THE OBJECTS OF VISUAL ATTENTION AND MEMORY

By

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To my parents, Shang-Bin Ko and Susie Ko, for their love and support.

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CHAPTER I

INTRODUCTION

Objects surround us. The world that we see is not comprised of unrelated colors and edges. Instead, these elements are integrated into objects to which we attend, remember, and act upon. This experience is provided by our psychological representations of the world. When we attend to cars on the road, or when we search for a pen on our desks, we are attending to object representations. When we are recalling a stop sign that we just passed, or remembering what we need from the grocery store, we are accessing memories about objects. Are the object representations of attention the same as the object representations of memory? My dissertation examines this question.

In this introduction, I will review previous work on the role of object representations in attention and the storage of objects in memory. I will end this section by discussing relationship between attention and memory, and propose that object representations are an important link between attention and memory.

Object representations in visual attention

Early research suggested that visual attention shifted across a spatial representation in a manner like a spotlight, processing all information within its scope. In Posner's (1980) spatial cueing paradigm, participants viewed two laterally arranged boxes. A central arrow cued the box inside which a target was likely to appear. Target detection was facilitated when the arrow validly cued target location, and was inhibited when the arrow invalidly cued target location. These effects were attributed to the endogenous orienting of attention to enhance information processing at the cued location.

What is the purpose of this spotlight? Treisman and Gelade (1980) proposed that spatial attention served to bind the different features of an object into a single representation. In their research, participants performed visual search within arrays of colored letters of varying set-size, and reported the presence of a target. If the target differed from distractors by one unique feature, like color, then the search rate did not increase as a function of set-size. If the target was a conjunction of features, like a blue letter A, then the search rate increased with the number of items in the array. This data supported a two-stage model. Prior to attentive processing, the elementary visual features of a scene are processed in a parallel manner. If the visual target involves more than one feature in a specific configuration, then visual attention must be deployed to bind these features to perceive such an object. Failure of attention resulted in an improperly bound object, i.e. an illusory conjunction (Treisman & Schmidt, 1982). Importantly, this implied that there is no true role of objects in driving attentional behavior. Attentional selection occurred at a stage earlier than that of object representation. Instead, object representation is the result of attentional selection.

Treisman and Gelade's (1980) theory its original form did not take into account effects of visual grouping. Prinzmetal (1981) showed a higher probability for participants to mistakenly conjoin two features if those features belonged to the same perceptual group rather than different perceptual groups. This held true even when the features were equidistant across the different conditions. Treisman (1982) later revised her theory by proposing that perceptual groups were formed with the same early vision process as feature analysis, and showed that perceptual grouping affected search for conjunctions, but not features. Similarly, Kahneman and Henik (1981) showed that Stroop effects were stronger when a response-incongruent word appeared inside a task relevant object, compared to a task irrelevant object. These findings suggested that objects were formed prior to attentional selection and could act as the basis of selection.

Duncan (1984) proposed that visual information was parsed into candidate objects in early vision to be selected by attention. In a divided attention task, participants briefly viewed a line and box that were spatially overlapping. The line varied in tilt and texture, while the box varied in size and the location of a gap appearing on one of its sides. Participants were then cued to report two attributes of the stimuli. Participants reporting two attributes from the same object performed better than those who reporting one attribute from each of two objects. These results showed clear evidence that visual form helped to drive attentional selection independently of spatial location. This supported the idea that visual information was grouped and represented as simple forms, or candidate objects, prior to attentional selection.

This finding drove a wealth of research into the understanding of objects and attention. Some of the major investigations that will not be reviewed in depth include whether objects of attention are represented within a spatial- or non-spatial frame of reference (Kramer & Jacobson, 1991; Vecera & Farah, 1994; Kramer, 1994; Logan, 1996), the automatic spread of attention within an object (Egly, Driver & Rafal, 1994; Goldsmith & Yeari, 2003), and the visual properties of an object representation (Watson & Kramer, 1994; Matsukura & Vecera, 2006).

How could objects help to explain attentional behavior? Desimone and Duncan (1995) proposed that perceived objects compete for representation at high-levels of cortical processing. Top-down signals, such as memory for the appearance of a target object, may bias the competition in favor of a specific object over other objects. Winning this competition results in the selection of one object over the others. In this way, object representations are a crucial determinant of attentional behavior – they are the units of attentional capacity limitations. Furthermore, Desimone and Duncan (1995) proposed one neural locus of competition to be the receptive fields in higher cortical areas of the ventral stream of cortical processing, known to represent the appearance of complex objects (Ungerleider & Mishkin, 1982). This means that the visual appearance of an object could be the primary input for attentional selection.

In contrast to defining a visual object's identity by its appearance, or its type, an object can be defined as a token, or its individuation from other objects. Pylyshyn (2001) noted two problems with defining an object's identity by its visual appearance. First, when looking for a target object based on its appearance, several other objects may satisfy the search criteria. For example, when searching the cabinet for my favorite coffee mug, I will encounter several other white and cylindrical shapes. Second, there are instances of viewing an object in which visual appearance must be ignored or discarded in order to maintain the object's identity. For example, I might think that a person walking from the far end of the hall is Bill, but upon closer inspection I discover that the person is actually Betty. The person must be perceived as the same object, even though my representation of their appearance changed. One powerful demonstration of how objects can be individuated as different tokens independent of their appearance is the multiple object tracking (MOT) task (Pylyshyn & Storm, 1988). In MOT, participants view several identically appearing objects, some of which are indicated as targets, as they move around a display. Since the objects appear identical, discriminating the targets from non-targets as the objects move cannot rely solely on visual appearance.

In summary, there is evidence that object representations can drive attentional behavior. An object representation can be defined by its visual appearance or type, but it can also be defined by its individuation from other objects, independent of its appearance. MOT exemplifies this latter brand of object-based attention, and was used as the primary measure of attention in the current research.

Object representations in visual memory

Sperling (1960) discovered that memory could be divided into two stages. The early, sensory stage is high in capacity and resolution, but short-lived and susceptible to masking. A later stage is low in capacity, more enduring, and information is recoded to verbal information (see Coltheart, 1980). Phillips (1974) suspected the existence of another memory that resembled the latter stage, but represented information visually. Participants viewed a brief display of random visual patterns, followed by a blank delay. Then, participants viewed another pattern and reported whether it was the same as the initial sample, or different by some minor change. Using this change detection task, he concluded that visual memory could be delineated into two stages. The early stage resembled that of Sperling's early stage. The latter stage consisted of a visual representation that was relatively low in capacity, but it was more enduring and resistant to masking. This stage was called visual short-term memory (VSTM).

What is stored in VSTM? Irwin and Andrews (1996) had participants memorize arrays of colored letters, and showed that memory capacity was similar for both color and letter information. The capacity for color and letter information was similar to that of letter information alone (Irwin, 1992). Together, these results suggested that all the information within a location was integrated into an object. Luck and Vogel (1997) directly examined this hypothesis by varying set-size and stimulus type in a change detection task. Participants were presented with displays of colored squares, black oriented bars, or conjunctions of color and orientation. The results indicated that the number of items stored steadily increased with set-size, but did not continue to rise when there were more than four items in the display. Importantly, there was no effect of stimulus type, indicating a similar memory capacity for simple features like colors, and complex conjunctions like colored bars. This suggested that information was already integrated as objects by the time of storage in VSTM, and these objects were the units of capacity limitation in VSTM. Lee and Chun (2001) later showed VSTM capacity to be determined by the number of objects, regardless of whether they were spatially overlapped or separate.

