OBJECT-SPECIFIC PRIMING BENEFIT ENHANCED DURING EXPLICIT MULTIPLE OBJECT TRACKING

by

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ABSTRACT OF THE THESIS

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The referential link between an external object and its corresponding mental representation has yet to be clearly defined. Visual indexes are primitive mechanisms that act as pointers to objects in a visual scene and can be linked to descriptive mental representations. These representations, or “object files”, have been demonstrated by object-specific preview benefits (OSPB), where a priming effect for object identity travels with the object in which information initially appeared. The present study explores OPSB effects during Multiple Object Tracking (MOT) to investigate the formation of object representations in a dynamic environment. All experiments reported used the MOT framework, where four identical circles moved unpredictably and independently on a computer screen. In Experiment 1, either one or two preview letters appeared briefly inside the circles during movement. At the end of the trial, one test letter appeared inside a circle and observers indicated whether or not the test letter matched any of the preview letters. Inter-stimulus intervals (ISI) between the preview and test letters varied at one, two, and four seconds (no tracking was required). Reaction times in the "same-object/same-letter" condition showed significant OSPB effects in both single and dual preview versions, but only during the one-second ISI. This suggests an automatic construction of object files that decay over time. To explore OSPB effects when attention is deployed during tracking, Experiment 2 required observers to track and identify the two objects that displayed preview letters prior to object movement (creating constant four-second ISIs). There was no OSPB effect in the non-tracking condition, which replicated the four-second ISI results in Experiment 1, but there was a significant OSPB effect in the explicit tracking condition. Experiment 3 further tested this effect by using novel symbols from an ancient alphabet (otherwise, the design was identical to Experiment 2). Again, a significant OSPB effect was observed only in the tracking condition. Taken together, these results suggest that feature binding to indexes occurs automatically, but attention is required to extend the persistence of these object representations. Such findings can inform models of referential links between external objects and mental representations.

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Introduction

Although mental representations are a primary component of cognition, little is known about the mechanism which connects a mental representation to a perceived object. To date, the philosophical literature has produced volumes of speculations about the referential link between the external world and our mental representations (Fodor & Pylyshyn, 1981; Frege, 1892; Grice, 1965; Noe, 2002; Perry, 1977; Pylyshyn, 2007; Quine, 1960). Of these theories, indexicals provide the most compelling framework for a solution to this reference problem (Perry, 1997). An indexical is a simple context-dependent linguistic "pointer" to objects that allows us to refer to *this* book or *that* cat. Without such a direct reference, it would be impossible to maintain object identity and to recognize an object in our environment. Indeed, an agent must have a causal reference to distinct items in the world for planning behavior and interacting with its surroundings. Therefore, an important research project in cognitive psychology is to explain how the brain creates and maintains a reference to external objects so that a pointer can be attached to detailed mental representations.

The goal of the current study is to explore the production of indexicals in the visual system by linking two theoretical frameworks: Visual Indexing and Object File theories. Taken together, these two theories provide a possible roadmap to solve the reference problem through their descriptions of early visual processes. Visual Indexing Theory provides an account for a primitive mechanism that simply locates and sticks to individual objects in a visual scene—a type of indexical that points to an external object. Object File Theory presents an account of how detailed object representations are formed by the binding of featural information. Together, these theories describe the initial formation of descriptive mental representations from the information received by the visual system.

Core to both these theories is the mechanism of attention and its various forms. Work on visual attention has uncovered much about the manner in which percepts are processed into meaningful higher-level representations. In particular, a deliberate and selective attention plays a crucial role in the construction of persisting object representations by allowing features from a visual scene to build a coherent representation incrementally (Treisman, 1998). Not surprisingly, attention has been a central focus of research that aims to understand perception and the nature of higher-level human cognition.

There are several forms of attention that are activated at different stages during cognition (Kastner & Ungerleider, 2000; Posner, 2004; Scholl, 2001; Theeuwes, Kramer, & Atchley, 2001). For example, Treisman describes three types of situation-specific attention: rapid preattention, global attention, and focused attention (Treisman, 2006). Rapid preattention occurs bottom-up and automatically in early visual processing and accounts for rapid enumeration mechanisms such as subitizing (Trick & Pylyshyn, 1993). Global attention captures the gist of a scene while top-down processes actively modulate focused attention to facilitate difficult cognitive tasks, such as detecting changes in a scene (Rensink, 2000). Consequently, human attention can be characterized as a combination of automatic bottom-up and controlled top-down processes. So then, how does visual attention process objects within a scene in a meaningful manner?

The biased competition model of attention states that object selection is the result of neural competition between different items in the visual field (Desimone & Duncan, 1995). Bottom-up attentional processes can select visually salient or other local properties for higher-level processing (Donk & Theeuwes, 2003; Itti & Koch, 2001; Theeuwes, 1994, 2004). Typically, the strongest neural response is computed locally and compared relative to other neural activations (Knudsen, 2007). According to a model of Koch (1985), such scene parsing follows a “winner-takes-all” neural process where the most active neural units in the early visual system bring certain feature clusters (e.g., luminance, motion) into a “saliency map”. Feature-saliency maps are context dependent, and saliency judgments rely on the relative contrast within a specific scene (Itti & Koch, 2001). From these feature maps, information can be organized to form a detailed object representation. According to Ullman (1984), top-down “visual routines” execute scene parsing by extracting spatial relations and various properties from the raw input of early visual processing (Ullman, 1984). Such visual routines assist in tracking contours, counting objects, or marking locations. It is believed that before the encoding of properties the visual scene must be parsed through a bottom-up mechanism (Rensink, 2000).

The selection of features can be facilitated by top-down processes that direct attention to a specific region of the visual scene. In this way, task demands (such as searching for a particular feature in a scene) can influence the outcome of bottom-up competition by directing focused attention towards specific information (Laberge et al., 1991). Additionally, top-down processes can override the automatic processes during intentional control of the visual system by suppressing the movement of attention to irrelevant items (Jonides & Yantis, 1988; Leber & Egeth, 2006). Visual working memory also serves the process of attending to information by modulating the competition of information selection at these different levels (e.g., saliency is lower-level, while shape perception is higher-level) and follows the constraints typical of information processing systems (Knudsen, 2007). Increasingly, scientists consider that the combination of bottom-up and top-down processes modulates attention given a specific situation (Connor, Egeth, & Yantis, 2004; Treisman, 2006; Watson & Kramer, 1999). Such interactions produce our subjective experience of focused attention.

