Research Article

SEEING TWO AS ONE: Linking Apparent Motion and Repetition Blindness

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Abstract—*Object tokens are episodic visual representations that mediate the ability to track visual events as they move about and change over time. Multiple tokens also allow the viewer to individuate multiple instances of a single type of object. In the present study, we established a functional link for object tokens in two seemingly disparate visual phenomena: apparent motion and repetition blindness (RB). In RB, repeated items are more difficult to perceive than unrepeated items. Using displays in which two sets of alphanumeric characters streamed in opposite directions across a computer screen in apparent motion, we found increased RB for targets appearing within a single apparent motion stream, relative to targets in different apparent motion streams. The results are inconsistent with refractory period or memory retrieval accounts of RB and support the role of object tokens in both apparent motion and RB.*

A person navigating through the visual environment not only needs to detect and identify the objects before him or her, but also to track these objects as they move about or as the person moves relative to them. People manage to do this despite the fact that the visual input is occasionally discontinuous because of blinks or eye movements. Several researchers have proposed that the coherent percept of objects intermittent over space and time may be mediated by abstract visual representations known variously as object files (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Treisman, 1988), FINSTs (FINgers of INSTantiation; Pylyshyn, 1989; Pylyshyn & Storm, 1988; Trick & Pylyshyn, 1994), sprites (Cavanagh, 1996), or object tokens (Kanwisher, 1987; Kanwisher & Driver, 1992), which maintain "the identity and continuity of an object perceived in a particular episode" (Kahneman & Treisman, 1984, p. 54). By linking visual type information (e.g., a car) with episodic spatiotemporal information (e.g., that particular thing racing down the road), object tokens allow the viewer to track objects over discontinuities in the visual input even as they move about or change over time. The viewer can also perceive multiple tokens of the same object by having separate object files each linked to the same object type but registered with different location information (Kanwisher, 1987).

A wide variety of visual phenomena reported in the literature have been successfully interpreted within the object token framework. The first considered here is an effect known as repetition blindness (RB). This was termed by Kanwisher (1987) and refers to the impairment in detecting or reporting repetitions of visually presented stimuli such as words, alphanumeric characters, or pictures. RB has typically been shown using rapid serial visual presentation (RSVP), in which a sequence of items is presented within the same spatial locus at a high presentation rate (8 to 12 items/s). For example, when subjects were presented with the RSVP sentence "It was work time so work had to get done," many would report, "It was work time so had to get done," omitting the second occurrence of the word "work" in the immediate verbal recall (Kanwisher, 1987). This RB deficit for repeated items is always measured in comparison to performance for unrepeated items, and has typically been shown for repeated events separated by one or two items (stimulus onset asynchrony, or SOA, of 200 to 300 ms). RB is not restricted to RSVP displays, having also been demonstrated for repeated stimuli appearing in simultaneous spatial arrays (Bjork & Murray, 1977; Egeth & Santee, 1981; Kanwisher, 1991; Kanwisher, Driver, & Machado, 1995; Luo & Caramazza, 1996; Mozer, 1989). RB does not appear to reflect a general reluctance or failure to report or recall repeated items (cf. the Ranschburg effect) because the effect disappears for events separated by more than 500 ms (the RB lag effect; Chun, in press; Kanwisher, 1987; Park & Kanwisher, 1994), or when the presentation rate is slowed (Kanwisher, 1987).

Thus, RB appears to occur at a perceptual stage of processing (Kanwisher, 1987; see also Hochhaus & Johnston, 1996), rather than during storage or retrieval. Kanwisher proposed that the phenomenon of RB supports a distinction between visual types and episodic tokens. Types are generic representations of a given object kind that become activated whenever the corresponding stimulus is present anywhere in the visual input. In addition, an activated type needs to be linked with an appropriate token (object file) that represents the item's episodic properties, such as spatial position or temporal order. This process of binding types to tokens is referred to as token individuation (or object file instantiation). RB occurs when the second occurrence of a repeated type is not individuated with a separate episodic token. The result is that the percept of the second occurrence becomes assimilated into that of the first occurrence. In other words, RB represents a failure to individuate two instances of a repeated item as two distinct perceptual objects or events.