Wheeler and Treisman (2002) alternatively suggested that the number of features that could be represented within any feature domain limited VSTM storage. Luck and Vogel (1997; Vogel, Woodman & Luck, 2001) had originally rejected this account by showing similar memory capacity for objects comprising of one or two colors. The latter condition had twice as many features from one domain as the former condition. However, this result could not be replicated by Wheeler and Treisman (2002) or Olson and Jiang (2002). Wheeler and Treisman (2002) also observed an impairment to change detection when the change trials involved colors between objects being swapped, rather than replacing an old color with a new one. They also noticed impairments when memory was probed using the whole array rather than a single item. They suggested that perception of the whole array placed demands on visual attention to properly bind all objects in the display. In other words, objects can only be represented in VSTM if attention is available to bind features into an object.

Olson and Jiang (2002) observed better change detection performance when features were integrated into objects rather than appearing separate in the display, despite there being some cost related to the number of overall features. Similarly, Alvarez and Cavanagh (2004) proposed that units of storage in memory would accept a minimal number of features that could be stored per object at an equal processing cost. When the number of features exceeded this minimum, objects would be stored with lower resolution, ultimately resulting in a lowered capacity. This account would fit well with Luck and Vogel's (1997) findings, given that they had used relatively simple stimuli.

What is the purpose of VSTM? Irwin (1991) proposed that VSTM facilitated the comparison of visual representations across eye movements. The retinal positions of objects change across saccades, so the visual system must determine whether the image of an object projected onto one retinal region prior to a saccade is the same as another object projects on a different region after the saccade. This could be solved by a representation that preserves the spatial relations between objects. Results by Phillips (1974) and Irwin (1991) showed that VSTM could fulfill this role.

Hollingworth, Richard and Luck (2008) proposed that VSTM could function as a means of gaze correction. Noting that saccades often fail to precisely land on their targets, Hollingworth et al. (2008) proposed that the appearance of objects, acquired prior to the saccade and stored in VSTM, could be used to correct such errors. Their participants were presented with a sample of colored dots, and instructed to saccade toward a cued dot. On some trials, the array rotated during the saccade, while vision was suppressed, inducing a saccade error. Memory for objects in the sample array was shown to be crucial in making corrective saccades to the target. When participants engaged in a concurrent change detection task that also required VSTM, gaze correction was significantly impaired. Together, this showed that VSTM facilitated object correspondence based on object appearance.

In summary, VSTM is a visual representation that is distinct from earlier sensory memories. It is low in capacity, but endures for several seconds and is robust to masking. The basic unit of storage has been shown to be integrated object representations. This finding received some controversy that will be further discussed in the General Discussion, but it has been supported by several studies. Some purposes of VSTM include facilitating the correspondence between different images of an object across saccades, as well as helping to correct erroneous eye movements.

The relationship between objects in attention and memory

There are object representations related to both attention and memory. Are the objects of attention and memory the different or the same? It would be beneficial for attention and memory to have distinct means of representing objects. If there are too many objects for attention to process, some of them could be stored in memory to alleviate the informational burden. However, one benefit for a common means of object representation between attention and memory could be object continuity. If objects change across time, attention would be required to track the object, but a form of memory would be required to retain a history of the same object.

Kahneman, Treisman & Gibbs (1992) proposed that a single representation is used in the accrual and retention of visual information. They proposed that an "object file" is established for each perceived object, and this representation maintains a history of information related to the object. The purpose of such a representation is to establish a means of stability and continuity for the object. This way, detected changes in the visual input can be related to objects that are already represented. If a change can be related to an object file, a single object could be perceived to be changing. If it cannot, a new file can be opened and the change could be perceived as a new object. Kahneman et al. (1992) proposed that object file continuity involved three operations: (1) a correspondence process determines whether a perceived object was previously seen or new, (2) if it was previous seen, a reviewing process retrieves previously viewed features of the object, and (3) an impletion process integrates current and reviewed information to produce the perception of a single object changing, rather than separate events involving distinct objects.

Earlier work focused on the reviewing process. Kahneman et al. (1992) presented participants with boxes containing letters. The letters disappeared and the boxes shifted location, either via real or apparent motion. Finally, one letter reappeared inside a box, and participants were instructed to name the letter rapidly. Letter naming was facilitated if the letter appeared inside the same box as at the beginning of the trial, compared to the same letter appearing in a different box, or compared to a novel letter baseline. This effect suggested that the information related to the box was retained and integrated across changes in time and space, producing the perception of the same object changing across time. Because the priming effect was specific to the object, Kahneman et al. (1992) suggested that it emerged solely due to continuity enabled by the object file. This effect has subsequently been referred to as the object-specific preview benefit. However, Henderson and Anes (1994) showed that under some conditions, a general priming effect not specific to the object accounted for more of the change in performance. Using a similar paradigm to Kahneman et al. (1992), Gordon and Irwin (2000) found object-specific priming when the initial and final inside the boxes matched semantically, i.e. a picture of a fish and the word "fish." This suggests that object file contain abstract, semantic information that is not specific to the episodic encoding of information. However, Mitroff, Scholl and Noles (2007) more recently showed that object-specific preview benefits occur with novel faces, showing that object files also support purely episodic information.

Some research suggests that one form of object-based attention uses the same object representations as visual memory. Vecera and Farah (1994) suggested that there were two kinds of object-based representations upon which attention could select. At a relatively early stage, attention could select perceptually grouped locations on a spatial representation. At a relatively late stage, attention could select objects with fully bound features that are not represented, and this selection could occur independent of spatial location. Awh, Dhaliwal, Christensen and Matsukura (2001) provided some evidence for this distinction. Both groups of researchers proposed that the latter representation was the same as those demonstrated by Duncan's (1984) results, and that they resided in

VSTM. Matsukura and Vecera (2009) had participants engage in dual-tasks that comprised of an object- or spatial-attention task and an object- or spatial-memory task. The dual-task interference was much larger when the two tasks tapped into a common dimension. The inference observed when object-based attention and memory tasks were concurrently performed suggested that the tasks shared a common basis of representation.

Wheeler and Treisman (2002) proposed that objects were represented in memory to the extent that attention was available to bind object features during storage. This is the same means of object representation in visual attention proposed by Treisman and Gelade (1980). Several subsequent studies that incorporated an attentional task during VSTM storage failed to support this account (Yeh, Yang & Chun, 2005; Allen, Baddeley & Hitch, 2006; Johnson, Hollingworth & Luck, 2008). However, Fougnie and Marois (2008) argued that the tasks used in these studies were not demanding enough to disrupt attentional binding of the object features. Their participants showed impairments in memorizing conjunctions while concurrently performing MOT, which supported Wheeler and Treisman's (2002) account. Although still debatable, this theory proposes one way that attention and memory could share the same means of object representation.

