Journal of Experimental Psychology:
Human Perception and Performance
1999, Vol. 25, No. 1, 243–255

0096-1523/99/$3.00

The Influence of Enantiomorphic Transformation on Transsaccadic Object Integration

John M. Henderson and Amy B. C. Siefert
Michigan State University

Two experiments investigated whether the left–right orientation of an object is retained and integrated across a saccade during object identification. In Experiment 1, participants moved their eyes to the target object and named it as quickly as possible. In Experiment 2, participants looked through an array of 4 target objects in preparation for an immediate recognition test. In both experiments, a peripheral preview of the target object was presented before fixation. The preview stimulus was identical to the target object, the enantiomorph of the target object, or a control stimulus. Naming latencies were faster (Experiment 1) and gaze durations were shorter (Experiment 2) when the preview was identical to the target than when it was an enantiomorph of the target, suggesting that left–right orientation was retained and integrated across saccades. The results constrain models of transsaccadic integration and object identification.

Although high-acuity vision is restricted to the fovea (Riggs, 1965), useful information about a visual stimulus can be acquired from beyond the fovea, retained across a saccade, and subsequently integrated with foveal information following fixation on that stimulus (Henderson, 1992a; 1994; Henderson & Anes, 1994; Henderson, Pollatsek, & Rayner, 1987; Irwin, 1991, 1992, 1996; Pollatsek & Rayner, 1992; Pollatsek, Rayner, & Collins, 1984; Pollatsek, Rayner, & Henderson, 1990; Rayner, 1975; Rayner, McConkie, & Ehrlich, 1978). One straightforward way to explain transsaccadic information integration is to suppose that a veridical sensory image of the presaccade stimulus is retained across the saccade and is then fused with the image derived from the stimulus once it is fixated (e.g., Brietmeyer, 1984; Davidson, Fox, & Dick, 1973; Feldman, 1985; Jonides, Irwin, & Yantis, 1982; McConkie & Rayner, 1976). In this type of sensory fusion system, the perceptual image formed during the two consecutive fixations could be aligned by tracking the extent of the saccade, by comparing the similarity of the images themselves, or both.

Despite the intuitive appeal and relative parsimony of the sensory fusion hypothesis, there is a large body of evidence that argues against it (for reviews, see Irwin, 1992, 1996; O'Regan, 1992; Pollatsek & Rayner, 1992). For example, when two dot patterns forming a matrix of dots are presented in rapid succession at the same spatial position within a fixation, a single fused pattern is perceived and performance (e.g., identification of a missing dot from the matrix) can be based on this percept (Di Lollo, 1977; Eriksen & Collins, 1967; Irwin, 1991; Irwin, Brown, & Sun, 1988). However, when the two patterns are viewed in rapid succession at the same spatial position across a saccade, no such fused percept is experienced and performance is dramatically reduced (Bridgeman & Mayer, 1983; Irwin, 1991; Irwin, Yantis, & Jonides, 1983; Rayner & Pollatsek, 1983; see also O'Regan & Levy-Shoen, 1983). This evidence derives from studies that have explored transsaccadic integration using either meaningless visual patterns or text as stimuli. Given that meaningful real-world objects may be processed by neural systems that are specifically dedicated to object analysis, it is possible that there are processes available to support transsaccadic object identification that would not be active during the processing of meaningless patterns or text. If this were true, perhaps transsaccadic integration during object identification might be supported by perceptually veridical representations. In the first study to examine transsaccadic object identification, Pollatsek et al. (1984) used a transsaccadic object naming paradigm. Participants were asked to move their eyes to a preview stimulus that was presented 5° or 10° to the left or right of fixation. During the saccade, the initial preview stimulus was replaced with a line drawing of a real-world target object that the participant was to name as rapidly as possible. The display change itself was not visible because it took place during the saccade when little useful pattern information is acquired (Matin, 1974; Volkmann, 1986). In one condition, the preview stimulus was identical to the target object; in a control condition, it was an empty box. Naming latencies were markedly reduced when the preview and target were identical compared with the control condition. This *preview benefit* (i.e., facilitation in identification latency given a useful preview) suggests that information about an object can be acquired, retained, and integrated across a saccade.

Contrary to the hypothesis that preview benefits for objects are based on sensory fusion, however, several studies suggest that real-world object integration across saccades

---

John M. Henderson and Amy B. C. Siefert, Department of Psychology, Michigan State University.

This research was supported by a grant from the National Science Foundation (SBR 9617274). We would like to thank Fernanda Ferreira, Andrew Hollingworth, and Karl Verfaillie for their insightful comments on a draft of this article.

Correspondence concerning this article should be addressed to John M. Henderson, Department of Psychology, Michigan State University, East Lansing, Michigan 48824-1117. Electronic mail may be sent to john@eyelab.msu.edu.

does not make use of veridical sensory representations. First, the transsaccadic preview benefit for an object is unaffected by a 10% change in the size of the object across the saccade (Henderson et al., 1987; Pollatsek et al., 1984, 1990). If pre- and postsaccade images were being integrated, there should be some cost associated with the size mismatch between them. Second, in a more direct attempt to determine whether contour information might be retained and integrated, Henderson (1997) presented as preview and target two complementary sets of contours of the same object. The change in contour neither increased the preview benefit, as might be expected if a composite image could be generated across the saccade, nor decreased the preview benefit, as might be expected if contour similarity is used to align the pre- and postsaccade images. Furthermore, participants found it difficult to determine whether the contour had changed during a saccade, suggesting that a veridical representation of the contour was not preserved.

One possible interpretation of the results of the transsaccadic integration research is that only abstract object information (e.g., the object's concept, identity, or name) can be retained and integrated across a saccade during object identification. However, three additional results have been taken to suggest that although transsaccadic object integration is based on representations that are less specific than a veridical sensory image, it may use representations that are more visually specific than concepts, identities, or names. First, using the transsaccadic object naming paradigm, Pollatsek et al. (1984) presented an extrafoveal preview that was either identical to the target object, a different pictorial exemplar of the same category as the target, or a control square. Although the different-exemplar condition produced considerable preview benefit, the preview benefit was larger in the identical-exemplar condition than in the different-exemplar condition. Pollatsek et al. (1984) interpreted this result as evidence that transsaccadic integration is based on specific visual properties (e.g., a representation of the general shape of the object) in addition to abstract object identities. However, because the different exemplars may also have represented different subordinate-level concepts (e.g., cat vs. kitten), it is possible that the reduction in preview benefit in the different-exemplar condition compared with the identical-exemplar condition was attributable to a reduction in the activation of conceptual information in an identity system that codes subordinate-level information. In this interpretation, the data would be consistent with the hypothesis that no information about visual properties was retained and integrated.

Pollatsek et al. (1984) also compared form-consistent preview and target pairs (e.g., tomato–ball) with form-inconsistent pairs (e.g., bat–ball). Naming latencies were faster for the visually similar than dissimilar pairs. Pollatsek et al. interpreted this result as further evidence that some visually specific shape information may be preserved across a saccade. However, naming latencies in the visually similar condition were not reliably faster than latencies in the control condition (an empty square). Thus, this visual similarity effect did not appear to contribute to the preview benefit and so may not reflect the nature of the representation that supports transsaccadic object integration.

In a third experiment, Pollatsek et al. (1984) compared the preview benefits for objects when they appeared in the same orientation with a condition in which the left–right orientation of the object changed across the saccade. This manipulation is important because the enantiomorphic transformation changed the displayed image without changing the semantic concept, identity, or name associated with that image. Pollatsek et al. (1984) found that there was a tendency for the preview benefit to be larger when left–right orientation remained constant than when it changed across the saccade, although this trend was only statistically marginal. A clear demonstration of additional benefit from an identical over an enatiomorphic preview would provide strong evidence that an object attribute more specific than the concept, identity, or name can be retained and integrated across saccades.