Traditional theories of attention hold that the deployment of focused attention is based on the locations of visual items (Posner, Snyder, & Davidson, 1980). This approach uses the "spotlight" analogy where attention is a small area in the visual scene, which can be moved around as needed. This spotlight can also act as a "zoom lens" and focus on details of the scene within the spotlight (Eriksen & Yeh, 1985). However, only the region within this spotlight can be selected for higher-level visual processing under this theory (for a review, see Cave & Bichot, 1999). This account of attention prioritizes spatial properties over featural properties (Liu, Stevens, & Carrasco, 2007) and highlights the role of location in selection processes.

Though location-based attention may explain some of the phenomenology of visual experience, recent studies characterize objects as the elementary units of attentive processing. Objects can be described as inferred organizational units based on the maintenance of their properties over time. Selective attention, including that described by competition models, appears to operate on objects as whole entities and in parallel (Desimone & Duncan, 1995). To this end, an object-based attention model argues that the visual system favors the selection of whole objects in a visual scene as opposed to properties such as location or individual features, and many studies provide substantial support for an object-based theory of attention (Baylis & Driver, 1993; Kahneman, Treisman, & Gibbs, 1992; Treisman & Zhang, 2006; Yantis, 1992; for a review see Scholl, 2001). For example, a brain imaging study observed increased sensitivity to features in a visual object as a whole, even when the task was to notice only one attribute of the stimuli (O'craven, Downing, & Kanwisher, 1999). In addition to the selection of salient items, the inhibition of irrelevant items in the visual scene has been shown to be object-based (Pylyshyn, 2006; Theeuwes & Godljn, 2002; Theeuwes, Van Der Stigchel, & Olivers, 2006). In fact, such inhibition is specific to the irrelevant objects marked for inhibition and does not occur in the empty space near those objects (Pylyshyn, 2006). This evidence supports the notion that object individuation can operate on both task-relevant and task-irrelevant objects. Such studies emphasize the importance of whole-object representations in cognitive processes even though location-based theories of attention continue to be investigated.

Representations of visual objects help us make sense of the world by providing the organizing structure of cognition and attention (Feldman, 2003). In particular, objects provide structures that allow for the binding of features in visual short-term memory, and this binding is largely dependent on attention (Wheeler & Treisman, 2002). Without the ability to identify an individual object and bind its features, an agent could not maintain an object’s identity or recognize it. Basic operations such as procuring food, avoiding predators, or navigating through traffic would be impossible. Therefore, it is necessary for the visual system to employ automatic operations that allow for more complex and meaningful patterns to be interpreted from visual stimuli. Prior to the encoding of features, however, an object must be identified with a place-holder or pointer and parsed from a visual scene as a discrete object (Pylyshyn, 1989). Without establishing an object's identity, features cannot be integrated to form a descriptive representation. The individuation of objects in a visual scene is a fluid and rapid process that is the basis for higher-level cognition.

Object individuation relies on the coherence of visual input that extends over space and time (Feldman & Tremoulet, 2006; Scholl, Pylyshyn, & Feldman, 2001). This is influenced by the spatial relationships among visual stimuli, including geometric factors such as good continuation, symmetry, and parallelism (Feldman, 2007). Both infants and adults are better at keeping track of discrete objects as opposed to identically-shaped but less cohesive substances such as sand or water (e.g. by pouring these substances). Infants in particular have trouble representing non-individuated entities such as sand but nevertheless can distinguish between cohesive and non-cohesive entities (Huntley-Fenner, Carey, & Solimando, 2002; vanMarle & Scholl, 2003). Furthermore, the splitting of an individuated object has been shown to reduce the information available for object representation and supports the importance of object cohesion for the maintenance of object-specific information (Mitroff, Scholl, & Wynn, 2004). The inability to individuate objects in the visual field when dealing with fluid substances highlights the importance of properties such as rigidity and cohesion (that extend over time) to facilitate object individuation.

The individuation of visual objects is the first step in solving the binding problem, which is the problem of how several features can be integrated to form a coherent object representation (Treisman, 1996; for a review, see Wolfe & Cave, 1999). Similar to the “saliency map” proposed by Koch and colleagues (Itti & Koch, 2000; Koch & Ullman, 1985), Treisman proposes a master map for feature integration (Treisman & Gelade, 1980). Here, property-specific mental maps correspond to different types of visual input, and attention can bind these properties together into discrete representations in a “master map”. As visual processing time increases, the number of features bound to an object increases, with 200 ms being sufficient for the grouping of substantial information (Feldman, 2007). Several infant studies provide further support for this type of feature binding into meaningful representations (Carey, 2001; Feigenson & Carey, 2003), but only after a certain developmental stage (Xu & Carey, 1996). Studies on human and non-human primates also have shown that feature binding interacts with object individuation, and this binding relies on the maintenance of individual objects over time (Cheries et al., 2006). The initiation of the object individuation process may not require the encoding of properties, though these properties may later be deemed important to warrant encoding. It is this early processing that is especially important for clarifying the referential connection between external objects and mental representations.

Visual Indexing Theory provides a framework for addressing the reference problem by proposing a data-driven preconceptual connection from discrete objects in the world to their mental representations via an automatic visual indexing mechanism (Feigenson & Carey, 2003; Leslie et al., 1998; Pylyshyn, 1989, 2001; Sathian et al., 1999). Visual indexes, like linguistic indexicals, are pointers to contextual items in a visual scene. These pointers are triggered by certain object properties, such as cohesion or rigidity over time, but the encoding of properties is not required to create these pointers (Pylyshyn, 1989). Once a pointer is assigned, the index can “stick” to and follow an object. The resulting preattentive “proto-objects” are simply identified as *individuals* and tracked by the visual system based on their individuality or “numerical identity” (Xu & Carey, 1996). Attention can then be easily shifted to these indexes depending upon task demands, and this attention can then strengthen feature binding to the indexes. If attention is not directed towards these “tagged” items, a temporal decay of these representations occurs (Yantis & Johnson, 1990).

An experimental paradigm for testing the visual indexing mechanism is the Multiple Object Tracking (MOT) task, where observers track several moving target objects among identical distractors on a computer screen (Pylyshyn, 1988, 2001). Observers can successfully track and identify four or five randomly moving objects under varying conditions, including trials where targets move behind occluders or change in shape and size. The indexing mechanism can maintain a reference or index between the perceiver and these objects simultaneously for extended durations. This mechanism can then be used by focused attention to build higher-level representations by integrating the features of these individuated objects, possibly through a master map of features (Treisman, 1998; Treisman & Gelade, 1980). This feature binding occurs in visual short-term memory, which is limited by the number of objects and the amount of featural information that can be represented (Alvarez & Cavanagh, 2004; Xu & Chun, 2006) and results from the competition of information trying to reach working memory. Ultimately, tracking is an object-based process and relies on the individuation of an object to succeed (Scholl, Pylyshyn, & Feldman, 2001). Figure 1 depicts a typical MOT experiment.