Another line of research has examined whether perceptual organization principles modulate VSTM storage. Woodman, Vecera & Luck (2003) showed that Gestalt principles could play a role in visual memory. Participants memorized colored squares that were organized into vertical columns in some trials. During maintenance, one of the objects was spatially cued, which resulted in its facilitated retrieval at the end of the trial. Importantly, items belonging to the same perceptual group as the cued item were retrieved more efficiently than those belonging to another group. Xu (2006) showed that

VSTM capacity could be modulated by the proximity and connectedness between the parts of each object. Object-based attention has also been shown to be modulated by how well parts of an object are connected (Watson & Kramer, 1999). Some researchers suggest that early Gestalt principles like connectedness, formed prior to attention (Driver, Davis, Russell, Turatto & Freeman, 2001; Russel & Driver, 2005; Kimchi & Peterson, 2008), are exactly what drives object-based selection (Avrahami, 1999; Marino & Scholl, 2005; Ben-Shahar, Scholl & Zucker, 2007). Together, these studies show that object representations in memory abide by the same grouping principles as the objects of attention, suggesting that memory and attention may use common object representations.

In summary, some research suggests that the object representations of attention and memory could be the same. One framework suggests that a single representation is used in the accrual and retention of object information. Some empirical evidence includes dual-task methods showing greater interference when both attention and memory tap into object-based processing compared to if they tap into separate domains. One line of research suggests that the two are functionally equivalent. In both visual attention and memory, objects are visual features bound together by sustained attention. Another line of research emphasizes that objects in attention and memory are formed by the same Gestalt principles, and that behavior proceeds similarly when these principles are adhered or violated in both attention- and memory-based representations.

What is an object?

The chapters that follow describe research conducted to examine whether the objects of attention are the same as those of memory or whether they the two are distinct.

The reasoning behind each investigation was tailored to fit a specific question. Each rationale can also be viewed as a different way to think about visual objects. In Chapter II, an object can be thought of as higher-order representations that could help reduce the cost of processing or storing information. One strategy to investigate the primary question is to examine whether attention and memory overlap in the capacity to use these higher-order representations. In Chapter III, an object is a single representation that results from relating different pieces of information. This stems from the idea that dynamic objects must be perceived as a single, continuous entity. If the process that provides this continuity involves both attention and memory, then it suggests that they both target a common object representation. Finally, in Chapter IV, an object is considered to be a representation that changes in a unified manner. An object is thought of as a unified entity with several features. What happens to the representation when one of these features changes? If an object is a unified representation, then perhaps the effect of changing one feature should affect the entire representation.

In the general discussion, the findings of these chapters are incorporated into a theory of visual object continuity. It ultimately conceptualizes objects as a mapping between bound features. Visual attention is thought of as a capacity for binding features, while visual memory is the retention of this binding. These components, together with others, form a circuit that determines object continuity.

CHAPTER II

DO ATTENTION AND MEMORY SHARE OBJECT REPRESENTATIONS?

Introduction

In this chapter, I investigated whether attention and memory shared a common resource of object representations. We can all imagine instances when we failed to see an object that was in plain sight. Perhaps one reason for this is that we were preoccupied with other objects in our memory. For example, someone could fail to see a stop sign on the road because he was remembering things to buy at the store. This might happen because attention and memory share a common resource to represent objects. In this introduction, I will present evidence to show that attention and memory are both limited by the number of objects that are represented. Then I will show how dual-task methods have been used to examine the relationship between attention and memory.

Attention to multiple objects

Attention can continually remain on objects that change over time. This is demonstrated by the multiple object-tracking (MOT) task, developed by Pylyshyn and Storm (1988). In MOT, participants are required to continually discriminate a set of target objects moving amongst identically appearing non-target objects. Pylyshyn (2000) argued that MOT was accomplished by a set of pre-attentive visual indices. According to his visual index theory, early perceptual processes segment the visual scene to extract candidate 'proto'-objects. A visual index is attracted to a candidate object in a pre-attentive, bottom-up manner and remains stuck to it, so that the index can move with the object. The index individuates its object from other objects, and can be used to further consult properties of the object. The properties that attract indices and the means that an index remains stuck on an object remain unspecified. In MOT, each target attracts an index. An index can remain stuck on an object even if it moves, demonstrating that the index is not committed to a location.

Although the role of the visual index in MOT is still debated (Scholl, 2009), there is strong evidence for the role of attention in MOT. For example, Oksama and Hyönä (2004) that individual differences in MOT performance were correlated with performance on other attentionally demanding tasks, such as attentional switching and spatial short-term memory. Tombu and Seiffert (2008) showed an increased impairment in MOT performance when participants discriminated an auditory tone that onset concurrently with a manipulation of tracking difficulty, compared to when they discriminated a tone prior to the manipulation. This result indicated that, in addition to visual attention, MOT involved a general form of attention that was not specific to any modality. This is called central attention.

How does attention operate in MOT? Yantis (1992) proposed that participants strategically grouped the multiple targets in order to attend to a single object. A single focus of attention would be directed to this morphing object during the tracking period. Yantis (1992) showed that informing participants of this strategy led to higher performance compared to those who were naïve to the strategy, although naïve participants eventually adopted the strategy on their own. This grouping strategy may also influence eye movement behavior during MOT (Fehd & Seiffert, 2008). Although there is evidence for the use of a grouped representation, this does not eliminate the representation of the individual targets. The targets must be represented individually on some level, because there is a limit to the number of targets that can be tracked (Pylyshyn & Storm, 1988), and performance decreases with set-size (Oksama & Hyönä, 2008). Also, the use of the grouping strategy still demands the representation of each individual object in order to update the shape and position of the continuously morphing object (Pylyshyn, 2000).

Cavanagh and Alvarez (2005) proposed that MOT is accomplished by multiple foci of visual attention. In their model, a focus of attention is centered over the location of each target, and it outputs information about the target to higher-level processes. This information is used to spatially shift the focus of attention in order to remain centered on the moving target. In support of this, Sears and Pylyshyn (2000) showed that detection of feature changes was faster for tracked targets than non-targets in MOT. Additionally, this benefit only applied to targets, and did not extend to non-targets that were spatially proximal to targets, suggesting that attention was not spread around the entire area encompassed by the targets.

Finally, there is evidence that attention adheres to the visual form of objects in MOT. Scholl, Feldman and Pylyshyn (2001) grouped targets and non-targets, so that the stimuli appeared like dumbbells. Performance was impaired in these trials relative to trials without such groupings. This indicated that attention selected the entire object associated with the target, impairing the discrimination between the target and non-target. This ruled out an account of attention selecting the spatial region surrounding the target. However, visual selection in MOT does not apply to all forms of grouping. Van Marle and Scholl (2003) also impaired MOT when the targets appeared like liquid substances pouring from one location to the next, compared to when targets were rigid squares. This showed that attention in MOT does not select arbitrary groupings, but may be selective for rigid forms rather than substances.

In summary, MOT uses a mode of attention that selects individual objects, rather than the spatial region encompassed by all targets or the spatial region around each target object. Although a strategy of grouping targets can be used, its benefits are modest, and individual objects must still be represented to use this strategy. The number of objects that can be represented limits attention in MOT.

Task related issues in VSTM

The role of object representations in visual short-term memory (VSTM) has been discussed in the Introduction. Although the purpose of Chapter II was to examine whether the object representations of VSTM are related to those of attention, the task I used to assess VSTM differed from standard methods in important ways. This section will discuss some of these issues and relate it to the method used in this chapter.

The primary task used to examine VSTM has been change detection (Phillips, 1974). In this task, participants briefly view a visual pattern, followed by a blank screen, and then a similar pattern. Their task is to report whether the two patterns are the same or different by any amount. The ability to perform this task depends on retaining information about the first display in some form of memory in order to compare it to the second display. Phillips (1974) suggested that this memory is visual, because it enables retention of complex visual patterns that are difficult to verbalize. Phillips also suggested that it is a form of short-term memory, since it can retain information without degradation over 600 ms, and then slowly degrades over the course of at least 9 seconds.

