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A Temporal Same-Object Advantage in the Tunnel Effect: Facilitated Change Detection for Persisting Objects

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Meaningful visual experience requires computations that identify objects as the same persisting individuals over time, motion, occlusion, and featural change. This article explores these computations in the tunnel effect: When an object moves behind an occluder, and then an object later emerges following a consistent trajectory, observers irresistibly perceive a persisting object, even when the pre- and postocclusion views contrast featurally. This article introduces a new change detection method for quantifying percepts of the tunnel effect. Observers had to detect color changes in displays where several objects oscillated behind occluders and occasionally changed color. Across comparisons with several types of spatiotemporal gaps, as well as manipulations of occlusion versus implosion, performance was better when objects' kinematics gave the impression of a persisting individual. The results reveal a *temporal same-object advantage*: better change detection across temporal scene fragments bound into the same persisting object representations. This suggests that persisting objects are the underlying units of visual memory.

Keywords: tunnel effect, object persistence, change detection, visual working memory, same-object advantage

A key task of visual processing is to transform the undifferentiated collection of features that characterizes our retinal input into the structured array of discrete object representations that characterize our perceptual experience. This challenge represents a paradigmatic type of inverse problem in visual processing. In the case of depth perception, for example, three-dimensional relationships exist in the world itself, but these are then collapsed during optical transmission and must be cleverly and laboriously reconstructed (Marr, 1982). The same problem characterizes our perception of objects: the world itself is divided into discrete independent entities, but these divisions are erased during optical transmission such that the visual system must then reparse undifferentiated scenes into their component objects.

These object representations then serve as the underlying currency for later cognitive processes. One such process is visual attention. Traditional models assumed that attention was fundamentally spatial in nature, selecting spatial areas of the visual field in the manner of a spotlight or a zoom lens (for a review, see Cave & Bichot, 1999). More recent models, in contrast, have demonstrated that in many cases the underlying units of attention are discrete objects such that selection is automatically constrained by object boundaries and may automatically encompass all of an object's visual features (for a review, see Scholl, 2001a). Similarly, recent work has shown that objects may serve as the underlying units of visual working memory. In one well-known recent experiment, for example, limits on visual working memory were found to be object-based: the task of remembering some features of simple objects (e.g., their colors) appeared to allow for recall of those objects' other traits (e.g., their orientations) with no additional cost (Luck & Vogel, 1997; cf. Alvarez & Cavanagh, 2004; Olson & Jiang, 2002; Vogel, Woodman, & Luck, 2001; Wheeler & Treisman, 2002; Xu, 2002).

This previous research has shown that discrete objects with bound features serve as units of attention and memory. Our goal in this article is to expand our conception of what it means to be an object, to encompass dynamic object persistence across time, motion, and periods of occlusion. In this way, we demonstrate that the spatiotemporal factors that constrain persisting object representations also constrain the encoding and maintenance of information in visual working memory. As a part of this project, we show that visual working memory advantages hold not only across the individual features of static objects, but also for the changing features of objects over time and motion.

Object Persistence and the Challenge of Spatiotemporal Visual Integration

In some visual phenomena, persisting objects are inferred despite a lack of direct evidence. Perhaps the clearest example of this is apparent motion, wherein the visual system interprets two flashes (one at location A, the other at B) as a single object that moved from A to B (e.g., Kolers, 1964). In other phenomena, however, the opposite situation obtains: the visual system is pre-

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sented with overt disruptions of visual input, through which continuity must be maintained. This type of challenge, involving incomplete visual input, has long been recognized and studied in the context of static object representations in such phenomena as amodal completion, wherein the visual system must cope with occlusion. In familiar demonstrations such as Figure 1a, for example (e.g., Kanizsa, 1979; Michotte, Thinès, & Crabbé, 1964/1991), we readily perceive one rectangle sitting atop another complete rectangle—although the incoming visual input does not specify this explicitly. This representation of a complete but occluded rectangle may not even exist at the earliest stages of visual processing, but must be constructed over time (cf. Rauschenberger & Yantis, 2001).

Nearly all of this work involves the completion of a single object in a static display with regions or parts that are spatially separated by additional occluding objects. Very little work, by comparison, has investigated how a similar end is achieved when an entire object becomes occluded for a moment in time (cf. Assad & Maunsell, 1995; Scholl & Pylyshyn, 1999; Yantis, 1995). That is, how does the visual system conjoin images that are *temporally* separated by an occluder, recognizing whether those images constitute distinct objects or stages of the same persisting object? Consider the case of a toy train that passes through a small tunnel (Figure 1b). On what basis does the visual system represent the images of the train before entering the tunnel and after emerging as two separate instances of the same enduring train?

Of course, we automatically see the train as persisting in this way, and moreover, there is a sense in which we *see* its motion during the period of occlusion. In fact, however, this is the same sense in which we see an amodally completed rectangle. Just as in that case, this seemingly automatic completion is not given in the input, but must instead be the result of a type of inference in the visual system. This "amodal integration" of temporally disjoint image fragments constitutes a challenging but crucial element of visual processing—one without which our perceptual experience would be incoherent. Perhaps because our visual systems meet this challenge so efficiently and automatically, however, there has been much less research on the basis of object persistence than on aspects of static object completion.

The Tunnel Effect

In this article, we explore dynamic amodal integration in an especially direct way by exploiting a well-known but understudied phenomenon called the "tunnel effect" (Burke, 1952; Michotte et al., 1964/1991) in which one object moves behind an occluder (the "tunnel"), and then a different object emerges from the other side of the occluder and continues moving. If the second object emerges at about the time and place that one would expect the first object to emerge, had it continued its motion, we tend to perceive the uninterrupted and uniform motion of a single object. In other words, we perceive the unobservable motion of the object behind the occluder, and "these 'amodal data' form the bridge between the modal phases and become an integral part of the total sensory experience" (Burke, 1952, p. 121).

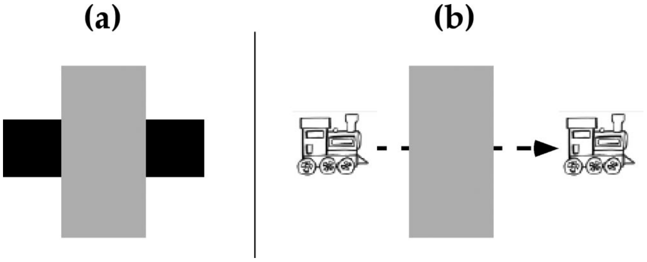

Figure 1. Examples of (a) amodal completion in space and (b) amodal integration in space and time.

Critically, the tunnel effect obtains even when the object emerging from the tunnel differs from the one that entered in terms of its surface features (e.g., turning from red to green; Burke, 1952) and its kind (e.g., turning from a kiwi to a lemon; Flombaum, Kundey, Santos, & Scholl, 2004). In this sense, the tunnel effect illustrates one way in which spatiotemporal information is prioritized relative to surface features in computing object persistence. In this situation, spatiotemporally continuous motion leads the visual system to discount the featural difference between the pre- and posttunnel objects, and thus to generate the percept of a single object (which changes its features while occluded) rather than the percept of two separate objects, one of which was initially hidden by the tunnel. In contrast, when an extra temporal delay is introduced between the occlusion of the first object and the emergence of the second, observers perceive the successive motion of two different objects—the first of which must remain hidden by the tunnel (Burke, 1952).[1]

This effect is not simply an isolated visual illusion, but can end up playing a major role in determining the underlying contents of our perceptual experience—that is, whether we see one or two objects. Without higher-level reasoning about what kinds of transformations are physically possible or likely, the perception of the tunnel effect may play a direct role in driving behavior. This was made especially salient in a recent comparative study exploring free-ranging rhesus macaques' perception of the tunnel effect in a foraging task (Flombaum et al., 2004). Monkeys watched as a lemon rolled down a ramp and came to rest behind a tunnel (Occluder 1) and then as a kiwi emerged and became occluded at the end of its path behind a screen (Occluder 2). When the kiwi emerged at about the time that the lemon should have (had it continued its motion), subjects searched for food only behind Occluder 2—apparently perceiving the lemon transform into a