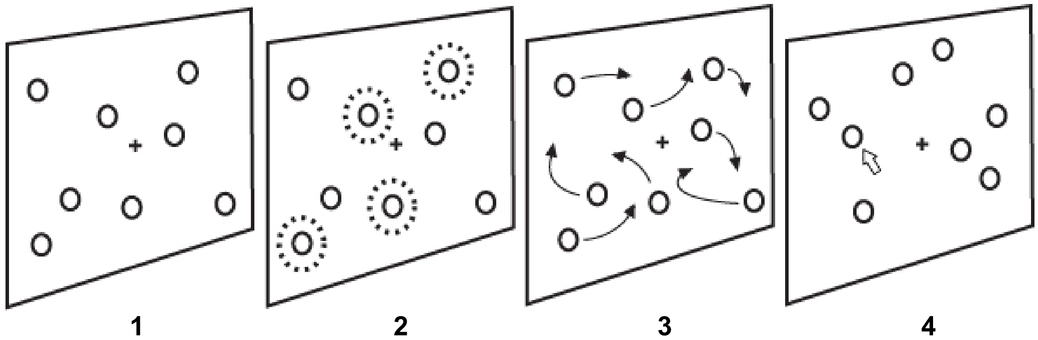

Figure 1. Set-up of typical MOT experiment. Panel 1 shows the initial display of eight objects and a center fixation cross. Panel 2 depicts the flashing of the targets that are to be tracked. Panel 3 depicts the objects moving randomly on the screen. The observers then select the targets in Panel 4.

Visual indexes describe a primitive early mechanism for object selection, but how is a meaningful representation created? Object File Theory provides a possible account for the construction of descriptive object representations that emerge from indexing (Kahneman, Treisman, & Gibbs, 1992). Object files are thought to connect low-level processing and higher-level visual experience and in this sense may be considered extensions of indexes. These mid-level representations provide a structure for the unified integration of object features over extended durations, which rely on spatiotemporal cues (Noles, Scholl, & Mitroff, 2005) and the allocation of selective attention (Treisman, 2006). Not all object files correspond to conscious perception, however, and unknown intermediary processes remain possible (Mitroff & Scholl, 2005). For example, displays with ambiguous object movement may produce the appearance of two objects bouncing off of each other, while they are actually streaming past each other (Mitroff, Scholl, & Wynn, 2005). The conscious experience of this phenomenon often contradicts the psychophysical data, suggesting a disjoint between low-level and high-level processing. In addition, features that have not reached visual attention also can be integrated into object files based on spatiotemporal cues (Melcher & Vidnyanszky, 2006). Therefore, attention does not always include a conscious percept of the features that become part of an object file. Although the exact format of object files remains open for clarification, these object files do provide a useful framework to describe the construction of object representations.

Object File Theory was developed from experiments that showed a preattentive phenomenon called *object-specific preview benefit* (OSPB). One of the seminal experiments describing OSPB used simple objects (e.g., empty squares) and simple preview stimuli (e.g., upper-case English letters) that moved briefly and uniformly across a computer screen (Kahneman, Treisman, & Gibbs, 1992). The two preview letters appeared inside two squares at the start of the trial and disappeared prior to movement. At the end of the movement that lasted up to 1,500 ms, a test letter appeared in one of the objects that was either one of the original preview letters or a new letter. Subjects were instructed to name the test letter as quickly as possible and their reaction time was recorded (see Figure 2). The OSPB effect was an object-based speeded recognition of form and shape in congruent-matching trials (where the same letter appeared in its original object). Speeded responses were not observed when the test letter appeared in the original location that did not have the original object present. This result emphasized the object-specific nature of the preview effect (as opposed to being location-specific). This OSPB became the basis for positing object file representations.

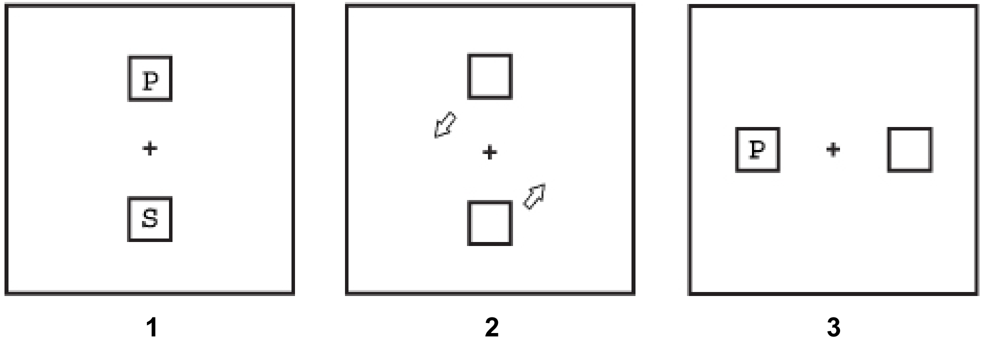

Figure 2. Original preview experiment with motion (Kahneman, Treisman, & Gibbs, 1992). Panel 1 shows original display with preview letters that appeared for either 20 ms or 1 second. Panel 2 depicts the movement of the empty objects that lasted 130 ms or 590 ms. Panel 3 shows the test letter that was to be named (a congruent-matching trial depicted).

A recent study modified the original OSPB experiment and found that the priming benefit, and object files, can persist for eight seconds (Noles, Scholl, & Mitroff, 2005). Instead of naming the letter as in the original study, subjects in this study indicated with a key press whether the test letter matched any of the preview letters. An OSPB was observed for congruent-matching trials as expected. Additionally, this study showed that object file representations can last up to five times longer than previously reported and can persist through several kinds of motion (e.g., oscillating, relative motion). Another recent study showed that object files can be created “after the fact” (e.g., after a brief stimulus display) and insensitive to the cues that define objects, but robust OSPB effects require an individuation of discrete objects (Gao & Scholl, under review). This suggests a link between a low-level indexing mechanism and high-level representations via individuated objects.

Object-based attention requires objects, and object files, as the units of visual attention. From a conceptual perspective, almost anything can be treated as an object, but the visual system has built-in constraints to individuate objects for cognitive processing.

Thus, objecthood is often perceived by top-down processes that are context- or goal-dependent even though the individual units of visual attention are determined in a bottom-up manner. In this way, Visual Indexing Theory and Object File Theory together may describe the connection between perception and cognition through object-based attention. The particular appeal of Visual Indexing Theory is the identification of a primitive causal mechanism that connects visual stimuli and mental representations without necessarily encoding properties. This mechanism is preattentive and does not rely on the higher-level conceptual system of human thought, yet object files and concepts can be attached to these indexes during thought. What remains unclear is how and when the object representations are constructed and the nature of the relationship between visual indexes, object file representations, and attention.

