosphor persistence cannot account for the present pattern of data.

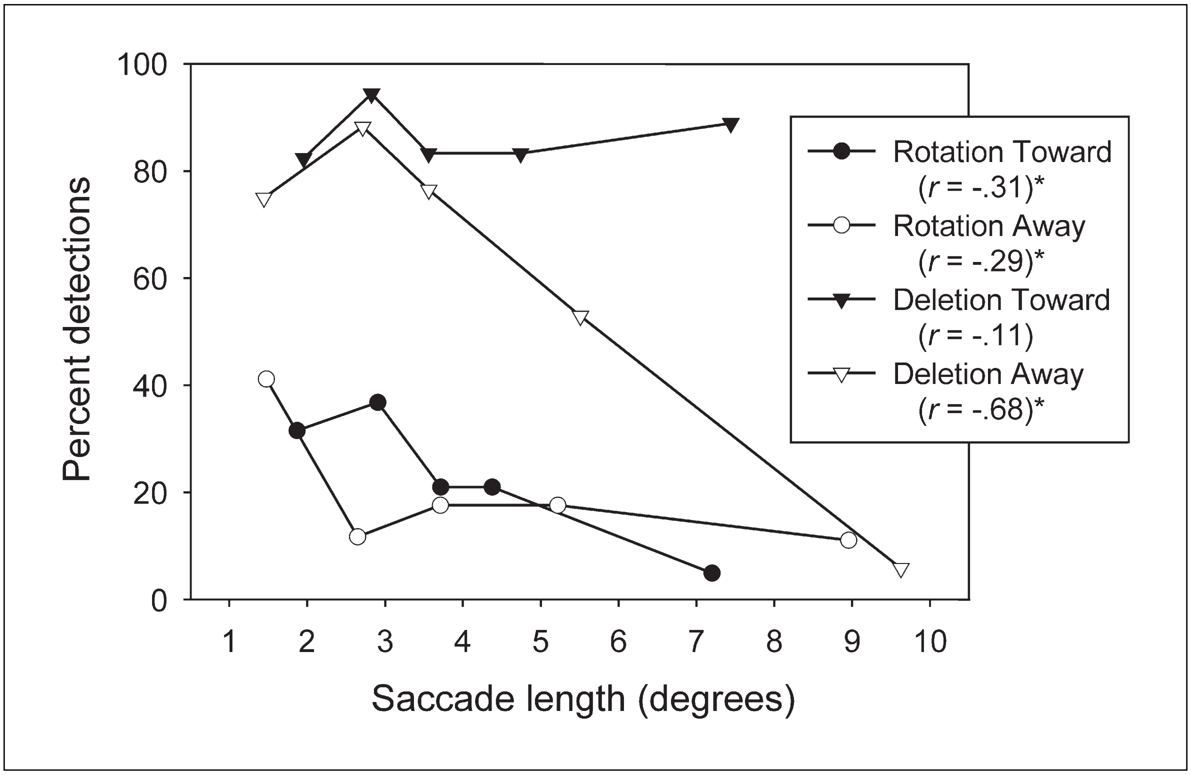

Fig. 3. Percentage of detections as a function of saccade length. For each condition, the mean of each saccade length quintile is plotted against the mean percentage of detections in that quintile. Point-biserial correlation coefficients that produced a reliable ($p < .05$) difference from a slope of zero are marked with an asterisk.

trials. Performance was even worse when the rotation occurred during a saccade to a nonchanging region of the scene. Participants missed the rotation on 92% of the trials in the rotation-control condition, leading to a detection rate that did not differ reliably from the 2.9% false alarm rate, $F(1, 20) = 1.62$, $p > .2$. Thus, although fixating an object immediately before or after it rotated did not invariably lead to detection of the rotation, it did increase detection performance.

The detection rate in the toward and away conditions was better for object deletions than for rotations, but still not perfect. Change detection was best when a target object was present immediately prior to a saccade to that object, but had disappeared when the eyes landed at that location (deletion-toward), a result consistent with saccade-target theory. But even in this condition, viewers failed to detect the deletion on 13% of the trials. When an object was present at fixation but missing after a saccade away from the object (deletion-away), the miss rate increased to 22% of the trials ($p < .05$). Thus, simply fixating an object did not guarantee that its disappearance from the scene a few 10s of milliseconds later would be noticed. However, fixating the target did increase the detection rate over that found when the target was fixated neither immediately before nor after the saccade: In the deletion-control condition, viewers missed the deletion on the majority (64%) of the trials.