Enantiomorphy and Object Recognition

In addition to providing a manipulation for investigating the nature of the representations that are functional during transsaccadic object integration, enantiomorphy is also of interest for theories of object recognition. Because we live in a 3-D world, we see objects from multiple viewpoints. A controversial issue in the study of object perception is the degree to which object recognition is based on viewpoint-dependent representations. There are currently two theoretical perspectives on this question. One class of theory posits that object recognition is viewpoint invariant. For example, the geon structural description theory proposed by Biederman (1987; Biederman & Gerhardstein, 1993, 1995) assumes that objects are represented as collections of volumetric primitives and their spatial relationships. This theory predicts that as long as the same geon structural description can be generated across views, an object should be equally recognizable from those views. In contrast, viewpoint-dependent theories assume that the representations that support object recognition include information about the view from which the object has been seen. These theories predict that objects should be more easily identified from previously seen views (Bülthoff & Edelman, 1992; Hayward & Tarr, 1997; Lawson & Humphreys, 1996; Tarr, 1995).

The long-term priming paradigm is often used to explore the role of viewpoint dependency in object recognition. In this paradigm, each member of a set of objects is presented for a brief duration. After a relatively long delay, a second set of objects is presented in a speeded recognition (e.g., naming) task. Some members of the second set are members of the first set seen from the same viewpoint, some are viewpoint-transformed versions of the members of the first set, and some are new objects. Identification latency and accuracy are typically found to be facilitated for objects that have been seen before, compared with objects that are new. The main question of interest is the magnitude of this priming effect for transformed objects. According to viewpoint-invariant theories, one view of an object should prime another view of that same object as well as it primes the identical view. Viewpoint-dependent theories, in contrast, predict that priming should not be as large for transformed views as for identical views.

When the priming paradigm is applied to enantiomorphs, the results have been mixed. Biederman and Cooper (1991) found complete invariance for both reflections and spatial translations in a priming task using line drawings of real-world objects, even though participants produced above-chance performance in an explicit test of their memory for object position and left–right orientation. Using a variation of the priming paradigm, Srinivas (1996) also found that enantiomorphic primes produced performance equivalent to identical primes on a fragment completion task with line drawings of real-world objects, again suggesting that left–right orientation is not supported by the object representation system. In a third study, Cooper, Schacter, Ballesteros, and Moore (1992) had participants study line drawings of unfamiliar possible and impossible 3-D objects. Following study, the participants were presented with brief displays of studied and nonstudied objects and judged whether the objects were structurally possible or impossible as 3-D entities. Although there was no priming for impossible objects, object decision accuracy for possible objects was primed both when the prime and target were identical and when the target was an enantiomorph of the prime. Importantly, the priming effect tended to be larger when the prime and target were identical to each other (.18 effect) than when they were enantiomorphic transformations of each other (.10 effect). Although no statistics were reported on this priming effect contrast (the reported contrast collapsed over the structurally possible and impossible objects), a post hoc comparison based on the reported mean square error from the interaction of item repetition (studied or nonstudied), object structure (possible or impossible), and transformation (identical or enantiomorph) suggests that it may have been reliable. Finally, Lawson and Humphreys (1996) used a picture matching task to investigate viewpoint specificity. Participants decided whether two sequentially presented views represented the same object. That study differed from the long-term priming studies in that the interstimulus interval (ISI) between the initial view of an object and the subsequent test view was short and no other objects intervened during that time. With an ISI of 585 ms, participants were faster to decide that two drawings represented the same object when they were identical than when they were enantiomorphs. In summary, several studies have reported complete viewpoint invariance for enantiomorphs in an object priming paradigm (e.g., Biederman & Cooper, 1991; Srinivas, 1996), whereas at least one study found an effect of enantiomorphic transformation on object priming (Lawson & Humphreys, 1996) and another found a trend in that direction (Cooper et al., 1992).

Experimental Overview

In Experiment 1, we investigated the influence of an enantiomorphic transformation on transsaccadic integration using an object naming paradigm. In Experiment 2, we used a silent object identification task: Participants viewed arrays of four objects while their eye movements were recorded, and preview benefits were computed from eye movement behavior. In both experiments, the influence of an enantiomorphic transformation on transsaccadic integration was explored by changing the presaccade preview to the postsaccade target stimulus during a saccade to that stimulus.

Experiment 1

Participants began each trial fixated on a fixation marker. A preview stimulus was then presented at an extrafoveal position either 10° or 20° to the left or the right of fixation. The participant executed a saccadic eye movement to the preview stimulus as quickly as possible once it appeared. During the saccade, the display was changed so that a target object occupied the former position of the preview stimulus. The display change was completed during the saccade so that the transient offset of the preview and onset of the target was not perceptually salient. The participant named the target object as quickly as possible once the saccade was completed. Naming latency was taken to reflect identification latency.

Four preview conditions were used to explore the nature of the representations that support transsaccadic integration. In the *identical condition,* the preview was physically identical to the target. In the *enantiomorph condition,* the preview stimulus was an enantiomorphic transformation of the target. Comparison of performance in these two conditions is of central theoretical concern. To the extent that the left–right orientation of an object is retained and integrated across a saccade, the preview benefit should be larger in the identical condition than in the enantiomorph condition. On the other hand, if only abstract information is preserved across saccades, the preview benefits in the identical and enantiomorph conditions should be equivalent.

To assess overall preview benefits, we included two control conditions. In the *simple control condition,* the preview stimulus was a meaningless saccade target (i.e., a square with a smaller square and plus sign at its center). In the *different-object control condition,* the preview stimulus for a given target object was the preview stimulus for one of the other target objects in the stimulus set. This preview stimulus provided a control condition in which incorrect task-relevant preview information was presented. We included two control conditions because it is not clear which type of control is more appropriate for assessing preview benefits (see also Pollatsek et al., 1984). A task-irrelevant square does not activate task-relevant perceptual, conceptual, or name codes, so preview benefits observed by comparing the identical preview condition with the meaningless control condition are not confounded with interference from inappropriate information activated in the different object control condition. On the other hand, the simple control stimulus is perceptually and cognitively less complex than the preview stimulus used in the identical condition and so may underestimate the preview benefit. By using both controls, we could be more confident that any preview benefits observed in the identical and enantiomorph conditions were attributable to facilitation effects in comparison to both no information (simple control) and misleading information (different object control).

We also manipulated saccade direction (left or right) and saccade amplitude (10° or 20°). No visual field effects have previously been observed in transsaccadic object identification experiments (Henderson et al., 1987; Pollatsek et al., 1984, 1990). The manipulation of saccade direction provided us with another opportunity to look for such effects. We manipulated preview eccentricity to investigate whether less specific information might be retained and integrated given a more distant, and hence more degraded, initial view of the stimulus.

Method

Participants. Twelve members of the Michigan State University participant pool took part in the experiment for course credit. All participants had normal vision or wore contact lenses. The participants had not taken part in previous eye movement experiments and were naive about the hypotheses under investigation.

Stimuli. The stimuli were 16 line drawings of common objects (8 artifactual and 8 natural) taken from Snodgrass and Vanderwart's (1980) set. These objects all had a name agreement score of 90% or greater (M = 97%) in Snodgrass and Vanderwart's norms. The objects were digitized using a Hewlett-Packard Scanjet IIc flatbed scanner, and stray pixels were removed using a commercial graphics program. Objects had to be of good quality following digitization, as judged by the experimenters. The viewing distance was 31.25 cm, and the objects subtended 5.32° on average along the longest axis. Enantiomorphs of each object were generated with the mirror reflection function in a commercial graphics program. The enantiomorphic version of each object that was used as the target image was randomly determined for each object and was maintained across participants. The different object control condition for each target was created by randomly combining the identical preview image for one object with the target image for a different object. The simple control preview stimulus was a square containing a smaller square and a plus at its center. The outside square subtended 3.55° in height and width, the inside square subtended 1.06°, and the target cross subtended 0.3°. The control stimulus thus provided participants with an effective saccade target but no information about the visual characteristics or identity of the target object.