The experiments reported in this paper aim to further our understanding of the construction of object representations by using a combination of the MOT and OSPB experimental frameworks, extending previous work by Kahneman et al. (Kahneman, Treisman, & Gibbs, 1992), Noles et al. (Noles, Scholl, & Mitroff, 2005), and Pylyshyn et al. (Pylyshyn, 2001; Sears & Pylyshyn, 2000). The objective of this project is to address the reference problem by using the visual indexing framework as the underlying structure for higher-level representations, namely object files. Specifically, the current study uses the dynamic and unpredictable MOT display to test for OSPB effects. Since the MOT task uses simple shapes that exploit the qualities of cohesion and continuity, experiments using this paradigm investigate primitive processes in early vision. Therefore, we tested for a preview benefit using implicit and explicit object tracking experiments in order to understand object file construction in early vision. Attention is thought to bind feature information to an object file, but at what point does this feature binding occur? Is this binding automatic and preattentive (i.e., a bottom-up process) or is it the result of a top-down deployment of selective attention?

In a previous experiment, we found evidence for the implicit tracking of objects even when tracking is not required (Haladjian & Pylyshyn, 2006) and other studies have also found an automatic binding of features at short durations (Blaser, Papathomas, & Vidnyanszky, 2005; Hommel & Colzato, 2004). We address the implicit nature of indexing and the construction of object files in Experiment 1 in order to determine when implicit indexing decays and how this might influence the OSPB effect. In this first experiment, we do not require the subjects to track objects but rather simply to notice the preview letters that appear briefly during the movement of the objects and indicate if the test letter appearing at the end of the trial matches or does not match one of the preview letters (the match/no-match judgment). We varied the inter-stimulus interval (ISI) in order to explore OSPB differences among various durations between the appearance of the preview letter and the appearance of the test letter. Since tracking and attention is not required in this experiment, feature binding should not be maintained for long durations. We expect only the shorter intervals to show a preview benefit, which would be indicated by faster reaction times when making the match/no-match judgments. This would support an automatic and implicit tracking of objects during the non-tracking trials, as observed in the previously reported experiments, in addition to an automatic construction of object files upon visual indexes.

To confirm the role of selective attention in feature binding, both tracking and non-tracking MOT trials were devised in Experiment 2. Since selective attention is thought to bind features to objects, explicit tracking trials should show a strong OSPB effect at longer ISIs. Such a result may be due to the fact that tracking during MOT involves a higher level of attentional demand. Specifically, tracking is thought to require a form of selective attention that acts upon the preattentive indexes in order to maintain them (Culham et al., 1998; Pylyshyn, 1994; Scholl, Pylyshyn, & Feldman, 2001). This attention allows features to be bound to indexes in visual short-term memory. In Experiment 2, subjects were shown two preview letters that disappeared prior to object movement. At the end of the four-second trial the objects stopped moving and a test letter was shown. The subjects then were required to make a match/no-match judgment indicating whether the test letter was the same as one of the preview letters shown at the beginning of the trial. In the explicit tracking trials, subjects also had to track and identify the target objects (i.e., the objects that displayed the preview letters). We expect subjects to respond fastest when the test letter is a "match" and appears in the original circle, as reported in previous OSPB experiments (Kahneman, Treisman, & Gibbs, 1992). Given the longer ISIs in these trials, this effect should only appear in the explicit tracking trials where selective attention is required for tracking and presumably will bind features to objects (Wheeler & Treisman, 2002; Yantis & Johnson, 1990). Such results could support the theory that object files are built upon indexes via object-based attention.

Another topic of interest is the nature of the representation that produces an OSPB effect. Specifically, is there an advantage for familiar English letters as typically used in these experiments or can we produce the same preview benefit using novel symbols? For this purpose, we used characters from the ancient Cypriot alphabet to test the underlying nature of the OSPB in Experiment 3, which was otherwise identical in design to

Experiment 2. According to a recent study, letter stimuli and geometric shape stimuli are processed in a manner that results in shorter response latencies in a recognition task for English letters (Bowles, Ferber, & Pratt, 2005). Experiment 3 investigates whether differences in reaction time and performance will be observed between the familiar English letters and the novel non-English symbols. We expect the non-English symbols to exhibit a decreased OSPB effect compared to English-letter trials due to the expected quicker processing of English letters, but otherwise a similar pattern of OSPB effects as observed in Experiment 2 are predicted.

Methods & Results

General Methods

Participants

All subjects were recruited from Rutgers University and received course credit or monetary compensation for their participation in one session that lasted 60 minutes.

Apparatus and Materials

A standard MOT design was used for these experiments (as described in (Pylyshyn, 2001; Pylyshyn & Storm, 1988)). All experiments were conducted on a computer running Windows XP and were programmed in MATLAB® Version 6.5 (The Mathworks, 2003) using the Psychophysics Toolbox 2.54 extensions (Brainard, 1997). The 22-inch CRT color monitor display in these experiments was set to a resolution of 1280x960 pixels and a frame refresh rate of 70 Hz. The total viewing angle of the display was approximately 36º. All object properties were identical (e.g., shape, luminance, color, motion algorithms). The stimuli consisted of four identical opaque circles with grey outlines on a black background. Each circle had a viewing angle of approximately 3.6º. The circles bounced off the sides of the screen at a set distance from the edge so that object movement occurred within a viewing angle of 30º. The movement of the circles was limited to a maximum displacement of eight pixels per frame (one frame = 38.46 ms), or 208 pixels per second (5.9º per second). Otherwise, the circle trajectories were unpredictable and allowed to overlap. Display luminance was manipulated by RGB values to create grey circle outlines (to minimize masking) and slightly brighter letter stimuli (RGB settings were [160, 160, 160] for circle outlines, and [200, 200, 200] for letters).

For each trial in Experiments 1 and 2, the preview and test letters were randomly chosen from the following set of upper-case English letters: A, B, C, D, E, F, G, H, K, L, P, R, Q, S, T, U, W, Y. The letters were presented in 42-point Lucida Console font (mono-spaced) and centered inside the objects. In Experiment 3, letters were used from the ancient Cypriot alphabet (dating to 300 BCE), which were obtained from a public online resource (Lo, 2007). See Figure 3 for the Cypriot symbols used in this experiment.

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Figure 3. Cypriot symbols used in Experiment 3.

Procedure

Subjects were seated approximately 60 cm from a 22-inch CRT monitor in a dark room without a chin restraint. The subjects were given verbal instructions as well as written instructions on the computer screen and pressed the space bar on the keyboard to start each trial. Unless otherwise specified, no instructions were given to explicitly track objects. In experiments that included both non-tracking and explicit-tracking trials, the non-tracking trials always preceded the explicit-tracking trials in order to avoid unintentional tracking due to practice effects.