A similar conceptual account has been applied to understanding apparent motion. Under appropriate spatiotemporal conditions, two discrete visual events are linked as a single object seen in motion (Anstis, 1980; Ternus, 1926/1938; Wertheimer, 1912/1961). The two events are interpreted as different states in the history of a single moving object, instead of being seen as two distinct objects. When conditions are not appropriate for apparent motion, the two events are perceived as two separate objects—two tokens are created instead of one.

In both apparent motion and RB, therefore, two events are perceived as one. Are the object tokens that subserve the percept of apparent motion related to the object tokens mediating RSVP? Despite the superficial similarities, intuition suggests that the two phenomena are qualitatively different. RB is highly dependent on the

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identity (visual types) of the critical items.[1] In contrast, apparent motion is often indifferent to large changes in figural identity. Dependence on figural identity can be shown in apparent motion only for carefully controlled stimuli (Green, 1986, 1989), whereas RB is robust for stimuli (e.g., letters) that do not trigger apparent motion correspondence (Navon, 1976).

Despite these differences, the goal of this study was to examine the relations between the two forms of tokens. If the two are linked, RB may be interpreted as a consequence of the general process that the visual system uses to assign tokens to spatiotemporally separated events. In other words, RB may reflect a bias in the visual system to minimize token creation whenever type information allows it to (Kanwisher, 1986). This bias would predispose the visual system to link two spatiotemporally distinct (but close) events as two views of a single moving object (allowing for apparent motion), and the same bias would produce RB.

Yet perceiving apparent motion and reporting a sequence or array of briefly flashed letter stimuli are clearly two different tasks. How can the two paradigms be linked? We explored RSVP streams that moved across the display rather than staying in one location. The observers' task in the main conditions was to report two target letters from this sequence. We positioned two streams of letters beside each other so that the two critical target letters would either be adjacent within one stream or identically placed in space and time but falling in separate streams. The grouping of the critical letters into one stream or two was controlled by the pattern of letters preceding and following the critical pair. We employed a bistable quartet sequence that typically produces a percept of either horizontal or vertical apparent motion (see Figs. 1a and 1b). As illustrated in Figure 1c, when this square matrix of stimuli is embedded within two parallel rows or columns of streaming items passing each other, perceived motion within the quartet is biased along the direction of the extended trajectory (Ramachandran & Anstis, 1986). In the present experiment, we presented two letter targets among digit nontargets within a bistable quartet sequence at the center of the display. By varying the context in which the bistable quartet appeared, we could manipulate whether targets appeared within or across motion streams. We compared performance on repeated letters and unrepeated letters; the difference provided a measure of RB.

In summary, our goal was to demonstrate a functional link between motion tokens and RB tokens. Apparent motion tokens were used to link a sequence of alphanumeric characters, producing a percept of an object changing its shape as it moved across the screen. RB represents a failure to individuate repeated component states (letters), and token individuation should be more difficult within objects, defined in this study by apparent motion. The empirical question was simple: Would RB be more likely to occur for two letters in the same apparent motion stream (object) than for two letters in different streams (objects)? Alternative theories for RB do not predict object-specific effects. Thus, RB would not be affected by our apparent motion manipulations if RB reflects some general reduction in detectability for repeated items due to refractoriness in early visual recognition, or if it reflects a selective bias against retrieving repeated items at a later stage of processing. However, stream-specific effects on RB would be found if the tokens hypothesized to underlie RB and apparent motion are tightly related. Repeated items appearing within a single moving object would be harder to detect than items repeated across two different moving objects.