Apparatus. The stimuli were displayed at a resolution of 800 × 600 pixels on an NEC Multisync XE 15-in. (38.1-cm) monitor driven by a Hercules Dynamite Pro super video graphics adapter card. The screen refresh rate was 100 Hz. The display changes required an average of 5.84 ms (minimum = 1.683 ms, maximum = 10 ms). The contours of the objects and markers appeared black (pixels off) against a gray (pixels on) background. The gray background was created by setting the red, green, and blue channels to an intensity value of 16, where white is an intensity value of 64 on each channel. Eye movements were monitored via an ISCAN RK-416 high-speed eyetracker. Signals were generated by the eyetracker at a frequency of 120 Hz, and the computer changed the display contingent on detecting an eye movement of greater than 0.5°. Display changes required a maximum of 18 ms from when the eyes crossed the 0.5° boundary, 8 ms to detect the position of the eye and 10 ms to complete the display change. Because a 10° horizontal saccade has a duration of more than 40 ms (Becker, 1989; Collewijn, Erkelens, & Steinman, 1988), the display change was accomplished during the saccade when vision was functionally suppressed. Vocal responses were collected with a voice key connected to a dedicated input–output (I/O) board; activation of the voice key stopped a millisecond clock on the I/O board and generated a system interrupt that was serviced by software. The eyetracker, display monitor, and voice key were interfaced with a 486-based microcomputer that controlled the experiment. The computer maintained a complete record of saccade and naming latencies.

Procedure. Participants provided data in two test blocks of 128 experimental trials each. Before each test block, participants were calibrated on the eyetracker and then were given a short practice block of 8 trials. The practice trials consisted of each of the eight conditions for the saccade direction tested in that block. A trial in the practice and experimental blocks consisted of the following events. First, a fixation display appeared containing three test fixation markers and a small cross that indicated the computer's estimate of the current fixation position. The participant fixated each test marker, and if the calibration was satisfactory (plus or minus 0.33° from each marker), the experimenter asked the participant to fixate the fixation marker to indicate that he or she was ready for the trial to begin. The experimenter then initiated the trial by pushing a silent button. The fixation display was replaced by a preview display containing the preview stimulus (either an object or the control box). The participant immediately initiated a horizontal eye movement to the preview stimulus. During the saccade, the preview stimulus was replaced by the target object. This display change was effected by changing the video page displayed from video memory; a display page change also occurred in the identical condition. The target display remained in view until the participant responded. The participant named the target object as quickly as possible. The computer recorded the latency of the eye movement and the latency of the vocal response timed from when the eye crossed the 0.5° boundary.

Each participant took part in two blocks of trials, one in which the eye movements were to the left (i.e., the left visual field preview) and one in which eye movements were to the right (i.e., the right visual field preview). The order of blocks was counterbalanced across participants. In each block, the participant saw 128 trials presented in a pseudorandom order. After a short rest, the participant received the second block, which consisted of the same trials in a new pseudorandom order. In each block, the 128 trials were produced by the within-subject factorial combination of 4 preview conditions (identical, enantiomorph, simple control, and different object control) × 2 eccentricities (10° or 20°) × 16 target objects. The experiment was completed in a single session that lasted about 45 min.

Results

The mean corrected naming latencies as a function of preview condition, preview visual field, and eccentricity are presented in Table 1. Corrected latencies excluded trials on which the naming latency was less than 150 ms, greater than 1,500 ms, or beyond 3 *SD*s from that participant's mean naming latency in that condition. Overall, 6.8% of the trials were excluded by these criteria, and the excluded trials were randomly distributed across conditions. The pattern of corrected latencies did not differ from the pattern before correction. In an initial analysis of variance (ANOVA) that included the order of saccade direction blocks (left then right vs. right then left) as a between-subjects factor, neither the main effect nor any interactions involving this factor was reliable. The remainder of the reported analyses were therefore collapsed over the order of saccade direction blocks.

Table 1
Mean Naming Latencies (in Milliseconds) as a Function of Preview Condition, Eccentricity, and Saccade Direction in Experiment 1

Eccentricity and saccade direction	Preview condition: Identical	Enantiomorph	Simple control	Different-object control	*M*
10°					
Rightward	630	662	755	822	717
Leftward	634	665	782	798	720
M	632	663	769	810	718
20°					
Rightward	630	668	751	796	711
Leftward	652	693	761	777	721
M	641	680	756	787	716

Overall, there was a reliable main effect of preview condition, $F(3, 33) = 76.17$, $MSE = 3{,}607$, $p < .001$, with a 126-ms preview benefit in the identical condition and a 90-ms benefit in the enantiomorph condition compared with the simple control condition and a 162-ms preview benefit in the identical condition and a 126-ms benefit in the enantiomorph condition compared with the different object control condition. It is important to note that the 36-ms preview benefit advantage for the identical condition over the enantiomorph condition was also reliable, $F(3, 33) = 28.90$, $MSE = 1{,}039$, $p < .001$. These data thus show a clear advantage of the identical preview over the enantiomorph preview. The 36-ms preview cost associated with the different object control condition compared with the simple control condition was also reliable, $F(3, 33) = 16.22$, $MSE = 1{,}900$, $p < .005$.

There was a tendency for the preview benefit to be mediated by the eccentricity of the preview, $F(3, 33) = 2.476$, $MSE = 1{,}693$, $p = .078$. This effect was apparently due to greater information acquisition when the preview appeared closer to the fixation point: Preview benefits were larger in the identical and enantiomorph conditions and preview cost was larger in the different condition at the 10° than at the 20° eccentricity. There was also a marginally reliable interaction of preview condition and saccade direction, $F(3, 33) = 2.301$, $MSE = 1{,}877$, $p = .094$. However, the advantage of the identical condition over the enantiomorph condition was the same for leftward (36-ms) and rightward (35-ms) saccades. The source of the marginal interaction appeared to be an increase in the cost associated with the different object preview, which was 15 ms for leftward saccades and 56 ms for rightward saccades. No other main effects or interactions were reliable. This effect could have been due to an increase in name competition for stimuli appearing in the right visual field.

To determine whether differences in preview benefits across conditions might have been caused by differences in the duration of the fixation before the saccade to the target, we conducted an additional analysis on the saccade latencies. Collapsed across conditions, the mean saccade latency was 234 ms. Saccade latencies were 37 ms longer when the preview appeared at 20° (252 ms) than at 10° (215 ms), $F(3, 33) = 34.40$, $MSE = 1{,}901$, $p < .001$. This latter effect was mediated by saccade direction, $F(3, 33) = 5.170$, $MSE = 533$, $p < .05$, with a 16-ms larger eccentricity effect for rightward than for leftward saccades. Finally, there was a reliable interaction between preview condition and eccentricity, $F(3, 33) = 6.931$, $MSE = 138$, $p < .005$. When the preview appeared at 20°, there was no difference in saccade latencies between preview conditions ($F < 1$). For a 10° preview, saccades to the simple control stimulus required more time to generate (227 ms) than did saccades to the identical (214 ms), enantiomorph (212 ms), and different object control (209 ms) previews ($p < .05$). The observed saccade latency differences do not undermine the main conclusions reached from the naming latency data.