In all experiments, four identical circles were presented at random locations on the computer screen and began moving as described above. At a predetermined point during the trial, one or two preview letters or symbols appeared briefly. At the conclusion of the trial, a test letter appeared and subjects were instructed to respond as quickly and as accurately as possible by pressing on the computer keyboard the letter “M” if the test letter matched a preview letter or “N” if the test letter did not match a preview letter. The inter-stimulus interval (ISI)—the duration between the offset of the preview letter and the onset of the test letter—was varied in Experiment 1 (i.e., one-, two-, and four-second ISIs) and set to four seconds in Experiments 2 and 3. Reaction times from the onset of the test letter and the subject’s match/no-match judgment were recorded. Practice trials were administered at the start of each experiment to ensure proper understanding of the task. Figure 4 depicts a typical set-up of the current experiments.

Several conditions were devised for these experiments. The “match” conditions were trials where the test letter matched a preview letter. The “congruent” conditions were trials where the test letter appeared in the original object that displayed a preview letter. This created the following four test conditions that had equal probability of occurrence within an experiment: 1) match/congruent; 2) match/incongruent; 3) no-match/congruent; and 4) no-match/incongruent. In trials with two preview letters, we distinguished between two types of match/incongruent trials where a test letter appears in either: a) an object that displayed the other preview letter; or b) non-target objects that did not preview any letters. These two match/incongruent conditions were combined for analyses. The primary measure of interest was the difference in reaction times between the match/congruent and match/incongruent conditions. All results were analyzed in SPSS using ANOVA and planned post-hoc comparisons with Bonferroni adjustments.

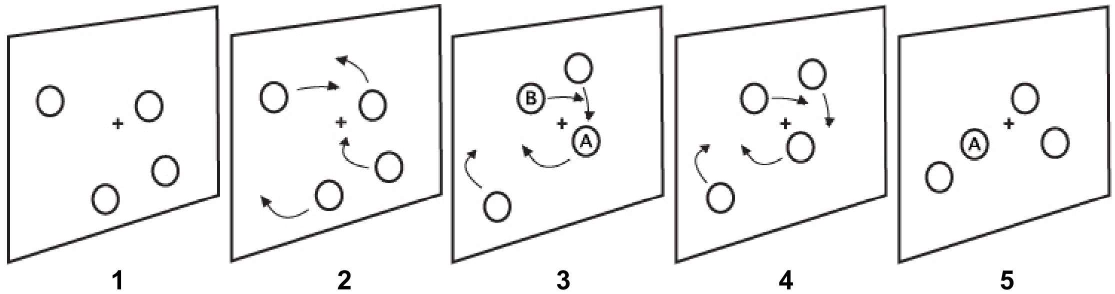

Figure 4. Set-up for Experiment 1. Panel 1 shows an initial display of four empty circles and a center fixation cross. Panel 2 depicts the random movement of the circles. Panel 3 shows two preview letters, which appeared for 500 ms during movement. Panel 4 depicts continuous movement after the preview letters disappear (this inter-stimulus interval was varied to last for one, two, or four seconds). In Panel 5, the observer responds if the test letter shown matches one of the preview letters (matching/congruent trial depicted).

Experiment 1

Experiment 1 extends our previous implicit tracking study (Haladjian & Pylyshyn, 2006) by testing for an implicit OSPB effect among various ISIs. The experiment consisted of three test blocks of 60 trials each (180 total trials). Three different ISI durations (between preview letter offset and test letter onset) were presented in random order in each block. Therefore, the six-second trials had one-second, two-second, and four-second ISIs. Each trial began with four empty circles that moved around the screen unpredictably and independently of each other. The subjects were instructed to focus on a fixation cross at the center of the screen and look for preview letters that appeared during the movement of the circles. At the end of the trial, a test letter appeared in one of the circles, which was either the same letter as one of the preview letters or a new letter chosen from the remaining set of available letters. The subjects responded with a key press indicating whether this letter was seen during the trial by pressing “M” for match and “N” for no-match. Accuracy and reaction times were recorded. No instructions for tracking were given.

Two versions of this experiment were conducted using one preview letter and two preview letters. In the Single-Preview version (n=21), only one preview letter appeared in the center of one of the circles for 154 ms and moved along with the circle. The Dual-Preview version (n=24) was identical to the Single-Preview version but displayed different preview letters in *two* of the objects simultaneously for 500 ms. Again, only one test letter appeared at the end of the trial. For both versions of Experiment 1, we expected subjects to respond fastest when a matching test letter appeared in a congruent circle, which would support an implicit object tracking and object file construction. This effect was expected to decrease for the longer ISIs due to temporal decay that occurs when selective attention is not deployed.

Results

Trials with reaction times for the match/no-match judgments exceeding three standard deviations from each subject's mean reaction time (for all conditions combined) were removed from the analyses, leaving 98.4% of the Single-Preview trials and 98.2% of Dual-Preview trials. Match/no-match responses were correct for 88.4% of the remaining cases in the Single-Preview version and 96.9% in Dual-Preview version, and only these cases were used in the analyses. The two match/incongruent conditions were combined for the analyses in the Dual-Preview version.

For the Single-Preview trials, the ANOVA results were significant for the one-second ISI ($F(3,61)=8.379$; $p=0.000$) and four-second ISI ($F(3,63)=4.496$; $p=0.006$). The primary comparison of interest was reaction time differences between the matching/congruent trials and the matching/incongruent trials. A planned post-hoc analysis using Bonferroni adjustments revealed a significant OSPB effect of 85 ms ($p=0.013$) in the one-second ISI trials. See Figure 5 for a summary of the reaction times.

In the Dual-Preview version, the ANOVA was significant for the one-second ISI trials ($F(3,70)=3.195$; $p=0.029$) and the two-second ISI trials ($F(3,72)=4.162$; $p=0.005$). Only the one-second ISI trials exhibited a significant preview effect of 63 ms ($p=0.007$); no other ISIs had significant OSPB effects. See Figure 6 for a summary of these reaction times.

Discussion

The observed preview effect only at short durations may be due to the lack of selective attention that is thought to maintain attention on indexed objects while tracking. Since active tracking was not required during this experiment, this could account for the lack of an OSPB effect during the longer ISIs, which may be due to a sort of memory decay. In addition, since letter correspondence to object identity was not explicitly necessary in this experiment, an object-specific feature binding was not maintained; only letter information was maintained for the match/no-match judgments. Experiment 2 explores whether or not the OSPB effect can be extended for longer durations during MOT by adding an explicit tracking task to the match/no-match judgments.