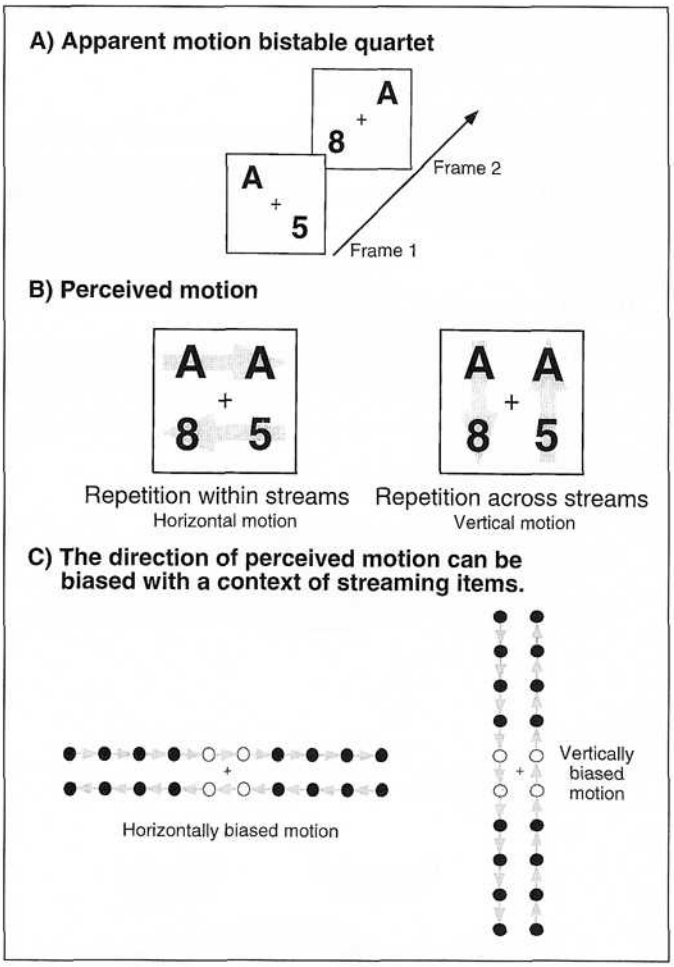

Fig. 1. Illustration of how apparent motion is perceived for bistable quartets. A sample display is shown in (a). Observers fixate at the center. Two stimuli are presented at opposite corners in the first frame, which is followed by two stimuli appearing at different corners in the second frame. The direction of perceived apparent motion is ambiguous; observers are equally likely to see the letters move horizontally or vertically (b). This bistable quartet can be embedded within a row or column configuration of items that stream across the display in opposite directions (c). Because of a preference for seeing linear motion, the perceived direction of the bistable quartet sequence is strongly biased along the direction of the trajectory implied (Ramachandran & Anstis, 1986).

1. Although highly dependent on visual types, RB appears to occur over visual representations abstracted away from the pure low-level visual image. RB has been shown for repeated letters or words that differ in letter case (Bavelier & Potter, 1992; Chun, in press; Egeth & Santee, 1981; Kanwisher, 1987; Marohn & Hochhaus, 1988; Mozer, 1989), and also for pictures that differ in size, orientation, or viewing angle (Kanwisher & Yin, 1993). RB is hypothesized to occur at an intermediate level of visual processing prior to the attainment of higher level conceptual representations. No RB is found for synonym pairs (Kanwisher & Potter, 1990).

METHOD

Subjects

Ten subjects from the Harvard University community participated in this study. All subjects were recruited via sign-up sheets and were paid for their participation. None of the subjects were aware of the purpose of the experiment.

Design

Observers were presented with displays like the one shown in Figure 2. On each trial, the display consisted of two streams consisting of alphanumeric characters moving in opposite directions in apparent motion; only two items (one from each stream) were visible in each time frame. Both streams passed over a central gray patch centered at fixation. Subjects were asked to detect one or two letters appearing among digit distractors within the gray patch as the two streams passed through this patch from opposite directions.