Performance on change detection does not just rely on the duration of delay period, but also of the time allowed to encoding the first display, or the encoding duration. Alvarez and Cavanagh (2004) showed that VSTM capacity is determined by the complexity of visual features, so that there is less memory capacity for increasingly complex items. However, Eng, Chen and Jiang (2005) showed that this effect of complexity was in part due to impairments related to perceptually encoding the stimuli. For this reason, it is important to display memory targets for a sufficient time in order to relate task performance to storage, rather than encoding processes. In the current study, participants perform a memory task that allows several seconds for perceptual encoding. Tasks used to assess VSTM also do not require a blank delay period, since VSTM is resistant to backwards masking (Phillips, 1974; Vogel, Woodman & Luck, 2006). In the current study, the period during which information is assumed to be stored in VSTM involved a visual display with moving objects. Since the memory used was unaffected by this display, I assumed the memory task to measure the use of VSTM rather than other visual memories, like iconic memory.

Shared capacity for object representation revealed by dual-task methods

Do attention and memory draw from a common capacity for object representation? Findings of object-based attention (Duncan, 1984) and object-based storage in memory (Luck & Vogel, 1997) have led some researchers to use dual-task methods to investigate this possibility. Barnes, Nelson and Reuter-Lorenz (2001) had participants judge the relative height of vertices appearing on the same object or different object while also memorizing digits, an object or a spatial location. The height judgment was superior when the vertices appeared on the same object (replicating Baylis & Driver, 1993), but this same-object advantage was reduced when participants concurrently stored an object, as opposed to a digit or location. A conclusion consistent with these results is that object-based attentional processes are used for object-based VSTM. Also, Matsukura and Vecera (2009) showed impaired accuracy on a memory task when it was paired with an attentional task. However, there was a greater detriment to accuracy on object-memory tasks when they were paired with an object-attention task compared to a spatial-attention task. Although these studies support the idea of common processing resources between attention and memory for objects, as opposed to space, they do not show whether attention and memory operate on the same object representations.

The dual-task method used in this chapter was developed by Fougnie and Marois (2006) to examine the relationship between attention and memory. They hypothesized that if attention and VSTM shared the same capacity, then concurrent performance of tasks demanding these processes should be mutually exclusive. Participants maintained a number of color-location conjunctions while concurrently tracking several moving objects. After tracking, participants were presented with a single object and reported whether it was the same or different than any object in the memory sample, and also reported whether a single probed object in the tracking task was a target or not. In other conditions, participants performed two interleaved change detection tasks, both involving conjunctions of color and location, in order to construct an estimate of mutual exclusivity on dual-task performance. The results of the MOT/change detection dual-task showed that the magnitude of dual-task interference was significantly less than that of performing two change detection tasks. In fact, the observed interference from the MOT/change detection dual-task was more similar to that of concurrent performing MOT and a verbal memory task. These results suggested that there were some distinct capacities between attention and memory, as assessed by MOT and change detection. However, the nature of the remaining overlap was still unknown. Part of the overlap could have reflected the common use of central attention, as suggested by the similar magnitude of interference observed when MOT was paired with change detection or a verbal memory task. It could have also stemmed from common use of spatial processing, since the change detection task involved conjunctions of color and location.

In this chapter, I hypothesized that one source of overlap could be a shared resource of object representations. In other words, it is possible that attention represents objects in the same way as memory. Two hypotheses were contrasted. An *independent objects hypothesis* proposes that attention and memory each have an independent set of object representations. While both attention and memory might share a limited resource for object-based processing, these would entail separate representations of objects. This hypothesis predicts no difference in task performance if the two processes targeted the same objects or different objects. In contrast, a *shared objects hypothesis* proposes that attention and memory share common object representations. The same object representations would be accessed by both attentional and memory processes. Targeting the same objects would activate fewer total object representations than targeting different objects. This hypothesis predicts more efficient task performance if the two processes targeted the same objects rather than different objects. I used the task developed by

Fougnie and Marois (2006) to contrast these hypotheses. The crucial manipulation was whether MOT and the memory task targeted different sets of objects, as in Fougnie and Marois' (2006) study, or if they targeted the same set of objects.

To preview, the results of Experiment 2.1 showed significantly decreased dual-task performance when MOT and the memory task targeted the same objects, supporting the shared objects hypothesis. This effect was called the same-object advantage. Experiment 2.2 examined the relative cost of features and objects in this paradigm, revealing that although there was a cost of features, the use of objects reduced this cost when the number of features was high. The results of Experiment 2.3 showed the same-object advantage even when the number of spatial locations across dual-task conditions was equal. Finally, Experiment 2.4 examined how much of the dual-task cost was related to memory for binding color features to specific objects in the display compared to memory for colors alone. Together, the results indicated that attention and memory shared a common capacity for object representation.

Experiment 2.1: Same-object advantage in a dual-task of attention and memory

We adopted a dual-task method to examine the object-based representations used by attention and VSTM. Attention to objects was engaged with MOT. VSTM was engaged with a memory task requiring participants to encode colors or shapes. The critical manipulation was whether these tasks targeted the same or different objects.

Method

Participants

The participants were Vanderbilt University students who participated in exchange for course credit. They were tested in accordance with Vanderbilt University's Policy for the Protection of Human Subjects and the APA 2002 Code of Ethics. There were 44 participants in Experiment 1. There were 22 participants in the color group, including 16 males, with a mean age of 20.4 ($s = 3.26$). There were 22 participants in the shape group, including 10 males, with a mean age of 19.68 ($s = 2.25$).

Apparatus and stimuli

The stimuli were presented on an eMac G4 using MATLAB and the Psychophysics Toolbox extension (Brainerd, 1997; Pelli, 1997). Observers sat 60 cm from the monitor. The visual display consisted of ten items within a white frame subtending 23.5 x 17.8 degrees visual angle (°) on a black background. For the color group of participants, items were white or colored dots each spanning 0.57° in diameter. The RGB values for each color were: red (255 0 0), yellow (255 255 0), orange (255 140 0), pink (255 105 180), magenta (150 0 139), green (0 255 0), blue (0 0 255), violet (148 0 230), turquoise (0 134 139), and light blue (132 112 255). For the shapes group, items were white dots or novel, white shapes that fit within 0.56°x0.56°. Examples of the shapes appear in Figure 2.1

The motion of the dots proceeded by first dividing the tracking area into a 5 x 5 grid, and positioning each dot to a grid coordinate with some random jitter. The initial directions of motion for each dot were randomly selected from 0 to 360 degrees in 5 degree steps. At each step, the direction of motion changed randomly from –20 to +20 degrees from the previous direction. The direction of a dot was shifted if it came within a certain distance to the edges of the tracking area. The dots also repulsed each other by a factor scaled according to the proximity of the surrounding dots, such that closer dots were weighted more heavily. These factors produced some variability in speed and changes in direction. The average velocity of a dot was 8.12 degrees of visual angle per second (°/s).