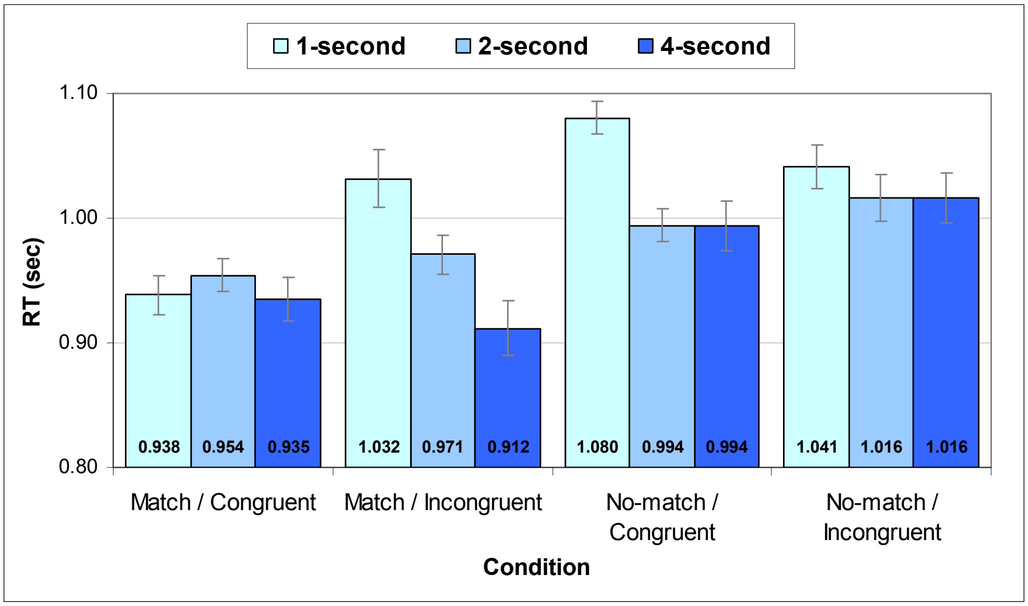

Figure 5. Experiment 1: Single-preview English letter reaction times. Reaction times for "match/no-match" judgments in trials with 1-, 2-, and 4-second ISIs (n=21).

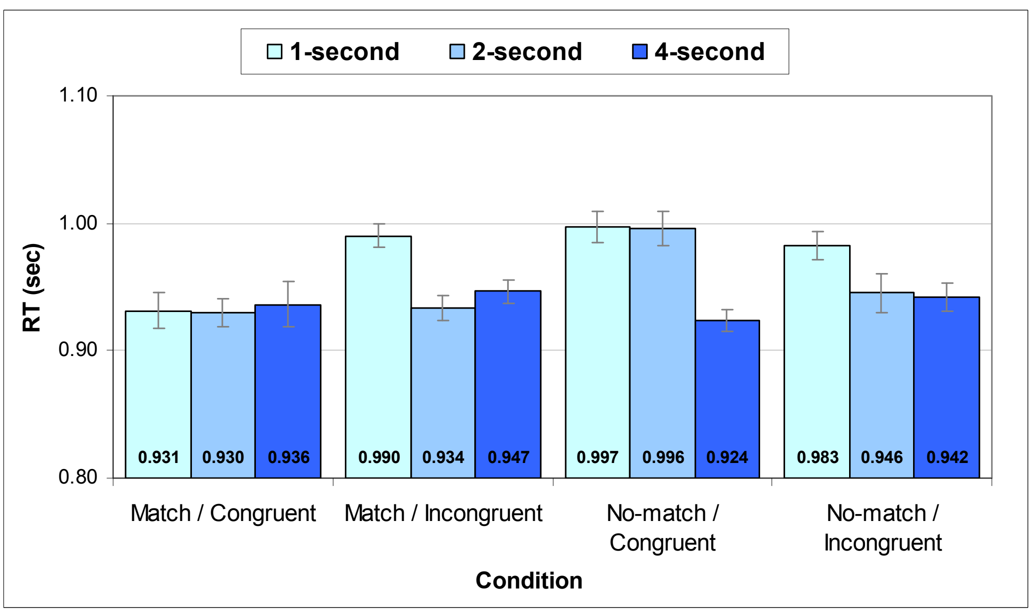

Figure 6. Experiment 1: Dual-preview English letter reaction times. Reaction times for "match/no-match" judgments in trials with 1-, 2-, and 4-second ISIs (n=24).

Experiment 2

This experiment uses an explicit tracking task to explore the effect of selective attention during longer inter-stimulus intervals. Nineteen Rutgers University undergraduates participated in Experiment 2. At the start of each trial, four circles were shown, two of which displayed random preview letters for two seconds (chosen from the set of English letters described above). The letters then disappeared and the empty circles moved around the screen in a random and unpredictable manner and stopped after four seconds. Hence, the ISI was constant in all the trials at four seconds. At the end of the movement, one test letter appeared in one of the circles. This test letter was either the same as one of the preview letters or a new letter chosen from the remaining set of available letters. The subjects were asked to respond as quickly and as accurately as possible and indicate whether the test letter matched one of the preview letters (by pressing "M" for match and "N" for no-match).

Two test blocks of 80 trials each were administered during one session. The first test block did not require any tracking of objects and provided a baseline for accuracy and reaction time when there was no explicit tracking required. In the second test block, the subjects were instructed to track the two "target" circles (i.e., the circles that displayed preview letters at the start of the trial). Subjects identified these targets with mouse clicks after making the match/no-match judgment at the end of the trial. In addition to reaction time, tracking accuracy was recorded in Block 2. Five practice trials were presented before each test block to ensure understanding of the task. The experimenter did not give any indication for tracking objects in Block 1.

Results

For each subject, outlying reaction times that were three standard deviations from the mean of all conditions combined were removed (98.0% of the total trials remained), and only correct match/no-match judgments were analyzed (96.1% of the remaining trials). ANOVA analyses revealed no significant reaction time differences between test conditions in the no-tracking trials ($F(3,54)=0.379$; $p=0.769$), which replicates the results observed in the four-second ISI condition in the Dual-Preview version of Experiment 1. The tracking trials, however, displayed overall reaction time differences in the test conditions ($F(3,54)=4.571$; $p=0.006$), with a significant OSPB effect of 108 ms ($p=0.001$). Figure 7 summarizes the reaction times for Experiment 2. Since it is easy to track two out of four objects, tracking performance was extremely high in this experiment with an overall target-tracking accuracy of 97.8% (SD=10.6%).

Discussion

Experiment 2 showed a robust OSPB effect in the explicit tracking block with ISIs of four seconds. The OSPB effects observed in the tracking trials may be due to the dual task demands of remembering preview letters and tracking target objects. This increased demand necessitates focal attention, which is believed to encourage the construction of object file representations in visual short-term memory (Luck & Vogel, 1997; Wheeler & Treisman, 2002). The results from Experiment 2 suggest that selective attention can bind indexes and object file representations together and allow them to persist through random movements for longer durations.