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[1] This dominance of spatiotemporal information is similar to that observed in apparent motion, where two featurally dissimilar flashes will still be perceived as subsequent stages of a single object as long as they occur in quick enough succession and in nearby locations (e.g., Dawson, 1991). Only when spatiotemporal factors are perfectly balanced can surface features affect the correspondence computed in apparent motion (e.g., Burt & Sperling, 1981; Green & Odom, 1986; Kolers & Pomerantz, 1971; Mack et al., 1989; Schecter et al., 1988). In other situations, effects of shape have been estimated to be up to 15 times weaker than proximity-based effects, and, as a result, many models of apparent motion explicitly ignore surface-feature information (e.g., Burt & Sperling, 1981; Dawson, 1991). Spatiotemporal priority may thus be a general principle of object persistence (Flombaum et al., 2004; Scholl, 2001b) that does not depend on explicit visual interruptions such as occlusion. In contrast to the tunnel effect, however, apparent motion cannot be used to study aspects of object persistence that depend critically on the manner of visual interruption at an occluding boundary, as is explored here.

kiwi on the basis of spatiotemporally continuous motion. (Other control conditions verified that the monkeys did in fact recognize the featural difference.) In contrast, when a brief pause interrupted the occlusion of the lemon and the emergence of the kiwi, monkeys searched for food behind both occluders, apparently perceiving two distinct objects, and assuming (on the basis of the featural difference) that the lemon must have remained in the tunnel. In this way, the tunnel effect directly influenced not only the monkeys' percepts, but also their subsequent spontaneous behaviors.

Spatiotemporal continuity not only trumps featural information in generating the percept of a single object, but the lack of spatiotemporal continuity, as in a temporal delay, will disrupt the percept of a persisting object through occlusion. In the tunnel effect, then, the boundary between spatiotemporally continuous and discontinuous motion appears to demarcate a boundary between the perception of a single and persisting object and the perception of two distinct objects in time and space. For this reason, the tunnel effect can serve as an especially direct and useful tool for understanding both how amodal integration through occlusion is accomplished, and more generally, how the visual system generates the percept of an object as the same enduring individual across time and motion.

A New Change Detection Paradigm: Temporal Same-Object Advantages

The initial demonstrations of the tunnel effect (Burke, 1952; Michotte et al., 1964/1991) were influential largely because of their phenomenological appeal: it really does look like the objects continue to exist (or not) depending on the spatiotemporal parameters. A limitation of Burke and Michotte's work, however, is the use of explicit verbal reports to quantify their observers' percepts. Observers in these experiments, as well as in most recent replications (e.g., Carey & Bassin, 1998; Wilcox & Chapa, 2004), are typically either asked how many objects they saw in a display or are asked to simply describe the display and the objects' motion so that these descriptions can later be sorted in various ways.

Such measures have at least two serious methodological limitations. First, such free descriptions are notoriously susceptible to higher-level response biases, making it difficult to confirm that the results of these experiments reflect what participants *see* in the displays as opposed to what they *believe* about them. In fact, recent debates about certain implementations of the tunnel effect have foundered over just this issue, with different results obtained depending on just how the descriptions are elicited (e.g., Carey & Xu, 2001; Wilcox & Baillargeon, 1998; Wilcox & Chapa, 2004; Xu & Carey, 2000). A second problem is that free descriptions and ratings do not easily allow the tunnel effect to be measured in a quantitatively precise manner, as is crucial for asking more detailed questions about the relative influence of various factors in the perception of persisting objects.

In the present experiments, we develop a new and indirect change detection paradigm that can be used to measure the tunnel effect without directly asking observers about their percepts. We show that this measure is sensitive both to classic effects and to more subtle and novel cues to object persistence. In developing this paradigm, we reasoned that just as the challenge of amodal integration is a dynamic analogue of static amodal completion, perhaps other indirect phenomena of static object-based processing might similarly have dynamic analogues. In particular, we have focused on the idea of a same-object advantage: work with a variety of paradigms has revealed that processing multiple features of a single object is facilitated relative to the processing of the same set of features when they belong to different objects.

This effect is manifested in several ways. One, already described, depends on visual working memory. Observers can better remember two colors when they come from the same object compared to different objects (Luck & Vogel, 1997; Vogel et al., 2001), although this effect may be limited to only specialized situations (Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002). Similarly, subjects in cueing tasks can more quickly detect a target if it appears within the same object, but in a different location from a brief cue, compared to when the cue appears the same distance from the target, but within the boundaries of a different object (Egly, Driver, & Rafal, 1994). More generally, subjects are better at reporting two features of a single object, compared to one feature from each of two objects, even when the two probes in each case are spatially equidistant (e.g., Duncan, 1984; Marino & Scholl, 2005; Watson & Kramer, 1999). All of these cases illustrate same-object advantages, wherein processing within a single object is facilitated relative to equated processing that must span two different objects.[2]

Here we ask whether *temporal* same-object advantages also exist, yielding a processing advantage for successive stages over time of a single object compared to encounters with distinct objects. Consider the tunnel effect in this context. A green disk passes behind an occluder, and a red disk emerges. On the basis of spatiotemporal continuity, we perceive the motion of a single object that has changed its features. In contrast, other manipulations will cause us to perceive two different objects with different features. Therefore, processing the red and green colors when we perceive a single persisting disk may be facilitated relative to the processing of these same color features under highly similar conditions that lead us to perceive two distinct objects.

We explored these predictions using a change detection paradigm. Participants watched displays that consisted of many small oscillating events (see Figure 2). In each event, an object emerged from behind an occluder, traveled a short distance, and then reversed direction and headed back behind the occluder. An identical object then underwent the same motion on the other side of the occluder, and this entire event cycled continuously during each trial. In some conditions, the displays supported the perception of a single object, so that each event is perceived as a single object

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[2] In some cases, such effects may be more accurately (if less naturally) described as "multiple-object disadvantages" (Baylis & Driver, 1993; Lamy & Egeth, 2002; Marino & Scholl, 2005). That is, in some cases, the difference between same-object and different-object conditions may in fact be caused by the extra necessity and difficulty of disengaging from one object representation to the selection of another, rather than any facilitation per se (e.g., via the automatic spread of attention along an object's contours). Moreover, with static stimuli, the presence of such effects depends on the nature of the task, and in other situations, the same comparisons can yield "same-object disadvantages" (e.g., Davis et al., 2000; Davis & Holmes, 2005). Because our results and interpretations are not affected by these subtleties, we will simply continue to use the term "same-object advantage" throughout this article, remaining agnostic on just how this difference is to be explained.

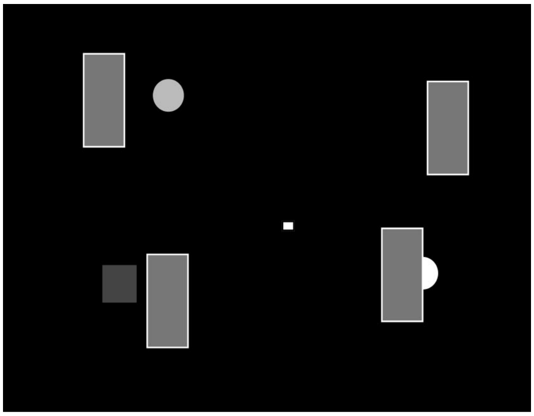

Figure 2. A static snapshot (not to scale) of a sample display in Experiment 1. Trials included several dynamic events. In each, an object emerged from behind an occluder, traveled a short distance, and then reversed direction and headed back behind the occluder, after which an identical object underwent the same motion on the other side of the occluder. These events cycled continuously during a trial. In the actual experiment, all occluders were gray, and all objects were brightly colored. Readers can view dynamic animations of the conditions from each experiment online at http://www.yale.edu/perception/tunnel/.

oscillating back and forth behind an occluder. Other conditions did not support object persistence so that each event is seen to contain two separate objects, although only one is visible at any given moment. During the course of a trial, a disoccluding object was occasionally a different color than the object that had become occluded a moment before, and the observers' task was to detect these sporadic color changes.