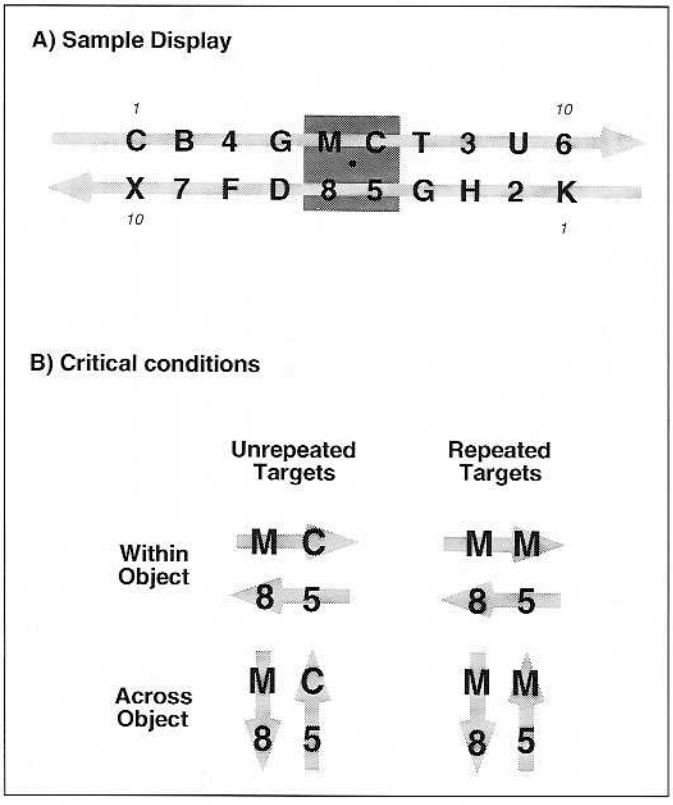

Fig. 2. A sample display (a) and critical conditions (b) from the present experiment. While viewing the display, observers fixated at the center of a gray patch in the middle of the screen. Two sequences of alphanumeric characters were shown using rapid serial visual presentation; the sequences began at opposite sides of the screen, and each streamed toward the other side. (The small numbers above and below the streams specify the time frames, 1 through 10, in which the corresponding letters appeared.) In the experiment, the direction and axes of motion, as well as the positions in which the letter targets appeared, were entirely counterbalanced. These two streams passed over the gray patch, which corresponds to a bistable quartet appearing at Time Frames 5 and 6. Either one or two letter targets were presented among digit distractors within the bistable quartet sequence. Observers were instructed to report any letters they saw passing over the gray patch. As shown in (b), the letter targets to be reported could be either repeated or unrepeated, and they were presented either within a single apparent motion stream or across two different apparent motion streams.

The four items presented within the gray patch always corresponded to Time Frames 5 and 6. Note that this sequence presented in isolation forms a bistable quartet for which the perceived direction of apparent motion is unstable and ambiguous, oscillating between horizontal and vertical motion percepts. Embedding this quartet within a row or column trajectory of items biases perceived motion along either the horizontal or the vertical direction. Thus, observers perceived two linear streams of items moving in opposite directions along either the horizontal or the vertical axis.

The quartet configuration of stimuli appearing at Time Frames 5 and 6 consisted of intermixed uppercase letters and digits. There were four possible configurations (conditions): In the single-target condition (a), only one target was presented. In the simultaneous condition (b), two letter targets appeared simultaneously within the same time frame. In the within-stream condition (c), the two letter targets appeared sequentially within a single motion stream. In the across-stream condition (d), the two letter targets were presented sequentially across different motion streams. Targets were either unrepeated or repeated, with an equal number of each type assigned to each dual-target condition (b, c, and d). Items could not be repeated in the single-target condition (a). The single-target filler trials were included to discourage guessing, and the simultaneous condition was added as a control to minimize possible biases against guessing repetitions. Little or no RB was predicted in the simultaneous condition because targets could only appear across streams, and the additional temporal simultaneity cue was expected to aid token individuation.

The experiment consisted of 96 trials per configuration condition (single target, simultaneous, within stream, and across stream), with an equal number of unrepeated and repeated targets in each condition (except for the single-target condition). In addition, the trials within each condition were fully counterbalanced for motion axis (horizontal vs. vertical) and motion direction (e.g., for horizontal motion: top object streamed from left to right, bottom object streamed from right to left, and vice versa), as well as the position configurations in which the letter targets could appear within the center quartet display. The experiment consisted of three blocks of 128 trials within which the trials were fully randomized. This design produced a total of 384 trials, with breaks initiated by the computer every 32 trials. Each session lasted approximately 1 hr.

The stimulus set consisted of letter and digit characters, excluding *O, I, 0,* and *1* to avoid confusion. Digits and letters were randomly chosen without replacement for the nontarget positions within the motion sequences.

Procedure

At the beginning of each session, observers were shown a demonstration of the stimulus sequence and then immediately queried whether they perceived a stream of items moving across the screen. All of the observers reported strong apparent motion. Task instructions were given on the screen and also verbally by the experimenter. Thirty-two practice trials were given to familiarize participants with the display and procedures.