Discussion

The finding that a robust preview benefit was observed in the enantiomorph condition compared with both of the control conditions suggests that representations that are abstracted away from left–right orientation are functional during transsaccadic object identification. This finding held regardless of which control condition was used for assessing preview benefits and so is unlikely to be due to any peculiarities inherent in the control conditions chosen. Most important for the purposes of the present study, the data strongly suggest that more visually specific information about an object than its identity, concept, and name can also be retained and integrated across saccades during object identification: The benefit derived from an identical preview of a target object was 36 ms greater than the benefit derived from an enantiomorph of that target object.[1]

---

[1] The enantiomorph effect observed here is similar in magnitude to the marginally reliable 41-ms enantiomorph effect observed by Pollatsek et al. (1984). In fact, the absolute magnitudes of the naming latencies in the two experiments are remarkably similar when the eccentricity conditions shared across experiments (10°) are compared: In the present experiment and the Pollatsek et al. (1984) experiment, the naming latencies were 632 ms and 632 ms in the identical conditions, 663 ms and 673 ms in the enantiomorph conditions, and 769 ms and 760 ms in the control conditions, respectively.

In addition to the preview benefits observed in the identical and enantiomorph conditions, there was also a preview cost associated with the different-object control condition compared with the simple control condition. A preview cost of this type has similarly been observed in previous experiments (Pollatsek et al., 1984). One interpretation of this cost is that it reflects a disruption in transsaccadic integration in the different-object control condition that is caused by a mismatch between visually specific information contained in the pre- and postsaccade representations. From this perspective, the fact that the benefit for the identical over the enantiomorph condition was the same magnitude as the cost for the different-object control over the simple control preview condition (36 ms in both cases) might be taken to suggest that both differences reflect the integration of visually specific information. However, it could also be that the similarity of the identity benefit and the different object cost was fortuitous and that the different-object cost arose from a mismatch between the preview and target images at the level of the identity, concept, or name. From the perspective of our central concern, it is not necessary that we determine the reason for the cost here; most critically, the additional benefit observed in the identical condition over the enantiomorph condition could not have been due to differences in identity, concept, or name because enantiomorphs are equated on these characteristics.

Experiment 2

Experiment 2 was designed to address two issues. First, we sought converging evidence for the finding that the left–right orientation of an object is preserved across saccades. Second, and more generally, we wanted to develop a new paradigm with which to investigate transsaccadic object integration. To date, the majority of studies that have focused on transsaccadic object identification have used the transsaccadic object naming paradigm. Although these studies have provided a great deal of important information, the transsaccadic naming paradigm has a number of characteristics that are not optimal for investigating natural transsaccadic integration.

First, because the transsaccadic object naming paradigm requires that attention be devoted only to a single object on each trial, there is no need for the participant to process any information at the fovea while extrafoveal information is acquired from the preview stimulus. Preview benefits in reading have been found to be reduced when foveal load is high (Henderson & Ferreira, 1990; Kennison & Clifton, 1995); it is possible that less visually specific information can be acquired when foveal analysis takes place simultaneously with extrafoveal information acquisition. Second, object identification during natural perception takes place at the same time that the viewer is building a conceptual and memorial representation of the viewed scene (Friedman, 1979; Henderson, Weeks, & Hollingworth, 1999; Loftus & Mackworth, 1978). Less capacity might be available to preserve and integrate visually specific information across a saccade when the viewer must engage in cognitive and memory processing simultaneously with object identification. Third, the transsaccadic object naming task uses the speeded overt production of the object name as the dependent measure. However, overt name production is not a necessary component of object identification. To the extent that at least some of the preview benefit observed in Experiment 1 and in previous experiments has been due to the overt generation of the object name, as argued by Pollatsek et al. (1984), it is important to determine whether similar preview effects can be observed in a task that does not require overt name production. Finally, all of the researchers who have previously examined transsaccadic object integration have used small sets of objects that were repeated many times over trials. For example, in Experiment 1, each of 16 objects was repeated 16 times for each participant. It is possible that when a small set of objects is used, participants learn a set of features that allows them to distinguish the objects in the set. Preview benefits might then reflect the participants' ability to selectively attend to and encode those features.

In Experiment 2 we addressed the above concerns by using the moving window paradigm (Henderson, McClure, Pierce, & Schrock, 1997; Henderson, Pollatsek, & Rayner, 1989). Participants viewed horizontal linear arrays of four line drawings of real-world objects while their eye movements were recorded. The participant's task was to identify the objects in the current array and then to decide whether an immediately following test probe word matched one of those objects. During array viewing, the display image was changed contingent on eye position so that the extrafoveal preview of an object could be manipulated before its fixation. On one third of the trials, all the objects in the array were visible throughout the trial; this was the identical preview condition. On another third of the trials, each object in the array except for the currently fixated object was replaced by a placeholder that contained no information about the object at that position; this was the control condition. On the final third of the trials, the left–right orientation of each object was different when the object was viewed extrafoveally and when it was fixated; this was the enantiomorph condition.

To produce a display change contingent on eye position, we placed a software-defined invisible boundary between each object, dividing the display into six regions of equal size (four objects and two markers at each end). As long as the viewer's line of regard remained in one region, the display did not change. When the line of regard crossed a boundary dividing two regions, the display changed. The nature of the display change depended on the preview condition. For example, when the line of regard crossed into Region 2 in the control condition, the object occupying Region 2 appeared and all other objects were replaced by placeholders. In this way, no extrafoveal preview information was available about an object before fixation on that object. As in Experiment 1, the display changes took place during the saccade from one object to another when vision was functionally suppressed.

The moving window paradigm provided us with the opportunity to address the limitations of the object naming paradigm. First, the moving window paradigm induces a foveal load because the viewer must identify and encode into memory the foveal object during each fixation. Second, the paradigm also introduces a general cognitive and memory load because the task requires that four objects be identified and retained in memory over the course of each trial. Third, the overt production of object names is not required (and in fact is impossible because of the use of a bite bar), so preview benefits cannot be due to the preparation of a naming response. Of course, name codes may be covertly activated to facilitate retention, but presumably the activation of short-term memory codes is more naturally tied to object identification than is overt name production. Finally, object repetition was minimal within a large overall set of objects: Participants saw 96 different objects over the course of 96 trials, with four repetitions of each object across trials. Under these conditions, it is less likely that participants could form expectations concerning the objects or could learn a simple set of features for distinguishing them.

To investigate the effect of preview information on transsaccadic integration, we measured the effects of the preview condition on the participant's eye movement behavior during object identification. We were particularly interested in the amount of time that the point of regard remained on an object when that object was first encountered, with preview benefits reflected as savings in this first-pass gaze duration measure. We generated three contrasting predictions for first-pass gaze duration. First, if extrafoveal information cannot be integrated across saccades during a complex viewing task, then gaze durations should be the same in the identical, enantiomorph, and control conditions (i.e., there should be no preview benefit). Second, if extrafoveal information can be integrated across saccades under these conditions, and if the integrated information is purely abstract, then there should be equivalent preview benefits in the identical and enantiomorph preview conditions. Third, if extrafoveal information can be integrated across saccades in this task, and if transsaccadic integration can be based on specific information concerning left–right orientation as well as more abstract information, then preview benefits should be observed in both the enantiomorph and identical conditions and the preview benefit for the identical condition should be larger than the benefit in the enantiomorph condition.

Method

Participants. Twelve members of the Michigan State University participant pool participated either for course credit or for pay. All participants had normal, uncorrected vision. Some participants had experience with eye movement experiments, but none had participated in Experiment 1, and all were naive about the hypotheses under investigation.