Although in all cases, the observers' task was simply to detect these pre- and postocclusion changes, we hypothesize that this task will be approached by the observers (and by their visual systems) in different ways across conditions. When the displays support the perception of a single persisting object traveling behind an occluder, this task amounts to comparing a single object's features before and after occlusion. In contrast, in displays that do not give rise to the tunnel effect, this task amounts to comparing the features of one object with those of a different object (even though the actual task is identical). Our critical prediction then, inspired by analogous static "same-object advantages," is that change detection will be facilitated under conditions that support the perception of a single enduring object (i.e., those which give rise to the tunnel effect) compared to those which do not.

We begin in Experiment 1 by applying this new paradigm to classical contrasts between spatiotemporally continuous and discontinuous trajectories. In Experiment 2, we then demonstrate that temporal same-object advantages are not simply driven by low-level factors that do not implicate object persistence, by exploring these contrasts with static objects and moving occluders. In Experiments 3 and 4, we manipulate object persistence more directly by contrasting objects that occlude and disocclude with objects that "implode" and "explode." (Readers can view dynamic animations of the conditions from each experiment online at http://www.yale.edu/perception/tunnel/.) We conclude that the underlying units of visual memory are discrete and persisting objects.

Experiment 1: The Tunnel Effect

In this experiment, we begin by verifying that our indirect change detection measure is sensitive to the classical contrasts studied in the original tunnel-effect experiments (Burke, 1952; Michotte et al., 1964), focusing on the contrast between spatiotemporal continuity and spatiotemporal gaps. Participants attempted to detect changes in three different types of events (see Figure 3): (a) *Tunnel events* enjoyed smooth and uninterrupted motion through the occluders (Figure 3a); (b) *Temporal Gap events* were identical except that successive motions in and out of the occluder were delayed by an additional 1 s pause (Figure 3b); and (c) the objects in *Spatial Gap events* still traveled horizontally behind the occluders, but the occlusion and disocclusion positions were vertically separated by a short distance along the occluding boundary (Figure 3c). We know from previous work that spatial and temporal gaps will attenuate the perception of persisting objects (Burke, 1952; Michotte et al., 1964), and so we predict here that change detection should be better for Tunnel events compared to Spatial Gap or Temporal Gap events. In this way, change detection may serve as a continuous, indirect, and quantitatively precise measure of the tunnel effect, obtained without ever asking participants directly about their percepts.

Method

Participants. We tested 26 undergraduates from Yale University. All participants had normal or corrected-to-normal acuity and were either paid $8 or were given a credit toward the completion of a class requirement.

Apparatus and stimuli. The experiments were run on an iMac computer using custom software written in C using the VisionShell graphics libraries (Comtois, 2005). Participants sat approximately 50 cm from the screen, without head restraint, so that the entire display subtended 32.12 × 27.84 degrees of visual angle. The monitor refreshed at 117 Hz, and all motion looked smooth.

Each trial consisted of a display that randomly included three, four, or five dynamic events and a white fixation square (.58 deg^2, located at the display's center), drawn on a black background. Each dynamic event included a solid disk or square (1.392 deg) in one of six available colors (randomly chosen as bright red, green, blue, orange, yellow, or white, with the constraint that no two objects ever simultaneously shared the same color) and a gray rectangular occluder (2.088 × 4.176 deg) with a white border. (We varied the number of events in each display for comparison to other experiments not reported here, but because these data alone did not yield any interesting patterns, we have collapsed the results across set size in all of the experiments reported in this article.) Each object oscillated in a horizontal plane, moving at a random velocity between 6.38 deg/s and 11.6 deg/s (with speeds varied between events but always constant within events). On each cycle, the object moved between 3.944 and 9.164 deg away from the occluding boundary (measured from the object's center) before reversing direction and heading back toward the occluder. The objects' initial positions and directions were randomly chosen from anywhere along these paths, resulting in generally asynchronous motions across events. The gray occluders were positioned at the center of each object's complete trajectory and remained stationary throughout a trial (occluding the shapes as they progressively disappeared behind them on each pass). Events were placed at random positions in the display, with the constraint that no object or occluder from an event could ever come closer than 2.088 deg to an object or occluder in another event (or to the fixation point).

Conditions. Three different event types were presented during each trial: Tunnel events, Temporal Gap events, and Spatial Gap events. At least one event of each type was present in the display during each trial, with the additional event types chosen randomly for trials with set sizes or four or

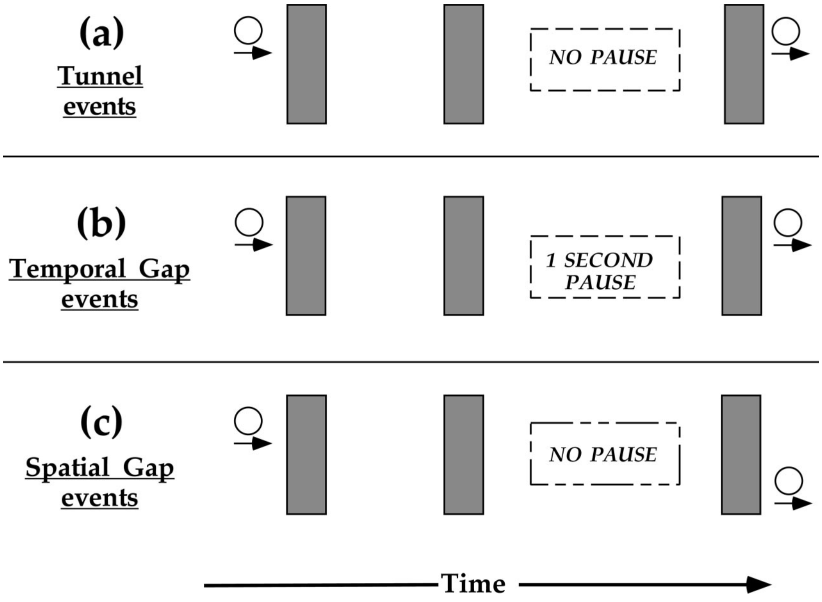

Figure 3. Schematic depictions (not to scale) of the three event types from Experiment 1. In *Tunnel events* (a), objects moved uninterrupted through their occluders. In *Temporal Gap events* (b), objects paused for a complete second upon every instance of occlusion. In *Spatial Gap events* (c), objects were displaced vertically along the occluder's boundary during each instance of occlusion.

five events. The unoccluded portions of each object's motion were identical in all three event types. Each object in a Tunnel event maintained its speed and vertical position throughout each instance of occlusion, thus tracing a spatiotemporally continuous path. (In other words, each object in this condition disappeared in space and time for just that duration and distance required by the occluder.) Each object in a Temporal Gap event moved in the same manner, but paused for 1 second during each instance of occlusion (regardless of its entering speed). This pause was not directly visible to participants because it occurred behind the occluder, and after it was completed, the object continued moving in the same direction and at the same speed with which it had entered the tunnel. The occlusion duration thus varied across events, but in all cases, each object emerged from its tunnel exactly 1 second after it should have, had it continually maintained its speed during the occluded portion of its motion. Each object in a Spatial Gap event moved in the same manner as in the Tunnel events, except that the points of occlusion and disocclusion were vertically separated by 2.784 deg (four object radii), as in Figure 3c. (The initial direction of vertical displacement was randomly chosen, after which the displacements changed direction on each instance of occlusion.) Thus, objects in Temporal Gap events appeared at the right place but the wrong time, while objects in Spatial Gap events appeared at the right time but the wrong place.

Procedure. Each participant completed 100 trials. Participants were instructed to watch the animations carefully, while attempting to fixate (although eye movements were not monitored) and to press a key as quickly as possible whenever they noticed an object emerge from an occluder with a color different from the object that entered that occluder. The instructions did not mention the three different conditions. Each trial lasted 15 seconds, during which between one and four color changes occurred. Color changes took place at randomly selected intervals, separated by a minimum of 2 seconds. On average, a total of 302 changes occurred in a single experimental session, with an average of 4.2 seconds between each change. Keypresses that occurred within 1 second of the first moment of disocclusion were counted as hits. Keypresses that did not follow changes within 1 second were counted as false alarms. All keypresses were accompanied by a tone, but no online feedback was given. This procedure was selected to maximize the unpredictability of when changes would occur, while still allowing enough time between changes so that during the analyses we could separate changes associated with different event types. This prevented us from counterbalancing the number of changes occurring to the various event types, in part, merely because the number of reappearances occurring to Temporal Gap events was, by definition, smaller than the number occurring to the other two event types over the course of a 15-second trial. We were nevertheless able to observe a large enough number of changes for each event type over the course of an experimental session to allow for robust comparisons.