The central gray patch was always present in the middle of the computer screen. Observers were instructed to maintain fixation on a black fixation dot at the center of the gray patch. The fixation point blinked briefly, followed by a fixed delay of about 1.5 s, after which the trial commenced with stimuli appearing at each side of the periphery (along either the horizontal or the vertical axis) and streaming toward the opposite side of the screen. Each letter appeared for 120 ms, with no interstimulus interval between items (8.33 events/s). Subjects were instructed to maintain fixation on the center, and to try to detect any letters (one or two embedded among digits) appearing over the central gray patch. Each trial consisted of 10 frames, with Time Frames 5 and 6 corresponding to the quartet sequence appearing at fixation over the gray patch. At the end of each trial, subjects entered their responses into the keyboard, pressing the space bar for any targets missed or not presented. Subjects were emphatically forewarned that target letters could be repeated within a trial and that they should respond separately to each occurrence.

Apparatus

The experiment was run on a Power Macintosh 7100/66 computer with an AppleColor High Resolution RGB monitor. The software used for running the experiments was MacProbe version 1.6.8, developed by Aristometric Computers. The letter stimuli were presented in Helvetica font, point size 24. Viewed from an average distance of 40 cm, the letter stimuli each subtended 0.72° × 0.86° in visual angle. The background was a uniform gray field. The center patch was a lighter gray field. To reduce variability in performance between subjects without changing the spatiotemporal parameters of the display, the contrast of the center gray field was adjusted according to a staircase based on each subject's performance. This contrast was adjusted on-line by the computer to target an average performance level of 75% correct for reporting both unrepeated targets.

RESULTS

The critical comparison is between performance on unrepeated versus repeated targets in both the within- and across-stream conditions. These are schematized in Figure 2b. Figure 3 shows the mean proportion of trials on which both letter targets were accurately reported. A robust RB effect was obtained, as measured by the overall lower level of performance for repeated targets in comparison to unrepeated targets. Moreover, the magnitude of RB was larger when both targets had appeared within a single apparent motion stream than when they had appeared in different streams. An analysis of variance (ANOVA) showed a main effect of repetition, $F(1, 9) = 29.96$, $p < .001$, and stream, $F(1, 9) = 13.00$, $p < .01$. Most important, there was a significant interaction between repetition and stream, $F(1, 9) = 11.01$, $p < .01$, confirming the larger difference between unrepeated- and repeated-target performance (RB) in the within-stream condition. Separate one-way ANOVAs within each condition revealed significant RB in the within-stream condition, $F(1, 9) = 45.28$, $p < .001$, and across-stream condition, $F(1, 9) = 6.28$, $p < .05$.

It is unlikely that the poorer performance for repeated targets in the within-stream condition can be attributed to a general difficulty for detecting letters within a single apparent motion stream because unrepeated-target performance was unaffected by the manipulation of stream ($M = 58\%$ within streams vs. 60% across streams), $F < 1$. Nor

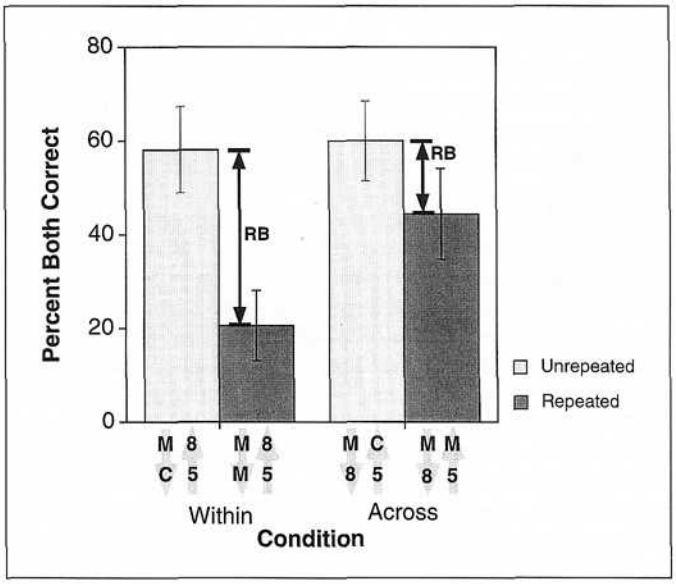

Fig. 3. Mean proportion of trials in which both targets were correctly reported for unrepeated and repeated targets within and across apparent motion streams. A sample stimulus configuration for each condition is schematized on the *x*-axis; in the experiment, the positions in which the letter targets were presented and the direction of motion were fully counterbalanced. In each condition, the difference in performance for unrepeated and repeated targets represents repetition blindness (RB). The error bars represent the standard error of the mean.

does the presence of RB reflect a general tendency against reporting repeated items: As predicted, the control condition in which the two letters appeared simultaneously revealed no difference for repeated targets versus unrepeated targets ($M = 63\%$ vs. 61%, respectively), $F < 1$.