Stimuli. The stimuli were 96 line drawings of common real-world objects, taken from the same pool as those in Experiment 1, and digitized in the same manner. As in Experiment 1, the enantiomorphic version of each object that was used as the preview and target image was randomly determined for each object. The objects were presented in linear arrays of four objects each, along with an initial and final marker (see Henderson et al., 1997). The beginning and ending marker was a circle containing a large cross and two concentric circles. These markers were included so that the first and last object would be laterally masked on both sides (as were the two central objects). Ninety-six arrays were created by combining the 96 objects. Each of the first 24 arrays were constructed by randomly selecting four objects without replacement from the entire set and then randomly placing those objects into each of the four central array positions. Each of the second, third, and fourth 24 arrays was created in the same way. In total, then, 96 arrays were created such that the 96 objects each appeared exactly four times across arrays, with each object appearing in a randomly chosen position and with a random selection of three other objects in each new array.

Viewing distance was 1 m, and the display area subtended 15.3° horizontally and 12.0° vertically. The object arrays were centered in that area. The largest object was 1.9° in diameter; the average object and the beginning and ending markers were 1.5° wide and 1.5° in height. There was about 2.4° between the centers of neighboring objects. In the control condition, a placeholder was used to replace each of the extrafoveal objects. This placeholder was a circle 1.5° in diameter and contained a centered plus sign that was about 0.3° horizontally and vertically.

Probe words were 96 names of common objects, one name for each array. No two arrays were given the same probe word. Half the probe words were used for the "yes" responses and named an object in its paired array. The other half of the probe words named objects that were not included in the experiment; these distractor probes were taken from the same class of objects as those used as "yes" probes (most named objects from Snodgrass & Vanderwart, 1980, that were not used in the experiment). Probe words were shown at the center of the display monitor in an Arial font at about three characters per degree and ranged from 1° to 5° across the set.

Apparatus. The display system was identical to that used in Experiment 1. Display luminance was adjusted to a comfortable level. The room was otherwise illuminated by a low-intensity, indirect light source.

Eye movements were monitored using a Generation 5.5 Stanford Research Institute Dual Purkinje Image Eyetracker (Crane, 1994; Crane & Steele, 1985), which has a resolution of 1′ of arc and a linear output over the range of the visual display used. A bite bar and forehead rest were used to maintain the participant's viewing position and distance. The position of the right eye was tracked, although viewing was binocular. Signals were sampled from the eyetracker using the polling mode of the Data Translations DT2802 analog-to-digital converter. This method produced a sampling rate of better than 1 sample per millisecond.

The preview conditions were defined by the viewer's line of regard within one of six regions: Each region was defined by two vertical boundaries (for the objects) or one boundary and an edge of the display area (for the end markers). The boundaries divided the display into six regions of equal size, with each stimulus centered within each region. As long as the computed line of regard was between two boundaries defining a region, the image for that region in that preview condition was displayed. As soon as the computed line of regard crossed into a new region, a display change was initiated. Thus, display changes were initiated during saccades between regions. In the control condition, whenever the line of regard crossed one of the two boundaries defining a particular region, a video page was presented that contained an image of the object in the current region and placeholders in all of the other regions. In the enantiomorph condition, whenever the line of regard crossed one of the two boundaries defining a particular region, a video page was presented that contained an image of the object in the current region and the nonreversed images of the objects in all of the other regions. In the identical condition, whenever the line of regard crossed one of the two boundaries defining a particular region, a video page was presented that contained an image of the object in the current region spatially displaced 3 pixels to the right and the nondisplaced images of the objects in all the other regions. The spatial displacement in the identical condition was included as a control for the display change itself in the other conditions. The display changes were completed in an average of 6.84 ms (maximum = 11 ms) after the eyes crossed a boundary.

Buttonpress responses were collected using a button panel connected to a dedicated I/O card; depressing a button stopped a millisecond clock on the I/O card and generated a system interrupt that was serviced by software. The eyetracker, display monitor, and I/O card were interfaced with a microcomputer running a 66-MHz 486 DX2 processor. The computer controlled the experiment and maintained a complete eye movement and buttonpress record for each trial.

Procedure. A bite bar was prepared for each participant when he or she arrived for the experiment. The participant was then positioned as comfortably as possible on the eyetracker, and the bite bar and a forehead rest were used to maintain viewing position. The eyetracker was then calibrated. Calibration consisted of having the participant fixate four calibration markers at the left, right, top, and bottom of the display area. Calibration was checked by displaying a calibration screen consisting of nine test positions (i.e., left, middle, and right of the top, middle, and bottom of the screen) and a fixation marker that indicated the computer's estimate of the current fixation position. The participant fixated the test positions, and if the fixation marker was ±5′ of arc from each, calibration was considered accurate.

Once calibrated, the participant saw 12 practice trials, 4 of each preview condition presented in a random order. The objects and probe words used in the practice trials were different from those used in the experimental trials. After the practice trials, any remaining questions were answered, and the participant then took part in 96 experimental trials. Participants were given an enforced break about halfway through the experimental trials and were allowed to take additional breaks after any trial, although most did not exercise this option.

A trial consisted of the following events. First, the calibration screen was shown and calibration was checked. The eyetracker was recalibrated whenever calibration was inaccurate using the ±5′ of arc criterion. After the calibration check, the participant fixated the left calibration position to indicate that he or she was ready for the trial to begin. The experimenter then started the trial. The fixation display was replaced by the trial display containing a linear array of two markers and four objects. The participant's initial fixation position in the array was on the leftmost marker. The participant looked through the array to identify the four objects and then terminated the display by manually pressing either of two response buttons. The button response caused offset of the object array and immediate onset (within the limitations of the screen refresh rate) of the probe word display. The probe word named one of the four objects in the array 50% of the time and named an object not included in the array the other 50% of the time. For the "yes" probe trials, each of the four object positions was probed an equal number of times. The participant pressed the left button on the response panel to indicate that the probe had been contained in the array and the right button to indicate that it had not. The probe remained on the screen until the participant responded. After this response, the calibration screen reappeared while the images for the next trial loaded into video memory.

The factorial combination of three preview conditions (identical, enantiomorph, and control) and two probe conditions ("yes" and "no" trials) created six experimental conditions. Each participant received 96 experimental trials, 16 trials in each of these six conditions (i.e., 32 trials in each preview condition). Because there were four objects in each trial array and 32 trials in each preview condition, each participant could contribute 128 data points per preview condition. Six stimulus lists were created such that each object array appeared once in each list and each array appeared in all six conditions across lists. Two participants received each of the six lists. The order of array presentation (and hence condition presentation) was determined randomly for each participant. The entire experiment lasted approximately 45 min.

Results

Eye movement data analysis. Raw data files consisted of time and position values for each eyetracker sample. Overall, about 3% of the data were lost because of a failure to keep accurate lock on the position of the eye. For the remaining data, saccades were defined as eye movement velocities greater than 6.58 deg/s. Once saccades had been identified, fixation positions (in pixel values) and durations (in milliseconds) were computed over the remaining data independently of the positions of the objects. The duration of a fixation was the elapsed time between two consecutive saccades. During a fixation, the eyes often drift. The x and y position of a given fixation was taken to be the mean of the position samples (in pixel values) taken during that fixation weighted by the durations of each of those position samples using the equations presented by Henderson et al. (1997). Individual fixations shorter than 90 ms were excluded from further analysis. Each fixation was then assigned to an object or marker based on its computed x and y pixel position. Scoring regions for the four objects and the two markers were defined by dividing the display area into six equal vertical strips with the stimuli centered in each strip. Each scoring region was the same as the boundary region defined for the preview conditions. A fixation was counted as belonging to the stimulus object (or end marker) occupying the same vertical strip as that fixation. All analyses were conducted using automated analysis programs.

For the analyses reported, the focus was on eye movement patterns over the four objects in each array as a function of preview condition. ANOVAs were conducted for each measure, with ordinal object position in the array and preview condition as within-subjects factors. The data were collapsed over response condition (yes or no) because these trials were equivalent during array viewing (i.e., participants could not know during array viewing which type of probe word they would receive after array offset).