Results

The change detection hit rate for each condition is depicted in Figure 4. Overall performance was low, but was roughly in line with that in previous studies. Previous static change detection studies (e.g., Luck & Vogel, 1997) involved forced-choice responses on each trial, which could then be subjected to signal-detection analyses and calculations of the number of objects that could be effectively monitored on each trial. In contrast, no such analyses are possible here, precisely because of the dynamic continuous character of the displays that is critical to our investigation of persisting object representations: changes occurred haphazardly in each ongoing trial, such that hits and misses could be easily identified, but no criterion for correct rejections could be identified. Even false alarms must remain ambiguous in this design since they cannot be assigned with certainty to any particular event type. (Our events oscillated as quickly as every 500 ms, meaning that any given false alarm occurred within a 1-second response window of many different reappearances from multiple event types.) As a result, our design allowed for performance in all conditions to be compared simply on the basis of hit rate. (This design was inten-

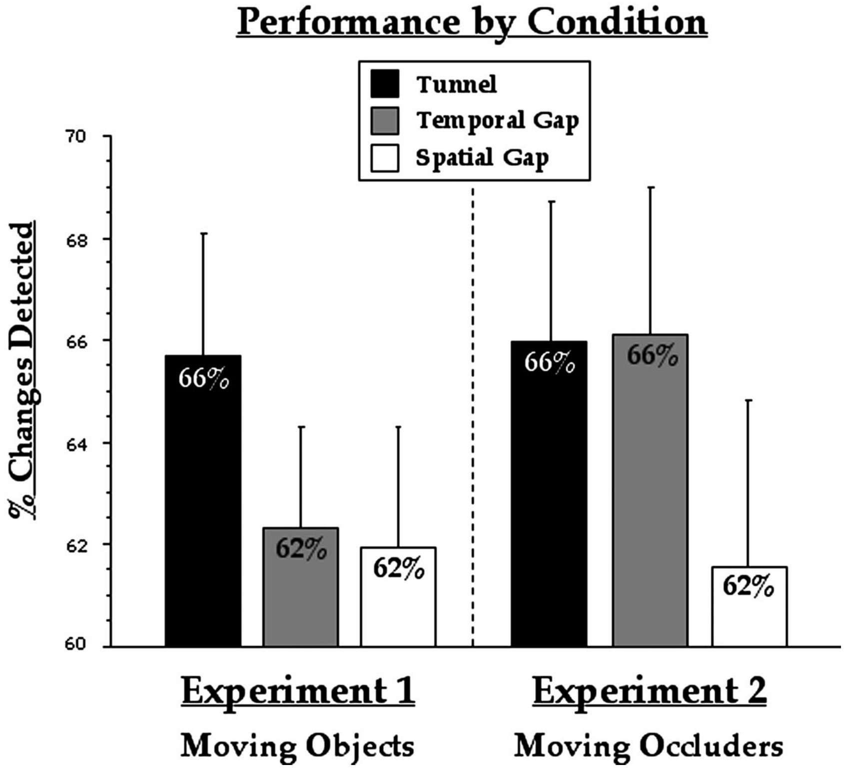

Figure 4 The percentages of changes detected, with standard errors, for Experiments 1 and 2, broken down by condition. In Experiment 1, with moving objects, accuracy was reliably better for Tunnel events compared to either Temporal Gap or Spatial Gap events. In Experiment 2, with moving occluders instead of moving objects, accuracy for Tunnel events was no different from accuracy for Temporal Gap events.

tionally chosen because we are interested in the process of detecting changes to an object as they occur, as opposed to via later inferences. Although this gives rise to some concerns about the role of false alarms, such differences cannot explain our results and are explicitly studied in Experiment 4.).

As is clear from Figure 4, change detection was better in the Tunnel condition than in either the Spatial Gap or Temporal Gap conditions. These impressions were borne out by statistical comparisons as follows. A repeated-measures analysis of variance (ANOVA) revealed a main effect of event type on the percentage of detected changes, $F(2, 25) = 4.200$, $p = .02$, $\eta^2 = .168$. Additional planned comparisons revealed that more changes were detected in Tunnel events than in either Temporal Gap events, $t(25) = 2.100$, $p = .04$, $d = .304$, or Spatial Gap events, $t(25) = 2.670$, $p = .01$, $d = .307$. To ensure that false alarms could not be differentially affecting the hit rates in these conditions, we also conducted the same analyses, now limited to only those changes not preceded by any false alarms. In other words, these analyses excluded all those changes where we know that in the moments immediately preceding an actual change the participant incorrectly believed or guessed that there was a change. These additional analyses revealed a qualitatively similar pattern of results: A repeated-measures ANOVA revealed a main effect of event type on the percentage of changes detected, $F(2, 25) = 5.571$, $p = .006$, $\eta^2 = .221$, and planned comparisons revealed that more changes were detected in Tunnel events than either Temporal Gap events, $t(25) = 2.932$, $p = .007$, $d = .474$, or Spatial Gap events, $t(25) = 2.565$, $p = .017$, $d = .330$.

Discussion

This experiment succeeded in quantifying the tunnel effect for the first time with an indirect and continuous dependent measure. Participants detected more changes when they occurred to objects that traversed spatiotemporally continuous trajectories (in Tunnel events) compared to objects that moved through instances of occlusion to emerge at either the wrong time (in Temporal Gap events) or the wrong place (in Spatial Gap events). In other words, change detection was facilitated for kinematics that, as described by Burke and Michotte (Burke, 1952; Michotte et al., 1964/1991), result in the impression of a single object that persists through occlusion, compared to kinematics that produce the impression of two different objects.

Moreover, through the use of change detection as a dependent measure, these results have implications for the underlying units of visual working memory. In particular, these results suggest that visual working memory is affected not only by how static scenes are parsed into objects, but also by how distinct views of objects are bound together into persisting object representations. Note that the requirements of the change detection task can be completely divorced from the kinematics of the moving objects. For each event, participants simply needed to store and maintain the color that appeared on one side of a gray box and then compare it, moments later, with the color that appeared on the other side of that gray box. These colors were visible for a considerable amount of time (between .68 and 2.9 s, depending on the object's speed and the distance that object traveled away from its occluder, but not an object's motion condition)—on average much longer than the 500 ms durations typically used in many static visual working memory experiments (e.g., Vogel et al., 2001). The durations of complete occlusion were especially brief, at most a little more than 1/10th of a second for Tunnel and Spatial Gap events and only 1.11 seconds at most for Temporal Gap events. Nevertheless, participants detected significantly fewer changes when an object's kinematics suggested that it did not persist behind its occluder. These results reveal a temporal same-object advantage for comparing features that are bound to the same enduring object representation over time and motion, compared to those which are bound to the representations of different objects.

Experiment 2: Moving Occluders

The results of Experiment 1 were interpreted in terms of persisting object representations as the units of visual working memory. To support this view, we now consider one possible deflationary interpretation in which the differences between the previous conditions are accounted for in terms of lower-level psychophysical constraints. Specifically, one might argue that the impairment we observed for change detection with spatial or temporal gaps is simply the consequence of the added difficulty that these manipulations may bring to the task, regardless of any implications for object persistence. For the Temporal Gap events, perhaps the additional duration over which the first color must be stored results in more visual memory decay, and thus impaired performance. Similarly, for the Spatial Gap events, perhaps comparing two colors is simply more difficult when they appear farther apart in space.

This deflationary interpretation appears unlikely because the two gap conditions essentially control for each other. That is, neither purported factor alone, either the greater distance or the longer duration, can by itself explain the results of Experiment 1. Rather, one must appeal to *either* factor, thus involving an independent post hoc explanation for each comparison. Nevertheless, because this type of interpretation is deflationary with regard to object persistence, we have addressed it experimentally in this and the next experiment.