Procedure

Each trial had four phases: encoding, tracking, memory probe, and tracking probe (Figure 2.1). At encoding, seven white dots and three memory targets appeared stationary within the frame in random, nonoverlapping positions. For different groups (n = 22, each), the memory targets were either three colored dots or three white shapes. Simultaneously, white circles cued three targets for tracking. In the Different-object condition, tracking targets were three white dots that were distinct from the memory targets. In the Same-object condition, the circles appeared around the memory targets, so that the tracking targets were the same as the memory targets. Participants were instructed to remember which colors or shapes belonged to each specific memory target, and prepare to track the circled items. Memory targets changed to white dots and the cues disappeared after 4600 milliseconds (ms), leaving ten identical white dots. For the tracking phase, all but three dots moved randomly for 3000 ms. In the Different-object condition, the memory targets were stationary, and in the Same-object condition, three non-target dots were stationary. Verbal encoding of memory stimuli was minimized with an articulatory suppression task. Participants repeated the word "the" aloud from the onset of encoding until the end of tracking and were monitored by the experimenter. For the memory probe, one white dot changed back into a memory target. On valid trials, this was the same feature that had appeared on that particular dot at encoding, and on invalid trials, this was one of the other two features presented at encoding. Half the trials were validly cued and the other half were invalid, split evenly between the other two features. For the tracking probe, a circle surrounded a target on valid trials, and surrounded a non-target on invalid trials. Memory and tracking probes never appeared on the same object, and validity of the memory and tracking probes were varied independently. Participants responded to each probe by pressing labeled keys.

We also included Single-task trials that resembled the Different-object condition, except that preceding text indicated which task the participant should perform. Participants responded to the relevant task and made a random keypress to the irrelevant task. An equal number of Same-object, Different-object, and Single-task trials were intermixed, with Single-task trials split equally between the memory and tracking tasks. There were 192 trials, split into four blocks of 48 trials.

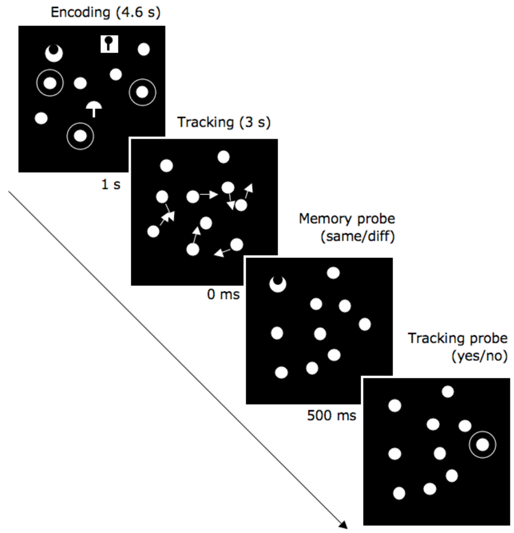


FIGURE 2.1
Depicted on the left is schematic of the basic paradigm, using shapes as an example. During the encoding stage, participants were presented memory and tracking targets. Visual features and tracking cues were removed after 4.6 seconds. During the tracking phase, white dots randomly moved around the screen. During the memory and tracking probe phases, probes for each task appeared with a response prompt.

Results and Discussion

The proportion of accurate trials was averaged across memory and tracking tasks for each condition. This measure was appropriate since the priority for each component task was not manipulated. By averaging the performance of the two Single-task conditions, I formed an estimate of ideal dual-task performance, called Expected. Any significant drop below this estimate was considered to result from dual-task interference (Fougnie & Marois, 2006). The data were submitted to a mixed design analysis of variance (ANOVA) to examine the effects of the between-subjects factor of Group (color, shape) x the within-subjects factor of Condition (Expected, Different, Same). There was no main effect of Group, $F(1,42) = 0.35$, $p = 0.56$, (partial eta-squared, $\eta_p^2 = 0.008$), but there was a main effect of Condition, $F(2,84) = 35.88$, $p < 0.001$ ($\eta_p^2 = 0.46$). The interaction approached significance, $F(2,84) = 2.9$, $p = 0.06$ ($\eta_p^2 = 0.06$).

Paired comparisons showed worse dual-task performance in the Different-object condition compared to Expected for both color, $t(21) = 3.53$, $p < 0.001$ (Cohen's $d = 0.57$), and shape, $t(21) = 7.74$, $p < 0.001$ ($d = 1.23$). These results replicated findings by Fougnie and Marois (2006), who showed a dual-task cost between tracking and change detection and suggested some overlap between attention and VSTM processes. Importantly, there was a same-object advantage in that the Same-objects condition was performed better than the Different-objects condition for both color, $t(21) = 4.18$, $p < 0.01$ ($d = 0.38$), and shape, $t(21) = 2.63$, $p < 0.05$ ($d = 0.36$). These results suggest a shared resource of object representations for attentive tracking and VSTM. In fact, no significant difference was found between the Same-object condition and Expected for the color group, $t(21) = 1.44$, $p = 0.16$ ($d = 0.22$) The abolished dual-task cost for color targets suggested a complete shared resource for attentive tracking and VSTM of color. There was, however, an observable difference between Same-object and Expected for shapes, $t(21) = 6.02, p < 0.001$ ($d = 0.82$). These results are shown in Figure 2.2.

These results cleared showed that when attention and memory targeted the same objects, there was a benefit to dual-task performance compared to when they targeted different sets of objects, supporting the shared objects hypothesis. In fact, dual-task performance in the color group was not significantly different from an estimate of ideal performance that we derived the Single-task trials. However, we observed some dual-task interference for shapes compared to this estimate. This could have reflected additional performance cost due to the complexity of the features to be stored in memory (Alvarez & Cavanagh, 2004; Xu & Chun, 2006). We examined the relative cost of features and objects in the next experiment.

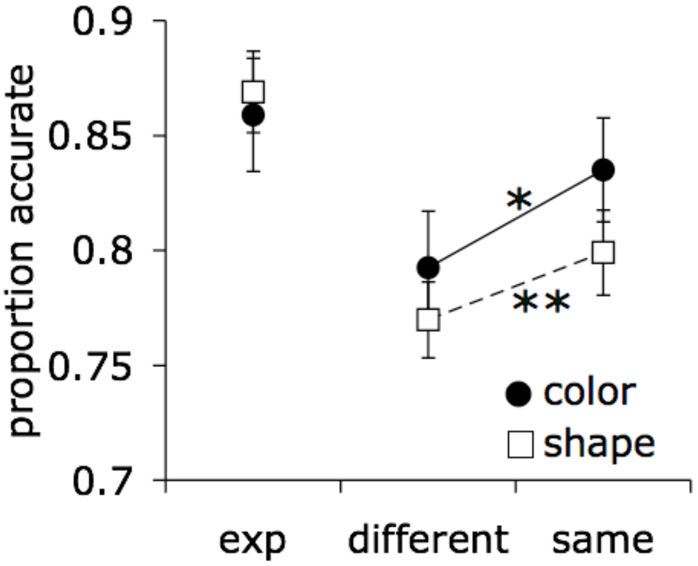


FIGURE 2.2
Depicted on the left are the results of Experiment 2.1. The y-axis depicts the proportion of accurate trials averaged across memory and MOT tasks. Errors bars are the standard error. $*p < 0.01$ (color group), $**p < 0.05$ (shape group).

Experiment 2.2: Is the shared capacity determined by features or objects?