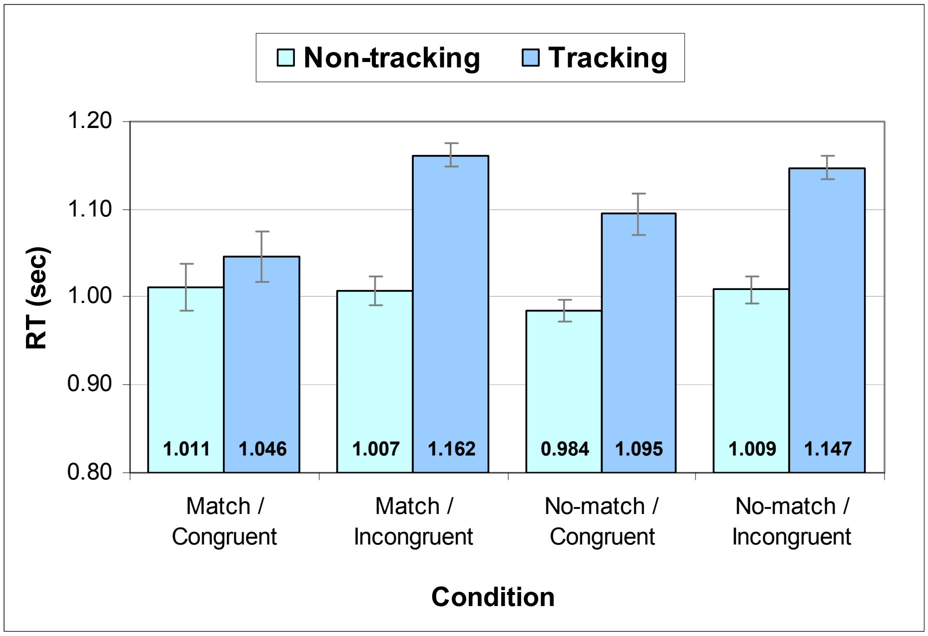

Figure 7. Experiment 2: Dual-preview English letter reaction times. Reaction times for "Match/No-match" responses for the non-tracking and tracking blocks (n=19).

Experiment 3

This experiment tested OSPB effects for symbols that do not have the familiarity or pronounce-ability of English letters (for English speakers) by using a set of characters from an ancient alphabet. If the OSPB effect relies on a familiarity effect, the priming benefit in this experiment should be weaker than that of Experiment 2, which used English letters. We conducted Experiment 3 to discover if we can obtain an OSPB effect for novel characters and if it differs from the familiar English letters.

Twenty-four students participated in Experiment 3. The design was identical to Experiment 2 except that the preview letters were symbols from the ancient Cypriot alphabet. Again, four circles were shown at the start of each trial, two of which displayed two different preview symbols for two seconds. These symbols were chosen randomly from the subset shown in Figure 3. The symbols disappeared and the empty circles moved around the screen for four seconds, creating a constant ISI of four seconds for all the trials. One symbol appeared at the end of the trial in one of the circles and the subject was asked to indicate whether this symbol was a preview symbol as quickly and accurately as possible (again, by pressing “M” for match and “N” for no-match).

Two test blocks of 80 trials each were administered during a single session. The first test block did not require the explicit tracking of objects and provided a baseline for accuracy and reaction time when there was no explicit tracking required. In the second test block, the subjects were instructed to track the two “target” circles (i.e., the circles that displayed preview symbols at the start of the trial) and identify them with mouse clicks after making the match/no-match judgment. In addition to reaction time, tracking accuracy was recorded in Block 2. The subjects were given five practice trials before each test block to ensure understanding of the task.

Results

Again in Experiment 3, the primary comparison of interest was the difference in the reaction times between the match/congruent and the match/incongruent trials (combined incongruent conditions). Outlier reaction times were removed from analyses as previously described (98.4% of trials remained) and only correct match/no-match judgments were analyzed (91.7% of remaining trials). ANOVA results for the non-tracking trials were significant ($F(3,70)=3.113$; $p=0.032$), but no OSPB effects were observed in this block. The block with explicit tracking also exhibited significant differences in reaction times ($F(3,70)=9.314$; $p=0.000$), with a significant preview effect of 74 ms ($p=0.048$). See Figure 8 for a summary of reaction times. Target-tracking performance was also extremely high in this experiment, with an overall accuracy of 98.1% (SD=10.8%).

Discussion

Using different stimuli, Experiment 3 replicates the results of Experiment 2. The preview effect for Cypriot symbols is smaller than the identical experiment with English letters, suggesting a speeded familiarity effect for the English letters. Otherwise, the results replicate those of Experiment 2, but with novel symbols instead of familiar letters. One possible confound in this experiment was the labeling of symbols that was reported by subjects. Several subjects stated during the debrief that they assigned names to the symbols in order to remember them (e.g., one symbol resembled a “lightening bolt” and another resembled a “tear drop”). This naming may explain the slower overall reaction times and may interfere with the intended test of perceptual matching.

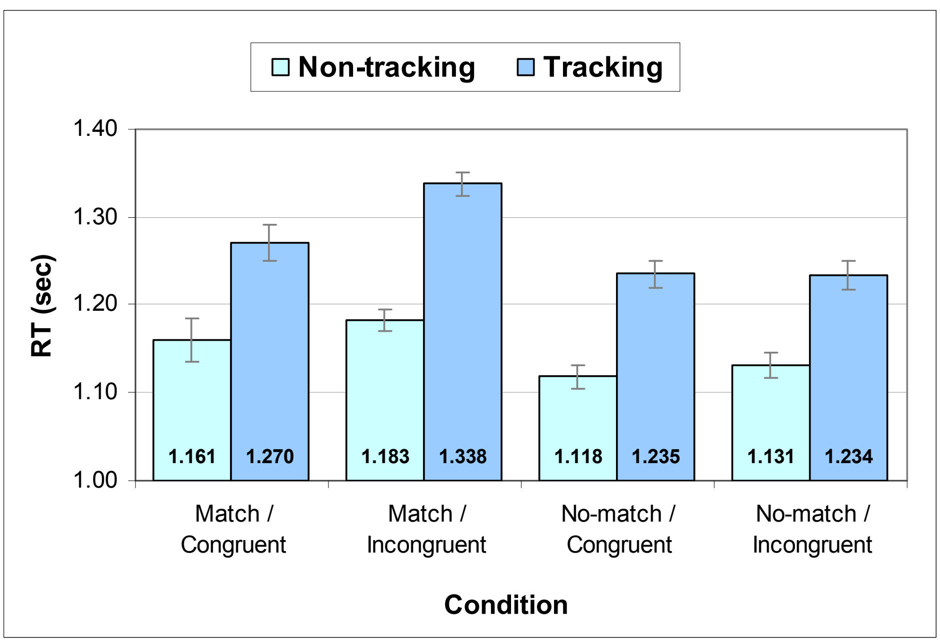

Figure 8. Experiment 3: Dual-preview Cypriot symbol reaction times.
Reaction times for “Match/No-match” responses for the first test block that did not require tracking (n=24).