We begin here by addressing the possibility that the Temporal Gap condition can be explained only in terms of duration-based memory decay. We do so by simply repeating Experiment 1 with moving occluders and stationary objects instead of moving objects and stationary occluders, a manipulation that has previously been used to study the role of object motion in feature binding (Saiki, 2003a, 2003b).[3] Using this method results in exactly the same temporal gaps but with different implications for object persistence. In particular, with moving occluders, the temporal gaps were no longer properties of the objects' kinematics, but instead were now properties of the irrelevant occluders. We thus predicted that the same temporal gaps in this experiment should not impair performance relative to Tunnel events because they hold no implications for object persistence. (In contrast, the Spatial Gap events still involve spatial jumps, which must be attributed to the objects themselves. These events were still included here in order to make the experiment as similar as possible to Experiment 1 and to allow for the interpretation of a possible null result with temporal Gap vs. Tunnel events.)

Method

This experiment was identical to Experiment 1 except as noted here. We tested a new group of 25 undergraduates from Yale University. In this experiment, the gray occluders moved back and forth horizontally at the same speeds as the objects in Experiment 1, while the colored objects remained stationary (centered with regard to each occluder's complete trajectory) throughout each trial. The objects progressively disappeared and reappeared whenever the occluders passed over them. The same three conditions from Experiment 1 were employed—Tunnel, Temporal Gap, and Spatial Gap events—involving the same spatial and temporal gap magnitudes, now realized with moving occluders. Temporal gaps were realized by having the occluder pause in its motion. Spatial gaps were realized by having the object displace vertically while occluded. As a result, participants never directly witnessed any motion for the colored objects in this experiment, although vertical motion was implied for the Spatial Gap events.

Results

As is clear from Figure 4, change detection was the same for Tunnel events and Temporal Gap events, although performance was impaired for Spatial Gap events. These impressions were borne out by statistical comparisons as follows. A repeated-measures ANOVA revealed a main effect of event type, $F(2, 24) = 4.71$, $p = .01$, $\eta^2 = .195$. Additional planned comparisons revealed that change detection in Tunnel events was no different from Temporal Gap events, $t(24) = .1$, $p = .92$, $d = .014$, although Spatial Gap events were impaired relative to Tunnel events, $t(24) = 2.400$, $p = .02$. $d = .294$. The lack of any difference between Tunnel and Temporal Gap events persisted when the analysis was limited to changes not preceded by any false alarms; in this situation, even the main effect of event type failed to reach significance for moving occluders, $F(2, 24) = 2.343$, $p = .11$, $\eta^2 = .0952$.

Discussion

The results of this experiment rule out the possibility that change detection is impaired in Temporal Gap events simply because of the added duration of occlusion. The duration of occlusion for both the Temporal Gap and Tunnel events in this experiment were identical to those values used in Experiment 1, but with moving occluders, they did not affect change detection. In other words, merely adding an additional second between the disappearance and reappearance of one of the colored objects does not in itself make the change detection task more difficult. Instead, this manipulation only becomes relevant when the pause must be viewed as a property of a colored object's motion—that is, when it defies one's expectation regarding when the object should complete its trajectory behind an occluder. Spatial gaps, in contrast, were still seen here as properties of the objects themselves, so performance was impaired as in Experiment 1. In the next exper-

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[3] We thank Yaoda Xu for suggesting this manipulation.

iment, we turn to a more direct manipulation of object persistence, also demonstrating that spatiotemporal interruptions alone do not account for the results of Experiment 1.

Experiment 3: Implosion and Explosion

In Experiments 1 and 2, we studied the influence of spatial and temporal interruptions simply because these were the manipulations that were contrasted with the tunnel effect in the original perceptual demonstrations of Burke and Michotte. If this new test of the tunnel effect is a direct measure of object persistence, however, then other cues to persistence should also influence change detection in this context. In this experiment, we explore a very different kind of cue to persistence that does not involve explicit spatiotemporal interruptions.

One reliable cue that the visual system might use to ascertain that an object will persist through occlusion is the fact that an object disappears and reappears in a manner consistent with occlusion—that is, disappearing gradually along a single contour adjacent to the occluder's edge and later reappearing in the reverse fashion. These types of transformations occur in real-world occlusion because of optics and depth relationships, and thus the visual system may be particularly sensitive to such cues. For this reason, we directly manipulated the local manner of disappearance and reappearance of the objects in this experiment. We contrasted normal occlusion (in *Tunnel events*) with a new type of *Implosion/Explosion event*. Objects moved just as in the tunnel events, but when they reached the occluders, they disappeared and reappeared by collapsing upon or expanding from their own centers of gravity rather than by disappearing from only a single edge at the occluder's boundary. This effect was achieved by drawing, at any given moment in time, only that portion of an object that should have remained visible next to the occluder as a smaller version of the same object (see Figure 5).

Critically, the objects in this condition still disappeared and reappeared at exactly the same locations, times, and rates as their Tunnel event counterparts (given each object's speed), but this manipulation does not support the perception of a single persisting object (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Scholl & Pylyshyn, 1999). In a multiple-object tracking paradigm, for example, observers can easily keep track of a number of haphazardly moving targets amid a group of featurally identical haphazardly moving distractors when the objects occlude and disocclude but not when they implode and explode (Scholl & Pylyshyn, 1999). This appears to be due to the fact that the implosion serves as a cue that the object has not merely gone out of sight, but has ceased to exist (Scholl & Feigenson, 2004). We thus predicted that by blocking the perception of a persisting object, Implosion/Explosion events should impair change detection in our task relative to normally occluding and disoccluding objects in Tunnel events.

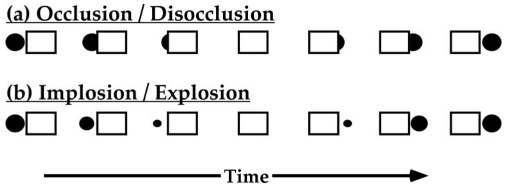

Figure 5 A schematic depiction of the local manner of disappearance and reappearance in the (a) Tunnel events and (b) Implosion/Explosion events of Experiment 3. See text for details.

Method

Participants. We tested 18 undergraduates from Yale University. All participants had normal or corrected-to-normal acuity and were either paid $8 or were given a credit toward the completion of a class requirement. The data from two participants were dropped from the analysis because they made more than 100 false alarms (and in fact had more than twice the mean number of false alarms for the remaining 16 participants).

Apparatus and stimuli. This experiment was run using the same computer and software platform as the previous experiments. Each trial consisted of a display that randomly included four or five dynamic events, a hollow white fixation square (.58 deg^2, located at the display's center), and five distractor objects, all drawn on a black background. Each dynamic event included a solid disk or square (1.276 deg) in one of nine available colors (randomly chosen as blue, green, red, aqua, purple, yellow, pink, orange, or light green, with the constraint that no two objects ever simultaneously shared the same color) and a black rectangular occluder (2.233 × 1.914 deg) with a dim gray border. Each object oscillated in a horizontal plane, moving at a random velocity between 4.143 and 4.833 deg/s (with speeds varied between events but always constant within events). On each cycle, the object moved between 2.712 and 3.988 deg away from the occluding boundary (measured from the object's center) before reversing direction and heading back toward the occluder. The objects' initial positions and directions were randomly chosen from anywhere along these paths, with the constraint that an object could not start out behind its occluder, resulting in generally asynchronous motions across events. The occluders were positioned at the center of each object's complete trajectory and remained stationary throughout a trial. The five distractor objects present in every trial were a random assortment (changed on each trial) of solid disks and squares also measuring 1.276 deg. These could appear in any of the nine colors available for the moving target objects with no constraints on repetition with one another, or with the colors of the target objects. These distractor objects remained stationary throughout a trial, and their colors never changed during a trial. Events and distractor objects were placed at random positions in the display, with the constraint that no object or occluder could ever come closer than 1.914 deg to another object, distractor object, or the fixation point.