The results of Experiment 2.1 showed a same-object advantage when attention and memory targeted the same set of objects. However, there was less of an advantage when the memory task involved complex shapes, rather than colors. This could suggest that some of the dual-task cost was related to the features involved in the memory task. Experiment 2.2 examined the relative cost of features and objects in our dual-task paradigm. By varying the target set-size, we were able to quantify the effect of increasing feature load separately from increasing the object load. This manipulation enabled the comparison of trials with a varying number of features but the same number of objects. It also enabled the comparison of trials with a varying number of objects, but the same number of features.

Method

The participants were 22 Vanderbilt University undergraduate students, including 7 males, who participated for course credit (mean age = 19, *s* = 1.14). The apparatus and stimuli were identical to that of Experiment 1. The procedure was identical to the color group of Experiment 1, with an added manipulation of target set-size. At set-size 2, the memory and tracking tasks each had two targets. However, the number of objects, or individual dots in the display, varied across dual-task conditions. In the Different-objects trials, there were four total target objects, while in the Same-objects trials, there were two total target objects. At set-size 4, eight objects were targeted in the Different-objects trials, and four objects were targeted in the Same-objects trials. The relevant features in this experiment were the color of the memory targets and the spatiotemporal continuity of the tracking targets. Across both dual-task conditions, there were four target features at set-size 2 and eight target features at set-size 4 (Figure 2.3).

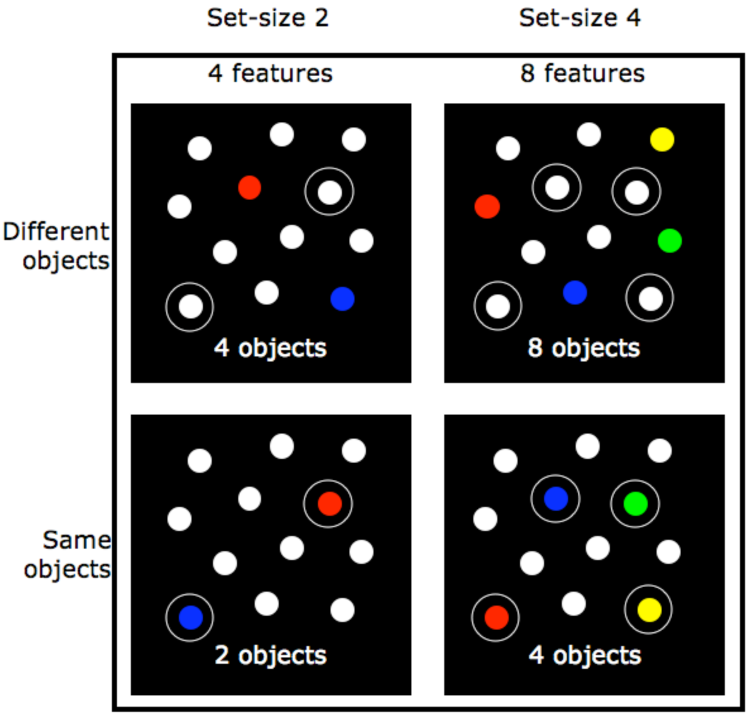


FIGURE 2.3
The encoding phase for Experiment 2.2 is depicted across the manipulation of set-size and condition. Feature-based costs were examined by comparing performance across conditions when the number of objects was equal (Different objects, Set-size 2 vs. Same objects, Set-size 4). Object-based costs by comparing performance across conditions when the number of features was equal, i.e. across conditions within each level of the set-size manipulation.

Results and Discussion

The data were scored as proportion accurate and submitted to a Set-size (2, 4) x Condition (Expected, Different, Same) ANOVA, which revealed main effects of Set-size, $F(1,21) = 131.13$, $p < 0.001$ ($\eta_p^2 = 0.86$), and Condition, $F(2,42) = 53.5$, $p < 0.001$ ($\eta_p^2 = 0.72$), and an interaction, $F(2,42) = 7.2$, $p < 0.01$ ($\eta_p^2 = 0.25$). Feature-based costs were examined by contrasting trials with the same number of objects, but involved a varying number of features. There was superior performance in the Different objects condition at set-size 2, compared to that of the Same objects condition at set-size 4, $t(21) = 7.09$, $p < 0.001$ ($d = 1.29$). Although the task in both conditions targeted four objects, the former condition involved four features while the latter condition involve eight features. This result demonstrated a feature-based cost.

Object-based costs were examined by contrasting the Same- and Different objects conditions at each feature set-size. The number of features was equal within each level of set-size, but the number of objects varied such that the Same-objects conditions had half the number of objects than the Different-objects condition. Although there was no difference when there were 4 total features, $t(21) = 1.66$, $p = 0.11$ ($d = 0.29$), performance was superior in the Same-objects compared to the Different-objects condition when there were 8 total features, $t(21) = 2.61$, $p < 0.05$ ($d = 0.48$). The same-object advantage arose in the latter condition possibly because task difficulty was sufficiently high at this set-size. These results showed that even though there were costs related to the number of features, there was a same-object advantage (see Figure 2.4).

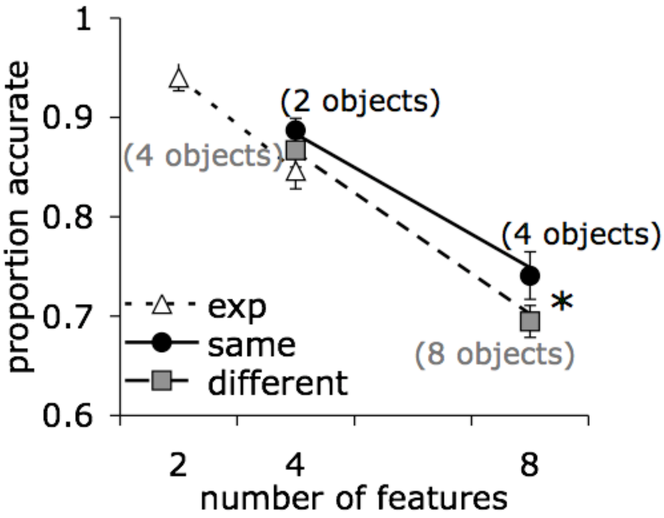


FIGURE 2.4
The results of Experiment 2.2 are depicted as performance varying as a function of the total number of target features. The number of objects in each condition appears in parentheses, with gray text referring to the Different objects condition and black text referring to the Same objects condition. Feature-based costs were observed, as shown by significant declines in performance as the number of features increased in both dual-task conditions. This occurred when the number of objects was equal (gray squares at feature set-size 4 vs. black dots at features set-size 8). However, a same-object advantage was observed when the number of features was 8. $*p < 0.05$.

Experiment 2.3: Are dual-task costs determined by spatial attention?

An alternative account of our main findings is that there were fewer attended locations, rather than fewer attended objects, in the Same-object condition compared to the Different-objects condition. Experiment 3 addressed this by adapting the task so that the memory task only involved one location rather than multiple locations.