Performance accuracy. Participants were able to determine the identities of the objects with a high degree of accuracy across all three preview conditions. Table 2 shows the mean proportions of hits and false alarms as a function of

Table 2
Mean Proportions of Hits and False Alarms as a Function of Preview Condition in Experiment 2

	Preview condition			
Measure	Identical	Enantiomorph	Control	*M*
Hits	.953	.948	.958	.953
False alarms	.12	.089	.109	.106

Table 3
Mean Percentage of Regions Fixated as a Function of Ordinal Region Position and Preview Condition in Experiment 2

Preview condition	Region 1	2	3	4	*M*
Identical	98.7	99.0	97.1	94.3	97.3
Enantiomorph	99.2	99.0	97.4	96.9	98.1
Control	99.0	100	99.7	99.5	99.5
M	99.0	99.3	98.1	96.9	98.3

Table 4
Mean First-Pass Gaze Duration and Mean Total Fixation Time in Experiment 2

Measure	Preview condition: Identical	Enantiomorph	Control	*M*
First-pass gaze duration (ms)	485	505	632	541
Total fixation time (ms)	610	609	778	666

preview condition. The overall hit rate was .953, and the overall false-alarm rate was .106. Performance did not differ as a function of preview condition, either for proportions of hits ($F < 1$) or for proportions of false alarms ($F = 1.638$).

Percentage of regions fixated. To be able to draw inferences about the influence of extrafoveal preview information on object identification from participants' eye movement behavior, we had to demonstrate that participants were fixating the majority of the target objects. Therefore, we examined the percentage of regions fixated, defined as the percentage of regions entered at least once by the point of regard after a saccade that originated from a launch position beyond the region, as an index of the spatial distribution of eye fixations in the arrays. Table 3 shows the mean percentage of regions fixated as a function of region and preview condition. Overall, participants fixated 98% of the regions. The effect of preview condition was reliable, $F(2, 22) = 40.40$, $MSE = 7{,}554$, $p < .001$, with 2.2% and 1.4% fewer regions fixated in the identical and enantiomorph conditions, respectively, compared with the control condition. The effect of preview condition was mediated by a reliable interaction with region, $F(6, 66) = 7.361$, $MSE = 0.0002$, $p < .001$. As can be seen in Table 3, there was a greater difference among conditions for the regions that were fixated later in the arrays, suggesting that the final objects were sometimes (on 3%–6% of the trials) identified from extrafoveal vision alone when preview information was available. Post hoc simple effects tests based on the error term from the interaction effect ($\alpha = .05$) indicated that the percentage of regions fixated was equivalent for the three conditions at the first ordinal position, the percentage fixated was higher in the control condition than in the other two conditions at the second and third ordinal positions, and the percentage fixated in the three conditions differed from each other at the fourth ordinal position. Despite these differences, at least 94% of all regions in all conditions were fixated. Thus, a more fine-grained analysis of the eye movement data to investigate preview benefit was warranted.[2]

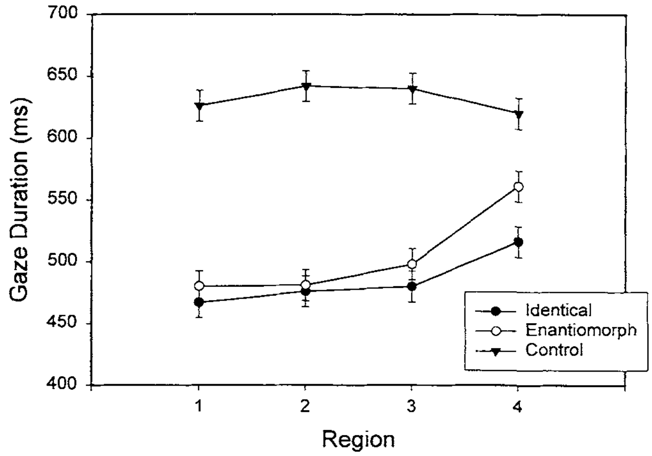

Figure 1. Mean gaze duration as a function of preview condition and ordinal region position in Experiment 2. Error bars represent standard error of the mean based on the mean square error for the main effect of preview condition.

First-pass gaze duration. The main dependent measure of interest, first-pass gaze duration, quantified the amount of time the participant's line of regard was directed toward an object the first time the object was fixated in a given array. This measure is critical because it reflects initial encoding time for an object (Antes, 1974; Friedman, 1979; Henderson et al., 1997; Henderson et al., 1999; Loftus & Mackworth, 1978; see Henderson & Hollingworth, 1998). First-pass gaze duration thus provides a fixation time analog of naming latency. If the left–right orientation of an object plays a role in transsaccadic object integration, then preview benefits should be larger in the identical condition than in the enantiomorph condition.

First-pass gaze duration was defined as the sum of the durations of all fixations between the first time the participant's line of regard entered and exited a region. The computation of a first-pass gaze duration for a region was conditional on that region receiving at least one fixation; regions that received no fixations did not contribute to the means. Figure 1 shows the mean first-pass gaze duration in each object region as a function of region and preview condition, and Table 4 shows the mean first-pass gaze

---

[2] We also examined the spatial distribution of fixation time across the arrays. The majority of fixation time was devoted to the objects and the initial marker (where the trial began), rather than to the background space between them, with most of the fixation time concentrated on the centers of each object. It is important to note that similar distributions were observed in the control condition and in the conditions that contained extrafoveal object information, suggesting that the markers served as adequate saccade targets. The observed distributions were similar to those reported previously (Henderson, 1993; Henderson et al., 1997) and showed that fixations were concentrated on objects rather than on background and on the centers of objects rather than on their boundaries.

duration as a function of preview condition, collapsed over region. Overall, mean first-pass gaze duration was 541 ms. The presence of an extrafoveal preview produced a benefit, $F(2, 22) = 40.40$, $MSE = 7{,}554$, $p < .001$, with 147 ms and 127 ms shorter first-pass gaze durations in the identical and enantiomorph conditions, respectively, than the control condition. A planned simple effects test indicated that the 20-ms difference between the identical and enantiomorph conditions was reliable, $F(1, 11) = 5.550$, $MSE = 1{,}769$, $p < .05$. Thus, as in Experiment 1, the benefit on object processing provided by an extrafoveal preview increased when the visual characteristics of the object remained constant across a saccade. Ordinal object position did not produce a main effect ($F < 1$), and the pattern of first-pass gaze durations across preview condition was not mediated by ordinal object position ($F = 1.063$).

Total fixation time. Total fixation time was defined as the sum of the durations of all fixations in a region, including refixations after saccades that originated to the right of the region of interest. Like first-pass gaze duration, the computation of total fixation time for a region was conditional on that region receiving at least one fixation; regions that received no fixations did not contribute to the means. Figure 2 shows the mean total fixation time in each region as a function of region and preview condition, and Table 4 shows the mean total fixation time as a function of preview condition, collapsed over region. Overall, the mean total fixation time was 666 ms. There was a reliable effect of preview condition, $F(2, 22) = 56.66$, $MSE = 7{,}977$, $p < .001$, with a 168-ms preview benefit in the identical condition and a 167-ms preview benefit in the enantiomorph condition. The 1-ms difference between the identical and enantiomorph conditions was not reliable ($F < 1$). The effect of preview condition was not mediated by region ($F = 1.218$). Finally, as can be seen in Figure 2, total fixation time was longer in the two intermediate ordinal positions than in the first and last positions, $F(3, 33) = 3.698$, $MSE = 13{,}076$, $p < .05$.[3]

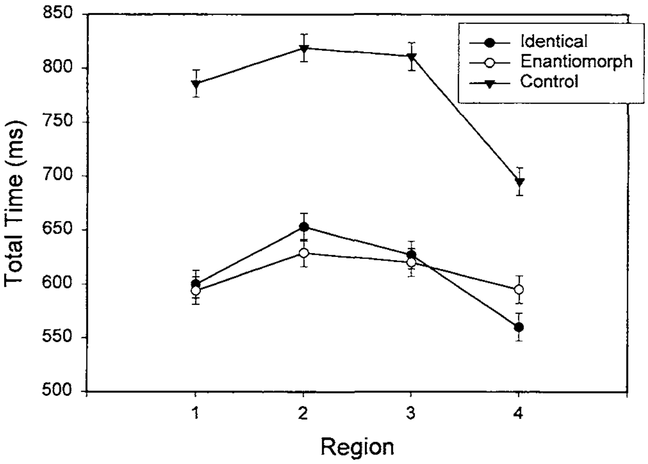

Figure 2. Mean total fixation time as a function of preview condition and ordinal region position in Experiment 2. Error bars represent standard error of the mean based on the mean square error for the main effect of preview condition.