Conditions. Each trial contained only one of the two event types: Tunnel events or Implosion/Explosion events. The unoccluded portions of each object's motion were identical for both event types. Objects in *Tunnel events* moved just as in the previous experiments. Objects in *Implosion/Explosion events* similarly appeared and disappeared progressively upon encountering their occluders. Each object appeared and disappeared, however, as a proportional version of the full-sized shape (either a circle or square), with an area that was matched to that of the visible portion of a partially occluding shape that would have been drawn at the same moment in a Tunnel event. In other words, whereas a square that had come into contact with an occluder in a Tunnel event would be drawn as a rectangle (i.e., a partially occluded square), that shape would be drawn at that moment in an Implosion/Explosion event as a smaller square adjacent to the occluding boundary, shrunk in place (see Figure 5).

Procedure. Each participant completed 5 practice trials and 120 experimental trials, split into two 60-trial blocks. One block contained Tunnel events and the other contained Implosion/Explosion events, with block order counterbalanced across subjects. At the start of each trial, the four or five target objects flashed three times (repeatedly disappearing and reappearing for 171 ms) before they began to move back and forth as described previously. The distractor objects did not flash and remained stationary throughout each trial. Participants were instructed to watch the screen carefully while attempting to fixate (although eye movements were not monitored) and to press a key as quickly as possible whenever they noticed an object emerge from an occluder with a color different from the object that entered that occluder. The instructions did not mention the two different conditions. Each trial lasted 10 seconds, during which between 1 and 4 color changes took place. Color changes occurred at randomly selected intervals, separated by a minimum of 1.75 seconds. On average, a total of 302 changes occurred in a single experimental session, with an average of 2.5 seconds between each change. Keypresses that occurred within 750 ms of the first moment of disocclusion were counted as hits. Keypresses that did not follow changes within 750 ms were counted as false alarms. A high-pitched tone accompanied all hits, while a low-pitched tone accompanied all false alarms.

Results

Overall performance in this experiment was slightly lower than in the previous two experiments (see Figure 6). This appears to be due to the fact that this experiment involved only trials with four or five events, whereas the previous experiments also included trials with three events (which, of course, proved easier). As depicted in Figure 6, participants detected a greater percentage of changes in Tunnel events than in Implosion/Explosion events, $t(15) = 2.689$, $p = .017$, $d = .518$. The same pattern of results emerged when we considered only those changes that were not preceded by any false alarms, $t(15) = 2.265$, $p = .04$, $d = .415$.

Discussion

The results of this experiment demonstrate an effect of object persistence on change detection in two ways. First, this experiment serves as an additional control for the interpretation of Experiment 1. Participants were significantly worse at detecting changes to Implosion/Explosion events compared to Tunnel events, although both types of events were characterized by the same spatiotemporal trajectories. In particular, the spatial distances and temporal durations that had to be bridged in the two conditions were always identical in this experiment. This confirms that the effects of the spatial and temporal gaps in Experiment 1 were driven by the implications of these gaps for the underlying persisting object representations and not by their brute psychophysical properties.

Second, these results illustrate the effects of direct manipulations of object persistence that go beyond previous studies in several ways. Perhaps most importantly, the results of this experiment show that object persistence affects visual memory even when computations of persistence may not be necessary. In the previous multiple-object tracking studies that have employed this contrast (Scholl & Feigenson, 2004; Scholl & Pylyshyn, 1999), maintaining persisting representations was in some sense the entire point of the task, and so it is perhaps less surprising that such manipulations of persistence would influence the attempt to maintain persistence under attentional load. In our experiments, in contrast, there is no need to track the objects at all. Whereas the objects in multiple-object tracking paradigm move on complicated unpredictable trajectories, our objects simply oscillate back and forth. In addition, recall that our instructions to observers never made any reference to object persistence: participants simply needed to determine whether an object that disappeared at one place had the same color as an object that appeared a moment later at another (entirely predictable) place. In other words, the maintenance of persisting object representations was not required of our observers in this experiment, and it was not required by the change detection task. Nevertheless, the implosion/explosion manipulation influenced change detection, suggesting that the underlying computations of persistence were in some sense obligatory.

It appears that the manner of an object's disappearance modulates the nature of the underlying object representations that are used by the visual system both for the deployment of attention in tracking, as seen in multiple-object tracking paradigm, and for the storage and maintenance of information in memory, as seen in this experiment.

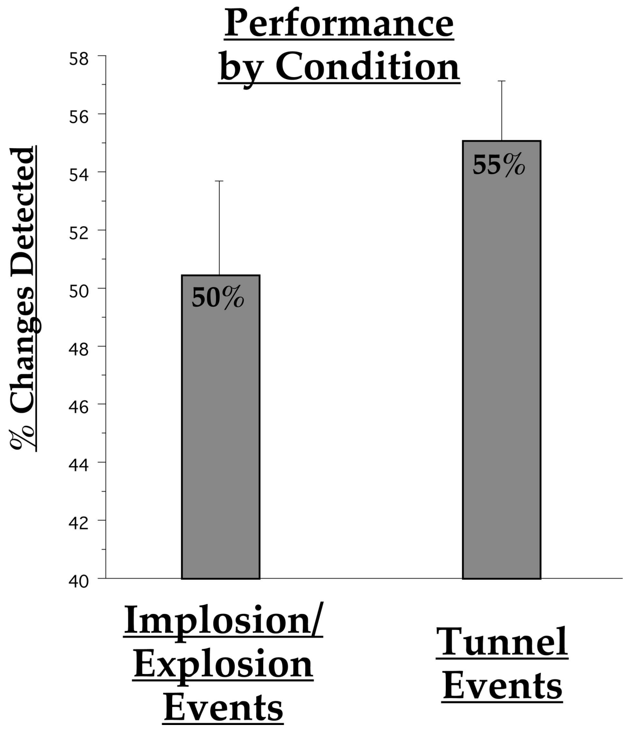

Figure 6 The percentage of changes detected, with standard errors, for Experiment 3. Change detection accuracy was reliably better for tunnel events compared to implosion/explosion events.

Experiment 4: A Signal Detection Measure of the Tunnel Effect

The methods developed in the previous three experiments were designed to emphasize on-line and dynamic change detection, and as such, we forced subjects to detect multiple changes in relatively long trials and to detect these changes at the moments that they took place. This testing system seemed most likely to produce results that would be sensitive to any temporal same-object advantages, as reported previously. These new methods, however, have one conceptual limitation: By including several changes within long trials that involved many local instances of occlusion and disocclusion, it is impossible to correlate a false alarm with a particular instance of dissoclusion, or to relate a participant's overall false alarm rate to his or her overall performance. To avoid exactly this kind of problem, most recent work exploring the units and capacity limits of visual working memory have included catch trials (i.e., in which no changes take place; e.g., Vogel et al., 2001). Results from these experiments can then be analyzed with signal-detection measures of performance that are modulated by guessing rate, such as *d′* and A′ (e.g., Grier, 1971; Pollack & Norman, 1964; Xu, 2002).

As we have just argued, it is unlikely that false alarms contributed to our results, because they were unchanged when we constrained the analyses to only those changes that were not preceded by a false alarm in that trial. Nevertheless, to more directly assess the role of guessing, in this final experiment we modified our new dynamic change detection paradigm so that subjects observed shorter (4 s) trials that included only a single color change in half of the trials and no color changes in the other half of the trials. As in Experiment 3, we compared trials that included only Implosion/Explosion events with trials that included only Tunnel events. Unlike Experiment 3, however, we compared performance for these two conditions in terms of A′ (a measure of subjects' ability to discriminate changes; Grier, 1971), rather than just in terms of their overall hit rate. As in Experiment 3, we predicted impaired performance in this experiment for Implosion/Explosion events compared to Tunnel events.

Method

This experiment was identical to Experiment 3 except as follows:

Participants. We tested 15 undergraduates from Yale University. All participants had normal or corrected-to-normal acuity and were either paid $4 or were given a credit toward the completion of a class requirement. The data from one participant were dropped from the analysis because their overall performance (measured as A′; .63), was more than two standard deviations below the group mean (.76).

Apparatus and stimuli. This experiment included displays with only a single set size, with five dynamic events and three stationary distractors. In addition, objects moved during each cycle from between 1.044 and 2.436 deg away from the occluding boundary (measured from the object's center) before reversing direction and heading back toward the occluder. (This gave rise to more oscillations, which was helpful given the decreased trial durations.)