Method

The participants were 21 Vanderbilt University undergraduates, including 9 males, who participated for course credit. The mean age was 18.9 (*s* = 0.92). The apparatus and stimuli were identical to Experiment 2.1, except that we used a different set of colors (see Experiment 3.1 for a description). At the start of the encoding phase, participants were instructed to memorize the colors of three dots that were serially presented at the center of the screen. Unlike Experiment 2.1, participants remembered only the colors themselves, not the binding of color and item. Each colored dot appeared at the center of the screen for 1 second, and was overlapped by a white dot for 1 second. At the start of the tracking phase, eight dots moved straight away from the center in different directions for 450 ms, followed by random motion for the remainder of the tracking phase (5500 ms). From the start of the tracking phase up to 1000 ms, three dots were shaded to indicate them as tracking targets. In the Same-objects condition, tracking targets were shaded in the same colors that had to be memorized. In the Different-objects condition, targets were gray. Before the probe phase, dots remained white and stationary for a short period of time. In the Different-objects condition, the dots were white and stationary for 250 ms. In the Same-objects conditions, the dots were white and stationary for an additional 1000 ms to offset the additional time that colors had appeared at the start of the tracking phase. The tracking probes were the same as those in Experiment 2.1. For the memory probes, a color previously shown at encoding appeared in half of the trials, and a new, previously unseen color appeared in other half of trials. In the Same-objects trials, if the color was previously seen, it appeared on the same object as it did at the beginning of motion. In the Different-objects trials, the color appeared on any of the tracking targets. The order of memory and tracking probes was counterbalanced across four blocks of trials, and they never overlapped the same object on a given trial (see Figure 2.6).

Results and Discussion

The data were scored as proportion accurate and averaged across tasks. A paired comparison showed superior accuracy in the Same objects ($\overline{X}$= 0.89, *SEM* = 0.01) compared to the Different objects condition ($\overline{X}$= 0.87, *SEM* = 0.01), $t(20) = 3.17$, $p < 0.01$ ($d = 0.4$). These results showed the same-object advantage, further supporting our hypothesis that attention and memory targeting the same objects is advantageous. The results of previous experiments could have shown a same-object advantage because the Same-objects condition required less spatial processing than the Different-objects condition. In Experiment 2.3, the same-object advantage was still observed even though the number of spatial locations across dual-task conditions was equal, supporting the idea that the source of the dual-task costs observed in these experiments is due to differences in the number of objects that must be represented in attention and memory.

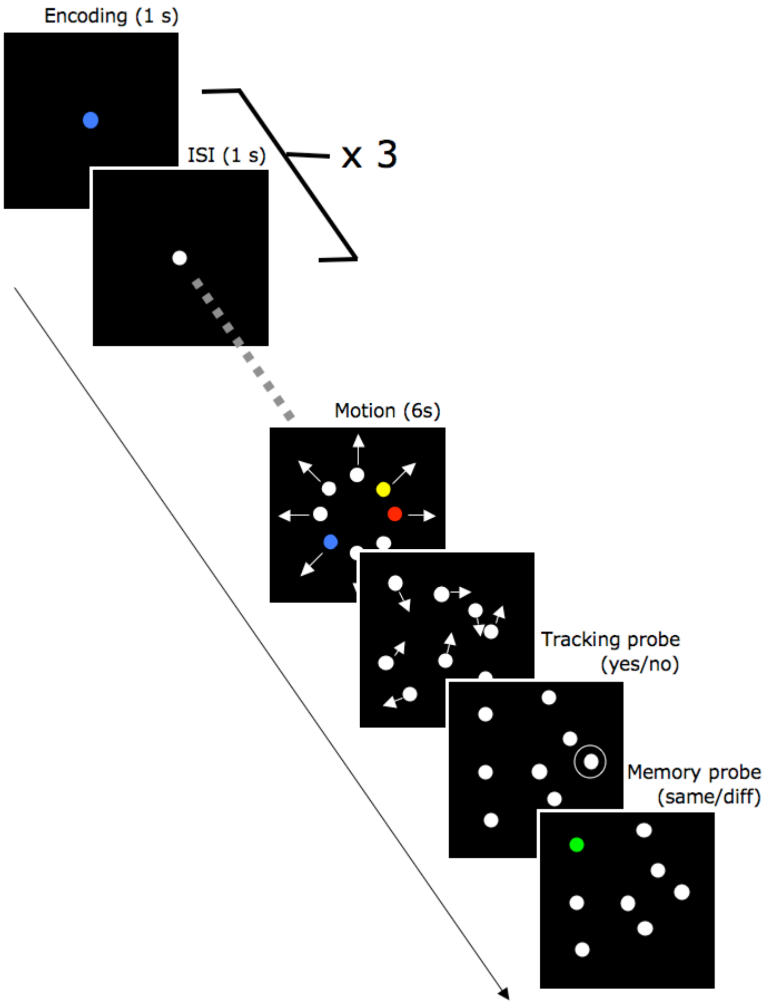


FIGURE 2.5
The method for Experiment 2.3 is depicted on the left. Each of the 3 memory targets was presented centrally, followed by a white dot, as depicted by the first two frames. For the tracking phase, dots initially moved radially away from the center for 450 ms and then moved randomly for 5.5 seconds. In the Same-objects condition (shown), tracking targets were shown in the memory color for 1 second at the beginning of the tracking phase. In the Different-objects condition, the tracking targets were grey for 1 second (not shown). The tracking and memory probe phases were the same as the previous experiments.

Experiment 2.4: Are impairments related to memory for binding or features?

Although a same-object advantage was observed in Experiment 2.3, the magnitude of the effect was relatively modest compared to previous experiments. Another source of dual-task cost in Experiments 2.1 and 2.2 could have been that the memory task required the binding of a feature, like color, to a specific object in the display, which was not required in Experiment 2.3.

The purpose of Experiment 2.4 was to examine the possibility that some dual-task cost observed in previous experiments could be related to the binding of color to a specific object. An alternative source of impairment is the loss of some features in memory. For the purposes of this study, memory loss of a feature is considered to be complete failure to store that feature, not a gradual decay of that feature. These two accounts were examined by manipulating the nature of the memory probe. There were two types of trials for when the color of the object probed for the memory task was invalid. In Misbound color trials, the invalid color appearing on the probed object was one drawn from a different memory target. In New color trials, the invalid color was one not previously seen in the trial. If some performance in Experiments 2.1 and 2.2 was impaired due to a failure to bind colors to specific objects rather than the loss of colors in memory, then participants may recognize the color on the probed object as one they had seen previously in the trial, but will still make errors about which color belonged to which object. This predicts the observation of dual-task costs in the Misbound color trials. If impaired performance was due to a loss of colors in memory, not feature binding, then participants may fail to remember some colors viewed at encoding, and will make errors even if the color on the probed object was not previously seen in the trial. This predicts the observation of dual-task costs in the New color trials.

Method

There were 13 participants (including 4 males) recruited from the Nashville community who were each paid $10 an hour, with a mean age of 22.2 (*s* = 4.09). The procedure was exactly like Experiment 2.1, except that there were two types of invalid memory probes. In the Misbound color trials, the probed object appeared in a color previously belonging to a different object. In the New color trials, the probed object appeared in a color not previously seen in that trial. The instructions to participants and procedure was identical to that of Experiment 2.1.

Results and Discussion

The data were submitted to a 2 x 3 ANOVA to examined the effects of Memory probe (Misbound, New) x Condition (Expected, Different, Same). There was no main effect of Memory probe, $F(1,12) = 0.31$, $p = 0.58$ ($\eta_p^2 = 0.02$), but there was a main effect of Condition, $F(1,12) = 13.07$, $p < 0.001$ ($\eta_p^2 = 0.52$) and a significant interaction, $F(1,12) = 4.14$, $p < 0.05$ ($\eta_p^2 = 0.26$). The interaction was examined by conducting paired comparisons in the bound and unbound trials. In the Misbound trials, dual-task costs were examined by comparing performance in the dual-task conditions to that of the Expected condition. This showed significant dual-task costs in the Different-objects, $t(12) = 7.7$, $p < 0.001$ ($d = 0.98$) and Same-objects conditions, $t(12) = 3.65$, $p < 0.01$ ($d = 0.62$). In addition, a same-object advantage was observed since performance in the Same-objects trials was significantly better than that of the Different-objects trials, $t(12) = 3.45$, $p < 0.01$ ($d = 0.53$). In the New color trials, there were no differences across any conditions (all *t*'s < 1.5). The results are depicted in Figure 2.6.