DISCUSSION

In the present study, the perceived grouping of apparent motion influenced the magnitude of RB. Observers had more difficulty reporting two repeated targets if they appeared within a single motion stream than if they were repeated across two different streams. The motion streams were defined by apparent motion, and all within-/across-object manipulations were achieved solely by varying the perceived direction of apparent motion within the critical display, which itself was identical for the within- and across-object conditions.

The observed influence of apparent motion on RB is incompatible with several alternative explanations for RB. One is the type (recognition) refractoriness hypothesis, an alternative perceptual account originally considered and rejected by Kanwisher (1987), and revived recently in a study by Luo and Caramazza (1996). According to the type refractoriness hypothesis, the second repeated item is missed because of refractoriness in type activation, leading to a temporary decrease in sensitivity for reactivation. Other researchers interpret RB as a memory problem or guessing bias rather than as a perceptual phenomenon. Fagot and Pashler (1995) related RB to the Ranschburg effect, which is widely accepted as a memory problem, reflecting the tendency to omit a repeated item from immediate recall more fre-

quently than an unrepeated item (see also Armstrong & Mewhort, 1995). Whittlesea and his colleagues (Whittlesea, Dorken, & Podrouzek, 1995; Whittlesea & Podrouzek, 1995) argued that repeated instances are encoded independently but nondistinctively, and RB occurs because repeated items are not well integrated with their respective contexts (see Downing & Kanwisher, 1995, for a critical commentary).

The present experiment allows us to distinguish among the various models of RB because both the spatial lag and the temporal lag between the two repeated items were held constant in both the across- and within-stream conditions. Type refractoriness, by definition, cannot be specific to each token or instance and should not be sensitive to our object-based perceptual-stream manipulations. Likewise, the memory retrieval requirements were identical in the across- and within-object conditions: Observers were required to report the letters in both cases. So both the type refractoriness hypothesis and the memory retrieval accounts predict no difference in RB between the two conditions. In contrast, we extend the token individuation hypothesis by positing that token individuation should be facilitated for two repeated items appearing within different objects. As predicted, a significant reduction in RB was shown when apparent motion was used to parse the two repeated items into two different object motion streams.

Are apparent motion tokens and RB tokens one and the same? Our results suggest they may be operating at different, but tightly linked, levels of a hierarchical representation of visual events. One is based on the spatiotemporal continuity of the objects themselves, and the other involves the component states forming the chained history of a given object. The former addresses the observation that moving objects are perceived as single entities, which may change shape over time. A viewer can watch a runner in a track event, racing down a lane, jumping over hurdles, and finally dancing with joy after setting a new record. Likewise, the stimuli in the present experiment are perceived as busy, frenetic objects moving across the screen as a stream of ever-changing shapes. The phenomenon of apparent motion links a sequence of states into a single object, distinct in its position and direction. Each such object must be indexed by a token or object file. In the displays we used, the constraint of minimizing the number of tokens assigned at this level leads to the perception of two moving objects rather than multiple flashed letters. Within each object description, separate tokens are needed to individuate the component states of the moving object. Tokens are assigned to states within the stream, and the constraint of minimizing the tokens is more potent for repeated states appearing within a single object than for repetitions across objects in the visual field. This token-minimization constraint leads to greater RB within streams than across.

In conclusion, the present study suggests that the tokens subserving apparent motion and RB are conceptually similar but operate at different levels of a token-assignment hierarchy. We also demonstrate that a token-minimization constraint in the interpretation of visual events can account for both apparent motion and RB within the different levels of this hierarchy. The paradigm we introduce provides astraightforward test to distinguish between various theories of RB, producing results that strongly support the token individuation hypothesis. Because the spatial and temporal parameters of the critical display were entirely constant across conditions, the present paradigm offers a novel tool to explore other object-based effects in visual attention.

Acknowledgments—This research was supported by National Institutes of Health (NIH) National Research Service Award EY06592 to Marvin M. Chun and NIH Grant EY09258 to Patrick Cavanagh. We thank Nancy Kanwisher and Molly Potter for many helpful comments on an earlier version of this manuscript.

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(RECEIVED 10/10/95; ACCEPTED 1/17/96)