Procedure. Each participant completed 5 practice trials and 160 experimental trials. The experimental trials consisted of four alternating blocks counterbalanced across subjects each of which included only Tunnel events or Implosion/Explosion events. Participants were instructed to watch the screen carefully while attempting to fixate (although eye movements were not monitored). They were told that some trials would include a single color change that could occur at any time between the beginning and end of a trial, while other trials would include no color changes at all. Each trial lasted 4 seconds, and participants were instructed to make one keypress at the end of the trial if they thought that there had been a color change and another keypress if they judged that no color change took place. A high-pitched tone accompanied correct responses, and a low-pitched tone accompanied incorrect responses. Half of the trials within each block were catch trials that included no color changes, and the other half of the trials included one change each. Color changes occurred at random times in a trial with the constraint that they could occur no sooner than 500 ms from the start of a trial.

Results

To analyze the results of this experiment, we measured participants' performance in terms of A′ (Donaldson, 1993; Grier, 1971; Pollack & Norman, 1964; Xu, 2002). A′ was calculated for each participant for each of the two conditions (Tunnel events and Implosion/Explosion events) with the following formula:

$$A' = .5 + \left[\frac{(H - g)(1 + H - g)}{4H(1 - g)}\right]$$

(Here H, the hit rate, was the participant's average accuracy for change trials, and g, the guessing rate, was 1 minus their average accuracy for catch trials; Grier, 1971.)

As depicted in Figure 7, overall performance was considerably better for Tunnel events compared to Implosion/Explosion events, $t(13) = 2.473$, $p = .028$, $d = .908$.

Discussion

The results of this experiment provide converging evidence with a slightly different paradigm for the temporal same-object advantage that we discovered in the previous experiments. Throughout this article, we have presented our results in terms of both (1) overall change detection and (2) change detection for only those changes that were not preceded by false alarms, due to the concern that differences in false alarm rates to different classes of stimuli could have somehow influenced our results. To bolster such inferences, however, this experiment measured performance via a signal detection method that corrected for guessing. In this way, our results can be more directly analyzed in terms of the broader literature on the units and capacity of visual short-term memory.

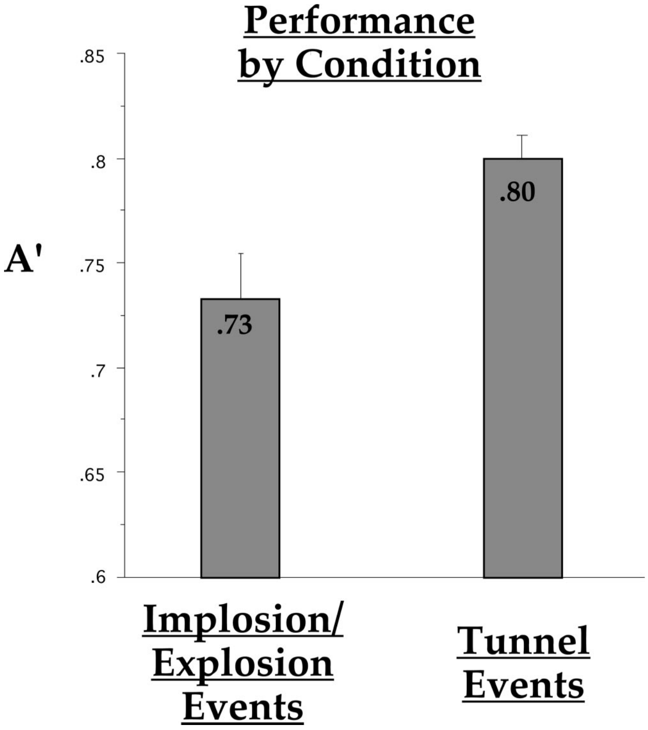

Figure 7 Performance with standard errors for Experiment 4, measured in terms of A′. Performance was reliably better for Tunnel events compared to Implosion/Explosion events.

General Discussion

In the four experiments reported here, observers were able to detect changes made between two temporal scene fragments more readily when these fragments were bound into the same persisting object representation—an effect that constitutes a type of "same-object advantage" in visual working memory for persisting objects. Change detection was reliably impaired by spatial or temporal gaps in the event trajectories (Experiment 1) and by local implosion/explosion transformations (Experiments 3 and 4). These effects were caused by a disruption of object persistence and could not be explained in terms of lower-level psychophysical factors (Experiments 2 and 3) or guessing (Experiment 4). In the remainder of this article, we explore the implications of these results for our understanding of the tunnel effect, same-object advantages, and visual working memory.

Quantifying the Tunnel Effect

We have employed the tunnel effect throughout this study because it seems to be such a direct, titrated, and phenomenologically salient demonstration of object persistence. For far too long, however, studies of the tunnel effect have had to rely on this phenomenological salience alone. To our knowledge, all previous studies of the tunnel effect in human observers have measured only perceptual reports (e.g., Burke, 1952; Carey & Bassin, 1998; Michotte et al., 1964/1991; Wilcox & Chapa, 2004). The change detection method introduced here serves as the first indirect and quantitatively precise measure of the tunnel effect in human observers. This new dependent measure can overcome several limitations of collecting only perceptual reports by attenuating the possibility of response biases and by providing quantitative measurements.

This is more than a minor methodological concern. Ambiguities fueled by perceptual reports have led to substantial confusion and debate regarding the tunnel effect in other contexts. In several recent infant-cognition articles, for example, Teresa Wilcox and her colleagues (e.g., Wilcox, 1999; Wilcox & Baillargeon, 1998; Wilcox & Chapa, 2004) have explored the nature of object individuation using an event involving a moving object that changes features while behind a narrow screen. Critically, this screen is too narrow for two objects to fit behind it, and the longer looking that results from such events is interpreted as reflecting the infants' surprise that a second distinct object appeared from behind the screen where it would not have fit. Other researchers, however, have criticized the logic of this design, suggesting that the longer looking instead reflects the infants' surprise at the single object having suddenly changed its features (e.g., Xu & Carey, 2000; Carey & Xu, 2001). This issue is important because the latter interpretation, the tunnel effect, does not need to involve object individuation at all (without a contrast to other conditions).

In an attempt to test these competing explanations, both groups have tested adults with such displays using verbal reports, but the debate continues: Carey and Bassin (1998; see also Carey & Xu, 2001, pp. 192–193) report evidence favoring the tunnel effect interpretation based on adults' descriptions, whereas Wilcox and Chapa (2004) suggest that these descriptions do not reflect adults' true "two-object" interpretations, which are more clearly reflected in their answers to more focused questions (e.g., "How is the event produced?"). These questions are not the last word, however, because they seem to tap more reasoned interpretations of such displays rather than the initial visual percepts (which might play a causal role in infants' looking behavior). Without taking a position on this debate here, we note simply that, in practice, the verbal reports from the adults in these studies have failed to unambiguously signal *how many* objects they perceived as being involved in the events. The change detection task used in the current study bypasses all of these problems because it measures the *consequences* of the tunnel effect, without asking subjects to reflect on what they saw.[4]

What Causes the Tunnel Effect?

In addition to testing standard controls that have been used to study the tunnel effect in past work (e.g., the spatial and temporal gaps employed in Experiments 1 and 2), we also used manipulations that have more direct implications for why the tunnel effect occurs in the first place. It is natural to see spatial and temporal gaps as manipulations that explicitly disrupt the tunnel effect, but the tunnel effect display itself is often taken as a sort of baseline, in which object persistence will occur by default due to spatiotemporal continuity, barring any interruptions.

In contrast, the results of Experiments 3 and 4 suggest that there are specific and necessary cues involved in the tunnel effect that actively support the perception of a single enduring object. In this experiment, the local manner of disappearance and reappearance at an occluding boundary controlled object persistence. When an object imploded, this served as a cue that the object had gone out of existence, but when the object occluded, this served as a cue that the object had merely gone out of sight. In other words, the local manner of the transformation in the tunnel effect—gradual disappearance along a single contour adjacent to the occluding boundary—actively signals to the visual system that the object continues to persist. This has also been shown to be true in multiple-object tracking, in which it is the nature of the disappearance cue (and not the manner of reappearance) that most directly influences tracking ability. Thus, tracking through occlusion followed by explosion is much easier than tracking through implosion followed by disocclusion (Scholl & Feigenson, 2004). In this way, the present study indicates that the tunnel effect does not merely occur by default when nothing prevents it, but that it is an impression that is actively built by the visual system in response to specific cues.