The analyses reported so far included all change detections. As can be seen in Figure 2, most of the detections occurred relatively quickly after the change (within 1,500 ms; denoted by the lower sections of the bars in the figure). Occasionally, however, viewers failed to detect a change initially, but subsequently noticed the change (crosshatched upper sections of the bars in Fig. 2). These late detections were observed on 7% and 14% of the rotation-away and deletion-away trials, 4% and 14% of the rotation-control and deletion-control trials, and about 1% of the rotation-toward and deletion-toward trials. The vast majority of the late detections occurred when the changed region happened to be refixated later during viewing.[3] These data show that stored information about object orientation and presence was sometimes consulted—but only when focal attention was directed back to the changed region, suggesting that some detection failures were due not to a failure to encode or retain information, but rather to a failure to consult that information until after the changed region had again been overtly attended.

To investigate the influence of visual eccentricity on change detection, we examined the relationship between detection performance and the spatial extent of the saccade that triggered the change in the toward and away conditions (see Fig. 3). The average extent of the saccade triggering the change was 4.2° and did not vary as a function of eye movement condition, $F(2, 40) = 1.5$, $p > .2$. To make the regression on saccade length meaningful, we included only data from trials in which the change was detected immediately following (within 1,500 ms of) the image change. As can be seen in Figure 3, there was a reliable effect of eccentricity on change detection in

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[3] Trials on which detection was neither immediate nor delayed until region refixation were very rare, occurring at most twice across all trials and participants in any condition.

three of the four critical conditions, with detection falling off as eccentricity increased. Still, change detection was poor in the rotation conditions even when the fixation immediately prior to or following target fixation placed the target in near-foveal vision. These data show that acuity limitations alone cannot account for failure to detect changes in the rotation conditions. Apparently, even when the quality of the visual input is very high, object orientation is not inevitably encoded, retained, or compared from fixation to fixation during scene perception.

Figure 3 shows that the length of the saccade affected detection rates when the object was deleted during the saccade away from that object (deletion-away), with a steep drop-off in performance following saccades with amplitudes greater than about 4°. Interestingly, however, when an object was deleted during the saccade toward that object, eccentricity played little role in determining detection accuracy; instead, detection was relatively good for object deletions even when the fixation prior to the change was between 7° and 8° from the next fixation on the (now eliminated) object. The difference in detection rates in the away-deletion versus toward-deletion conditions as a function of eccentricity again suggests that information about the presence or identity of the target of an impending saccade is preferentially encoded (Deubel & Schneider, 1996; Henderson, 1996) and plays a special role in supporting visual stability across saccades (Irwin et al., 1994; McConkie & Currie, 1996).

CONCLUSIONS

Consistent with much prior work in the transsaccadic-integration literature (Irwin, 1992; Pollatsek & Rayner, 1992), as well as more recent change detection studies (see Henderson & Hollingworth, 1999; Simons & Levin, 1997), the present data strongly suggest that the visual system does not create a composite representation by overlaying images from consecutive fixations. If it did so, then scene changes during a saccade should be highly salient. Instead, viewers often failed to notice apparently obvious changes when those changes took place during a saccade. Particularly striking was the poor detection performance when neither the pre- nor the postchange fixation was on the changing object. In this control condition, 90° rotations were detected less than 10% of the time, and even deletions were detected less than 40% of the time, findings in line with those reported by McConkie (1990) and Grimes (1996). In fact, given that viewers were asked to memorize object details in preparation for a difficult memory test and were explicitly instructed to monitor the scenes for changes, performance in this study probably overestimates the sensitivity of the visual system to image changes under more typical viewing conditions. Thus, the poor change detection performance observed here supports the view that there are limitations to the visual information that is encoded, retained, and compared from fixation to fixation.

At the same time, it is clearly too simplistic to suggest that a completely fresh scene representation must be generated anew during each fixation (O'Regan, 1992). First, although change detection was difficult in the present study, it was not impossible, particularly for objects that had just been or were about to be fixated. Thus, fixated scene regions receive preferential encoding and comparison across saccades. Second, changes were sometimes noticed only when the changed region was refixated after the change had taken place. These data suggest that information may sometimes be encoded and retained across saccades, but consulted only when the eyes (and focal attention) are directed back to the changed region. Third, the deletion of an object that was about to be fixated was particularly salient, even when the object was viewed from a relatively distant position prior to the deletion. These data strongly suggest that the presence or identity of the object about to be fixated is preferentially encoded, retained, or compared across a saccade. Taken together, the results of this study highlight the active, selective nature of visual information acquisition and representation during scene viewing.

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