Discussion

Consistent with the naming latency data of Experiment 1, the first-pass gaze duration data from Experiment 2 strongly suggest that information more visually specific than the abstract concept, identity, and name is functional across saccades: The benefit derived from an identical preview of an object was 20 ms greater than the benefit derived from an enantiomorph of that object. At the same time, the finding that a robust preview benefit was observed in the enantiomorph condition suggests that representations that are abstracted away from left–right orientation are also functional during transsaccadic object identification. These results were obtained in a viewing task that required attention to be focused on a fixated object at the same time that information from extrafoveal objects was acquired and retained, required the construction and retention of a memory representation over multiple fixations, did not require overt name production, and used a large set of objects that were minimally repeated over trials.

The difference between the identical and enantiomorph conditions was smaller in Experiment 2 (20 ms) than in Experiment 1 (36 ms). Thus, there is some evidence that the identity benefit was exaggerated in Experiment 1, where a limited set of items were seen under low perceptual and memory load. Because the objects were repeated twice as many times in Experiment 1 (eight times each) as in Experiment 2 (four times each), we might have expected the identity benefit to be smaller in the former experiment; the effects of viewpoint specificity have typically been found to decrease with object repetition (Jolicoeur & Milliken, 1989). However, we think that the cross-experiment comparison must be treated with extreme caution given that different participants and different sets of objects were used in the two experiments. Furthermore, it is interesting to note that in Experiment 2 the enantiomorph effect tended to be larger at the regions less likely to be fixated (Regions 3 and 4) than at regions more likely to be fixated (Regions 1 and 2). This finding might suggest that participants were sometimes able to identify an object parafoveally (Henderson et al., 1997) and were more likely to skip parafoveally identified objects at the end of the display. In this view, the objects that were fixated at the end of the display were more likely to be those that had not been parafoveally identified. The larger enantiomorph effects for the objects at the end of the display might then suggest that the enantiomorph effect is due to a process that integrates partial representations across the saccade before identification. In any case, the most striking result is the similarity of the advantage for the identical condition over the enantiomorph condition across the different para-

---

[3] An open question is why the effects of enantiomorphy disappear in total fixation time. We suspect that total fixation time data are simply more noisy and therefore that small effects are more difficult to detect in these data.

digms used in the two experiments and despite the repetition of objects.

A question that arises when using the moving window paradigm to explore transsaccadic integration is whether the benefits reflect integration of previously acquired extrafoveal information with current foveal information (preview benefits), integration of previously acquired foveal information with current extrafoveal information (postview benefits), or both. On the one hand, this question is not critical for using the paradigm to explore transsaccadic integration because all three interpretations involve transsaccadic integration. At the same time, the question is of interest from the perspective of the allocation of visual processing resources during dynamic viewing. The results of previous studies have suggested that these benefits arise primarily from the stimulus about to be fixated next (Henderson et al., 1989; see also Deubel & Schneider, 1996; Henderson, 1992b; Hoffman & Subramaniam, 1995; Shepard, Findlay, & Hockey, 1986; Rayner et al., 1978). Furthermore, an indirect source of evidence concerning the possibility of postview processing in the present study was provided by the total fixation time measure. If the objects were typically processed in postview as well as in preview, then we might expect that the eyes would return more often to an object in the enantiomorph condition (where the objects changed left–right orientation after the eyes moved on) than in the identical condition. Thus, the postview hypothesis predicts that the difference in fixation times between the identical and enantiomorph conditions should be exaggerated in the total time measure. Contrary to this prediction, the identical and enantiomorph conditions produced equivalent total fixation time values.

Finally, the dissimilarity of the first-pass gaze duration and total time measures, in combination with the similarity of the first-pass gaze duration and naming latency measures, is consistent with the view that first-pass gaze duration is more reflective of initial object encoding processes than are less fine-grained eye movement measures (Henderson et al., 1997).

General Discussion

The two experiments reported in this article were designed to investigate the nature of the representations that are retained and integrated across saccades during the identification of meaningful, real-world objects. The primary question was whether more specific information than an object's concept, identity, or name can be retained and integrated across a saccade. In Experiment 1, we investigated the nature of transsaccadic integration using an object naming paradigm. In Experiment 2, participants examined linear arrays of four objects while their eye movements were recorded. Despite relatively large differences in the nature of the viewing situation and the task, both experiments converged on two main results. First, a large preview benefit was derived from the enantiomorph preview compared with the control conditions. This result suggests that object representations abstracted away from left–right orientation are retained and integrated across a saccade. Second, the preview benefit was larger in the identical condition than in the enantiomorph condition, suggesting that a representation that codes left–right orientation is also retained and integrated across a saccade.

Transsaccadic integration during object identification can be accounted for by a model with the following four assumptions: First, the preview image of an object leads to the computation of an abstract structural description of that object (Carlson-Radvansky & Irwin, 1995). Second, a matching process attempts to match the structural description that is computed from the preview to stored object models that are consistent with that description. The activation of stored models may take place from the preview even if the preview leads to an incomplete structural description. Third, if the computed structural description is sufficiently detailed to allow a good match to one stored object model, then other information associated with that model may be retrieved, such as the object's basic level concept and name. Finally, preview benefits arise because both the computed structural description and the stored representations that they contact can be retained across a saccade and integrated with similar representations that are generated during the subsequent fixation. Although the computed structural description does not appear to include veridical information about the specific contours contained in the image (Henderson, 1997), the present results strongly suggest that the description does include viewpoint information about left–right orientation. Evidence reported by Verfaillie, De Troy, and Van Rensbergen (1994) suggests that viewpoint information about in-depth orientation can also be retained and integrated across saccades.

Current theories of object recognition differ depending on whether they assume that the functional object representations are viewpoint invariant (Biederman, 1987; Biederman & Gerhardstein, 1993, 1995) or viewpoint dependent (Bülthoff & Edelman, 1992; Tarr, 1995). Consistent with the latter class of theory, our results suggest that a view-dependent representation that encodes information about left–right orientation is initially constructed for real-world objects. This information is retained at least long enough to support transsaccadic integration. Furthermore, the information that is retained about left–right orientation is not tied to a particular position on the retina: In the present study, information about left–right object orientation was initially generated from a peripheral view of the object and then integrated with a foveal view. Thus, the orientation information is retinally invariant.

Conclusion

The purpose of the present study was to investigate the nature of the representations that are retained and integrated across a saccadic eye movement during real-world object identification. The results of the two experiments presented here converge on the conclusion that both abstract representations and more visually specific representations that code left–right orientation are functional in the retention and integration of object information across saccades.

References

Antes, J. R. (1974). The time course of picture viewing. *Journal of Experimental Psychology, 103,* 62–70.

Becker, W. (1989). Metrics. In R. H. Wurtz & M. E. Goldberg (Eds.), *The neurobiology of eye movements* (pp. 95–137). Amsterdam: Elsevier.