A Temporal "Same-Object Advantage"

The phenomenon employed in our studies is the tunnel effect, and the dependent measure is change detection, but the actual type

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[4] In this way, our results serve the same goal as the manual-search measure of the tunnel effect introduced by Flombaum et al. (2004) for use with nonhuman primates. Note that these two paradigms—change detection in adults and search in monkeys—are complementary in that neither could be easily used with the other population. Nonhuman primates cannot be readily trained to perform change detection as in the present study, and in any case, the use of manual search was developed precisely in order to measure spontaneous representations and percepts. Manual search, however, could not be used with human adult observers precisely because of its explicit nature: adults will simply search in all of the places where they *believe* objects to exist, regardless of where they may *see* objects move.

of effect which gives rise to our results is a "same-object advantage." Same-object advantages have proven influential in the study of visual cognition where they have served as perhaps the most influential demonstration that discrete objects are the underlying units of both visual attention (e.g., Egly et al., 1994; Marino & Scholl, 2005; Watson & Kramer, 1999) and visual short-term memory (e.g., Luck & Vogel, 1997; Vogel et al., 2001). There has remained some ambiguity, however, about just what it means to be an object in a same-"object" advantage. In one sense, this term turns out to be too strong, because such effects can also be observed using stimuli that do not involve full-fledged "objects" (Ben-Shahar, Scholl, & Zucker, 2003; Marino & Scholl, 2005). In another sense, that is especially relevant here, however, the typical notion of objecthood that has been employed in such demonstrations is too weak. As has been especially well characterized in discussions of objecthood in infant cognition (e.g., Mitroff, Scholl, & Wynn, 2004, 2005; Spelke, 2000, 2003; see also Moore & Enns, 2004), an inherent part of our conception of objecthood is that objects *persist* as the same individuals over time. Previous work with same-object advantages, however, has always been limited to static stimuli (or has employed motion in a very different way, for example, by using many dots that stream continuously through a single patch—itself treated as the relevant "object," and which never itself moves (e.g., Valdes-Sosa, Cobo, & Pinilla, 1998). Our study, in contrast, demonstrates a same-object advantage for persisting objects over time, motion, and through periods of visual disruption.

In our experiments, participants detected more color changes when they occurred to objects that were seen to persist through occlusion. Our interpretation of this result rests on the assumption that changes made to persisting objects will be more salient, because one color must be replaced by another in the very same representation in short-term memory. In contrast, when a color change occurs between two temporal fragments of the world that are not bound into the same object representation, there is presumably no *replacement* at all: A representation of one object (containing one color) simply decays, and then a *new* representation (for the new object) is constructed, which may contain a new color. In other words, we think that the change detection advantage for persisting objects occurs because at the level of the underlying representations, they are really coded as changes, whereas "changes" in events involving spatiotemporal gaps or implosion are not already represented in the mind as changes. Instead, they require an extra, overt process of comparison. It is thus the object-representations themselves that appear to be the limiting currency in detecting these feature changes, which is why we describe these phenomena in terms of a same-object advantage.

There is perhaps one alternate way of interpreting these results, however, which does not demand an appeal to object persistence. According to this "anomaly detector" view,[5] subjects are simply good at detecting any sorts of anomalies—whether they are color changes or trajectory violations—but they remain poor at determining what kind of anomaly they have seen. Thus, subjects may be less accurate at detecting changes in the "odd" cases involving spatiotemporal gaps and implosion simply because those events themselves seem somehow odd, and their oddity is confused with the color changes they are being asked to detect. This interpretation strikes us as unlikely for several reasons. First, there is to our knowledge no independent evidence for the existence of this type of "anomaly detection," which would make it a post hoc invention for this study. Second, we actually doubt that the spatiotemporal gaps and implosion events are seen as especially odd or anomalous in our experiments, simply because they occur with such regularity in crowded displays. (If this were true, subjects would have been continuously struck by oddity every second or so, throughout the entire 40-min session.) Third, even if these events were seen as anomalous, it strikes us as unlikely that a spatiotemporal event such as an imploding object could be mistaken for a surface feature such as a color. (These types of features seem like irreconcilable "apples and oranges.") Fourth, in contrast, the appeal to object persistence and same-object advantages has a tremendous amount of independent motivation. Finally, our appeal to object persistence is also able to naturally explain other results with the tunnel effect (such as the searching behavior of rhesus monkeys, as discussed previously), which cannot be explained by any type of anomaly detection.

Overall, our results do more than extend the notion of a same-object advantage to dynamic stimuli (although that can also be important; cf. Flombaum & Scholl, 2005): they also illustrate how the categorical nature of the motion (as cueing persistence or not) can play a decisive role in determining whether a same-object advantage will obtain. Thus, a temporal component must figure into any theory of how and when same-object advantages arise. Although this is perhaps not normally how we think of "objects" (perhaps because of the far greater amount of work that uses static stimuli), we suggest that objects should always be thought of in this way: Part of what it means to be a visual object is to maintain the same identity over time.

The Units of Visual Working Memory

Because our experiments employed change detection in order to measure object persistence in the tunnel effect, our results also have implications for the nature of visual working memory. Change detection, after all, is often treated as a direct probe of visual working memory in which a stored representation must be compared with the current state of the world (cf. Luck & Vogel, 1997; Mitroff, Simons, & Levin, 2004). Note, however, that some important differences distinguish the methods developed here and those employed in change detection studies that are designed to investigate the phenomenon of "change blindness" (e.g., Rensink, 2002; Simons & Rensink, 2005). In typical change blindness experiments, participants are either alerted to the fact that the display will include a change (but with no knowledge of the kind of change that it will be), or they are not alerted to the fact that there will be any changes in the display at all. In our experiments, however, participants are aware of exactly the kinds of changes that will occur in the display, and they also know the precise moments and locations at which those changes can occur (i.e., only when and where an object is disoccluding). We suspect that this foreknowledge is an important factor in obtaining our results because it means that subjects attempt to remember the colors of objects as they disappear.

For these reasons, we believe that our experiments have more in common with sequential change detection paradigms wherein sub-

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[5] We thank an anonymous reviewer for raising this alternative.

jects are similarly alerted to the kinds of changes that may occur between clearly defined memory and test displays (e.g., Luck & Vogel, 1997; Vogel et al., 2001). Previous change detection studies of this variety have been used to argue that the underlying units of visual memory are discrete objects rather than unbound features (e.g., Luck & Vogel, 1997; Vogel et al., 2001). Our results support this view, with the added implication that these object representations are not static "snapshots" of bound features, but can endure over time, motion, visual disruption, and featural change. The units of visual working memory, in other words, are *persisting* representations. Previous work on object-based visual working memory has involved some controversy about just how the capacity limits are determined (e.g., in terms of unbound features, bound features, or information content; see Alvarez & Cavanagh, 2004; Saiki, 2003a, 2003b; Wheeler & Treisman, 2002), but this debate does not really affect the implications of the present results. In this context, rather than focusing on the factors that mediate the capacity limits of visual memory, our experiments illustrate several factors that influence the maintenance and destruction of these memories in the first place. Visual working memory might have a limit of roughly four objects, but any individual token memory is more likely to be discarded if the relevant object "implodes."

Conclusions: Persistence and Visual Cognition

By measuring the consequences of the tunnel effect for visual memory using change detection, we have shown that the tunnel effect reflects actual rules and assumptions that are used in visual processing, and which then have consequences for other aspects of cognition. Performance in this task reflects the difference between perceiving a single object or two distinct objects, despite the fact that the task itself was completely orthogonal to the number of objects in each event. Subjects in our experiments merely needed to decide when they saw a new color on the screen, not when they saw a new object. That object persistence still plays a role in this context is a testament to the real consequences of the tunnel effect for other aspects of cognition such as visual memory.

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