Table 1. Summary of OSPB effects in all three experiments.

	Preview effects (ms)	Standard error	*p**
Experiment 1: One preview letter (n=21)			
Non-tracking trials, 1-second ISI	85	27	0.013
Non-tracking trials, 2-second ISI	49	29	0.549
Non-tracking trials, 4-second ISI	17	29	1.000
Experiment 1: Two preview letters (n=24)			
Non-tracking trials, 1-second ISI	63	19	0.007
Non-tracking trials, 2-second ISI	12	18	1.000
Non-tracking trials, 4-second ISI	11	27	1.000
Experiment 2: Two preview letters (n=19)			
Non-tracking trials, 4-second ISI	6	33	1.000
Tracking trials, 4-second ISI	108	29	0.001
Experiment 3: Two preview Cypriot symbols (n=24)			
Non-tracking trials, 4-second ISI	27	24	1.000
Tracking trials, 4-second ISI	74	28	0.048

Note: Preview effects = matching/incongruent RT – matching/congruent RT .

* *P*-values were obtained from planned post-hoc comparisons using Bonferroni corrections.

General Discussion & Conclusion

The current experiments support theories of object-based attention and automatic feature binding during short ISIs, which is only observed at longer ISIs when explicit tracking is required. In Experiment 1, the observed feature binding during short intervals provides further support for the implicit tracking nature of the visual indexing mechanism as previously reported (Haladjian & Pylyshyn, 2006). This feature information decayed over time, which may be due to task-specific demands that did not maintain the automatic feature binding that occurred at short durations. In other words, selective attention was not used to follow objects and bind features during these trials. One limitation of this first experiment should be noted. Since subjects did not encounter trials where the preview letter appeared in empty space, they may have employed the strategy of attending to all moving circles. Though the preview effect is not as strong as that observed in the explicit tracking trials in Experiment 2, a follow-up experiment with a control condition in which a preview letter appears in the space between objects should be conducted.

The reduction of a preview benefit in the trials that contained two preview letters instead of one preview letter may be explained by an interference of binding when multiple objects are indexed and tracked. Various studies suggest that we cannot maintain more than one feature conjunction at a time (Treisman & Zhang, 2006; Treisman & Gelade, 1980), and this limit may be related to a decreased OSPB effect in the dual-letter preview trials. In addition, previous MOT studies have shown that the individual identities of successfully tracked objects often are confused, and the current results may be another indication of this difficulty in identity maintenance (Pylyshyn, 2004).

When the experiment also required tracking the targets that displayed the preview letters, feature binding persisted and resulted in a robust OSPB effect (as observed in Experiments 2 and 3). Since the objects were constantly moving in random trajectories, the priming benefit can be attributed to an object-specific effect as opposed to a location-specific effect. Other studies have shown similar results where selective attention is key to the creation of persisting object-specific feature encoding (Noles, Scholl, & Mitroff, 2005; Treisman, 2006; Wheeler & Treisman, 2002; Wolfe & Bennett, 1997). Similarly, in a previous MOT experiment that required observers to respond to a feature change in objects, quicker reaction times were observed when changes occurred in tracked targets than in nontargets (Sears & Pylyshyn, 2000).

An OSPB effect also was observed for novel symbols in Experiment 3. The pattern in subject performance replicated that of Experiment 2 with English letters, but with overall slower reaction times. Feature binding benefits from experience, hence familiarity (e.g., representations from long-term memory such as English alphabets) may be observed through a speeded reaction time (Colzato, Raffone, & Hommel, 2006). The increase in reaction time when responding to the Cypriot symbols also may be due to a strategy of assigning names to the symbols, as reported by several subjects. This limitation should be addressed in future studies by eliminating “easily namable” symbols and presenting the stimuli for shorter durations. Furthermore, previous studies have shown that object individuation and task-specific reaction time increase as a function of display size (Mccarley & Mounts, 2007). The spatial distribution of objects also influences the selection process by reducing the efficiency of the suppression of distractors when they occur at greater distances (Kastner & Ungerleider, 2001). Such findings, together with the interference of maintaining multiple indexes, may account for the slower reactions times in all three experiments, since our displays are larger than the original OSPB experiments.

In sum, the experiments reported aim to further our knowledge about mental representations by clarifying the nature of object file representations during the basic operation of tracking. Attention interacts with these processes and can be characterized as exerting both bottom-up and top-down influences. Early visual processes tend to be bottom-up, as observed in visual indexing. However, top-down demands can act upon these primitive mechanisms through selective attention and build descriptive representations such as object files. An OSPB effect is taken to be an indication of this incremental representation-building process. The link between indexes and object files can be attributed to preattention, as shown by Experiment 1, and extended through the deployment of selective attention, as shown by Experiments 2 and 3. The current experiments, however, do not explicitly describe the process by which attention shifts and binds object properties, but rather suggest that this process occurs along a temporal continuum and begins in early vision with the indexing mechanism. Object representations appear to rely on selective attention to maintain the object-specific information that travels automatically with objects at short durations.

The MOT experimental design has been important for supporting the indexing mechanism and can relate to the performance of many human skills, such as playing team sports or navigating through traffic. Such knowledge of the visual system can inform computer models in replicating human vision. Further investigation of the application of attention upon visual indexes should be considered using a hybrid of the MOT paradigm.

For example, a follow-up study could explore whether object files can be constructed through a covert attentive task in order to determine the conditions that encourage implicit attention. In addition, combining this framework with neural-based models would be useful in explicating the types of attention systems involved during visual indexing and object file construction. A collaborative effort to understand better the bottom-up automatic processing of indexes and object files would benefit this theoretical framework.

In conclusion, object-specific information travels with moving objects implicitly during short intervals (roughly one second) and selective attention extends these OSPB effects to longer durations (at least four seconds). Object files may rely on visual indexes for the construction of object representations through a selective and object-based attention, and this study provides further support of this relationship. The combination of these processes not only shows an interaction between bottom-up processes and mental representations, but also supports a framework that connects objects in the world to their representations via indexes and object files. Similar to indexicals in language, visual indexes provide an account for referring to items in a visual scene. Developing a framework that posits a direct referential mechanism between the perceived world and mental representations is crucial for understanding how humans interact with the external world and helps to solve the reference problem. Not only will this bring us back to some of the original motivations of psychology's emergence from philosophy in attempting to understand the mind, but this also will shed light upon conscious experience in our everyday world.

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Publications

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