Biederman, I. (1987). Recognition by components: A theory of human image understanding. *Psychological Review, 94,* 115–147.

Biederman, I., & Cooper, E. E. (1991). Evidence for complete translational and rotational invariance in visual object priming. *Perception, 20,* 585–593.

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1162–1182.

Biederman, I., & Gerhardstein, P. C. (1995). Viewpoint-dependent mechanisms in visual object recognition. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1506–1514.

Breitmeyer, B. G. (1984). *Visual masking: An integrative approach.* New York: Oxford University Press.

Bridgeman, B., & Mayer, M. (1983). Failure to integrate visual information across successive eye fixations. *Bulletin of the Psychonomic Society, 21,* 285–286.

Bülthoff, H. H., & Edelman, S. (1992). Psychophysical support for a 2-D view interpolation theory of object recognition. *Proceedings of the National Academy of Sciences, 89,* 60–64.

Carlson-Radvansky, L., & Irwin, D. E. (1995). Memory for structural information across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1441–1458.

Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1988). Binocular co-ordination of human horizontal saccadic eye movements. *Journal of Physiology, 404,* 157–182.

Cooper, L. A., Schacter, D. L., Ballesteros, S., & Moore, C. (1992). Priming and recognition of transformed three-dimensional objects: Effects of size and reflection. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 43–57.

Crane, H. D. (1994). The Purkinje image eyetracker, image stabilization, and related forms of stimulus manipulation. In D. H. Kelley (Ed.), *Visual science and engineering: Models and applications* (pp. 15–89). New York: Marcel Dekker.

Crane, H. D., & Steele, C. M. (1985). Generation-V dual-Purkinje-image eyetracker. *Applied Optics, 24,* 527–537.

Davidson, M. L., Fox, M. J., & Dick, A. O. (1973). Effect of eye movements on backward masking and perceived location. *Perception & Psychophysics, 14,* 110–116.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36,* 1827–1837.

Di Lollo, V. (1977). Temporal characteristics of iconic memory. *Nature, 267,* 241–243.

Eriksen, C. W., & Collins, J. F. (1967). Some temporal characteristics of visual pattern recognition. *Journal of Experimental Psychology, 74,* 476–484.

Feldman, J. A. (1985). Four frames suffice: A provisional model of vision and space. *Behavioral and Brain Science, 8,* 265–289.

Friedman, A. (1979). Framing pictures: The role of knowledge in automatized encoding and memory for gist. *Journal of Experimental Psychology: General, 108,* 316–355.

Hayward, W. G., & Tarr, M. J. (1997). Testing conditions for viewpoint invariance in object recognition. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 1511–1521.

Henderson, J. M. (1992a). Identifying objects across saccades: Effects of extrafoveal preview and flanker object context. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 521–530.

Henderson, J. M. (1992b). Visual attention and eye movement control during reading and picture viewing. In K. Rayner (Ed.), *Eye movements and visual cognition* (pp. 260–283). New York: Springer-Verlag.

Henderson, J. M. (1993). Eye movement control during visual object processing: Effects of initial fixation position and semantic constraint. *Canadian Journal of Experimental Psychology, 47,* 79–98.

Henderson, J. M. (1994). Two representational systems in dynamic visual identification. *Journal of Experimental Psychology: General, 123,* 410–426.

Henderson, J. M. (1997). Transsaccadic memory and integration during real-world object identification. *Psychological Science, 8,* 51–55.

Henderson, J. M., & Anes, M. D. (1994). Effects of object-file review and type priming on visual identification within and across eye fixations. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 826–839.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 417–429.

Henderson, J. M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. In G. Underwood (Ed.), *Eye guidance while reading and while watching dynamic scenes* (pp. 269–293). Amsterdam: Elsevier Science.

Henderson, J. M., McClure, K., Pierce, S. J., & Schrock, G. (1997). Object identification without foveal vision: Evidence from an artificial scotoma paradigm. *Perception & Psychophysics, 59,* 323–346.

Henderson, J. M., Pollatsek, A., & Rayner, K. (1987). The effects of foveal priming and extrafoveal preview on object identification. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 449–463.

Henderson, J. M., Pollatsek, A., & Rayner, K. (1989). Covert visual attention and extrafoveal information use during object identification. *Perception & Psychophysics, 45,* 196–208.

Henderson, J. M., Weeks, P. A., Jr., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 210–228.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics, 57,* 787–795.

Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cognitive Psychology, 23,* 420–456.

Irwin, D. E. (1992). Perceiving an integrated visual world. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 121–142). Cambridge, MA: MIT Press.

Irwin, D. E. (1996). Integrating information across saccadic eye movements. *Current Directions in Psychological Science, 5,* 94–100.

Irwin, D. E., Brown, J. S., & Sun, J. (1988). Visual masking and visual integration across saccadic eye movements. *Journal of Experimental Psychology: General, 117,* 276–287.

Irwin, D. E., Yantis, S., & Jonides, J. (1983). Evidence against visual integration across saccadic eye movements. *Perception & Psychophysics, 34,* 35–46.

Jolicoeur, P., & Milliken, B. (1989). Identification of disoriented objects: Effects of context of prior presentation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 200–210.

Jonides, J., Irwin, D. E., & Yantis, S. (1982). Integrating visual information from successive fixations. *Science, 215,* 192–194.

Kennison, S. M., & Clifton, C. C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 68–81.

Lawson, R., & Humphreys, G. W. (1996). View specificity in object processing: Evidence from picture matching. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 395–416.

Loftus, G. R., & Mackworth, N. H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 565–572.

Matin, E. (1974). Saccadic suppression: A review and analysis. *Psychological Bulletin, 81,* 899–917.

McConkie, G. W., & Rayner, K. (1976). Identifying the span of the effective stimulus in reading: Literature review and theories of reading. In H. Singer & R. B. Ruddell (Eds.), *Theoretical models and processes in reading* (pp. 137–162). Newark, DE: International Reading Institute.

O'Regan, J. K. (1992). Solving the "real" mysteries of visual perception: The world as an outside memory. *Canadian Journal of Psychology, 46,* 461–488.

O'Regan, J. K., & Levy-Shoen, A. (1983). Integrating visual information from successive fixations: Does transsaccadic fusion exist? *Vision Research, 23,* 765–768.

Pollatsek, A., & Rayner, K. (1992). What is integrated across fixations? In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 166–191). New York: Springer-Verlag.

Pollatsek, A., Rayner, K., & Collins, W. E. (1984). Integrating pictorial information across eye movements. *Journal of Experimental Psychology: General, 113,* 426–442.

Pollatsek, A., Rayner, K., & Henderson, J. M. (1990). Role of spatial location in integration of pictorial information across saccades. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 199–210.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81.

Rayner, K., McConkie, G. W., & Ehrlich, S. (1978). Integrating information across eye movements. *Cognitive Psychology, 12,* 206–226.

Rayner, K., & Pollatsek, A. (1983). Is visual information integrated across saccades? *Perception & Psychophysics, 34,* 39–48.

Riggs, L. A. (1965). Visual acuity. In C. H. Graham (Ed.), *Vision and visual perception* (pp. 321–349). New York: Wiley.

Shepard, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 38A,* 475–491.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6,* 174–215.

Srinivas, K. (1996). Size and reflection effects in priming: A test of transfer-appropriate processing. *Memory & Cognition, 24,* 441–452.

Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of viewpoint dependency in the recognition of three-dimensional objects. *Psychonomic Bulletin & Review, 2,* 55–82.

Verfaillie, K., De Troy, A., & Van Rensbergen, J. (1994). Transaccadic integration of biological motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20,* 649–670.

Volkmann, F. C. (1986). Human visual suppression. *Vision Research, 26,* 1401–1416.

Received February 21, 1997
Revision received August 12, 1997
Accepted January 21, 1998 ■