These results suggest that differences in performance between conditions were primarily determined by failure to correctly bind features to specific objects, rather than the loss of feature information in memory. The observation of the same-object advantage suggests that the cost of binding is significantly reduced when attention and memory target the same objects rather than different objects. This may suggest that the binding of features to objects is enhanced by attention, such that the binding is stronger when the focus of attention remains on the object rather than when attention shifts to other objects. This agrees with a theory proposed by Wheeler and Treisman (2002), and supports the results of Fougnie and Marois (2008), who found that feature bindings in memory decay when visual attention is sufficiently occupied by another task like MOT.

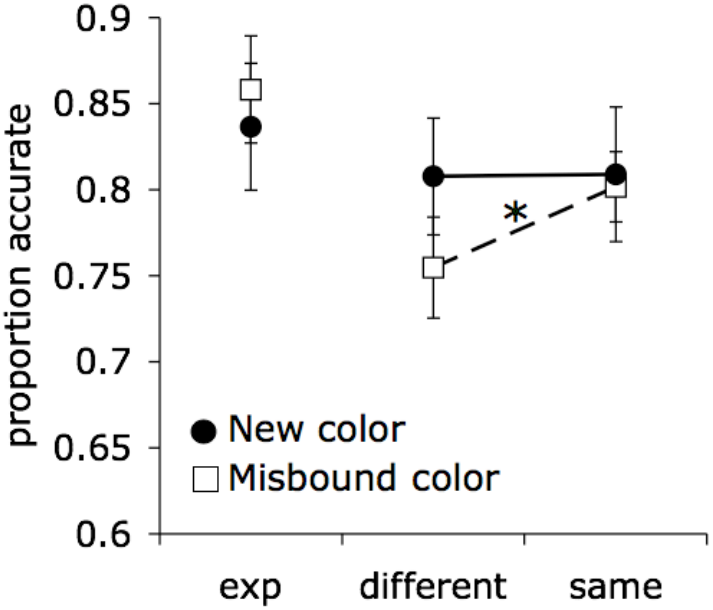


FIGURE 2.6
The results for Experiment 2.4 are depicted on the left. *$p < 0.01$.

General Discussion of Chapter II

This chapter presents research investigating whether attention and memory share a common or distinct capacity for the representation of objects. The results of the four experiments in this chapter showed an advantage to dual-task performance when the two component tasks targeted the same objects rather than different sets of objects. The components tasks were MOT, which involves attending to visual objects, and a memory task requiring VSTM, which involves storing visual objects. Experiment 2.1 provided a basic demonstration that targeting the same objects across both tasks led to an advantage in dual-task performance, both when participants memorized colors and complex shapes.

We called this result the same-object advantage. Experiment 2.2 revealed that the total number of features exerted a cost on the dual-task. However, this cost was reduced when the information was integrated into the same objects compared to when they were distributed across objects. Experiment 2.3 showed that when the number of spatial locations was equal across the same- and different-object conditions, there was still a same-object advantage. Finally, Experiment 2.4 showed that some of the dual-cost observed in the previous experiments came from binding features to objects. Together, these results suggest that attention and memory share a common resource for representing objects. When attention and memory are simultaneously required, performance is superior when they target the same objects.

What is the object representation used in the dual-task?

What do the results of this chapter reveal about the objects that are shared by attention and memory? The results of Experiment 2.1 showed that dual-task performance in the Same-objects condition was significantly lower than the expected performance derived from the Single-task trials when the memory task involved shapes. This could have reflected the cost of storing complex features. Alvarez and Cavanagh (2004) showed that change detection performance was inversely related to the complexity of the memorized objects. For example, participants showed greater capacity when the memory task involved colored squares compared to when it involved random polygons. These findings suggested that visual features exert a cost upon VSTM storage. However, as the information per object approached zero, only about 4 or 5 objects could be represented in VSTM, suggesting that the number of objects was still an important limiting factor. They proposed that the total VSTM capacity could be conceived of as slots, each of which could only hold a minimal number of features without decay in resolution. However, the resolution decays as the features related to a given slot exceed this minimum threshold. The results of Experiment 2.2 confirmed that features exerted a cost in the dual-task paradigm. The results showed a significant performance cost that varied with the number of features when the number of objects was equal across the Same- and Different-objects conditions. These findings agreed with those of Olson and Jiang (2002), who showed that although features exerted a cost onto VSTM capacity, there was a benefit to reducing the number of objects when the total number of features was high.

One common criticism of object-based attention is that the number of objects is often confounded by the amount of spatial processing. The results of Experiment 2.3 showed a significant same-object advantage even when the total number of relevant locations was equal across conditions. This supported the idea that the difference between the two dual-task conditions in previous experiments was driven by the number of objects across the conditions, and not by spatial processing. However, the same-object advantage observed in Experiment 2.3 was relatively modest. One possibility for this modest effect was that the memory task did not require binding colors to specific objects, unlike the previous experiments. It was possible that a portion of the dual-task cost in our paradigm was related to successfully binding features to specific objects. This was directly examined in Experiment 2.4. In some trials, the memory task required binding of features to objects, while in others it did not. The results showed dual-task costs only when the memory task required the binding of features to objects. What is the source of errors in binding features to objects? One possibility is the dividing of attention across several objects resulted in non-optimal allocation to each object, resulting in binding errors (Treisman & Schmidt, 1982).

Together, the results of these experiments reveal some properties of the object representations shared by attention and memory. The fundamental unit of the capacity for representation may be individual features, since we showed performance costs related to more complex shapes compared to colors, as well as costs related to the total number of features required for representation. However, integrating feature information into objects could be an important way to compress the information that is represented. The number of objects that could be represented is limited, and this limitation is independent of spatial processing. Conceiving visual features as the smallest the units of processing differs from ideas of Cowan (2001), who proposes that capacity limitations should be characterized in terms of the highest-order representation in which information can be recoded. However, this might only be useful if information can be recoded into higher-order representations without error. In the current study, features exerted some cost even when they were integrated as objects. This might indicate that the means of integration are imperfect or weak. This fits with the idea that the means of integrating features into objects is attentionally-mediated binding. Dividing visual attention, as required in the tasks of this chapter, could impair necessary bindings, revealing some cost related to features.

The object representations used in the current chapter could be object files (Kahneman et al., 1992). The primary finding of this chapter suggested that a single representation was used for the accrual of new information, as the spatial updating of MOT required, and the retention of old information, as required by the memory task.

One advantage of a single representation for updating and memory is to preserve continuity. An object that is changing over time, like a moving object, must be perceived as a single, continuous entity over the course of its change. The visual system must deploy a process that makes a correspondence between different states across time. Any correspondence process must use some form of memory because older states of the object, which are no longer in view, must be related to the current state of the object. For example, to perceive a man walking across the street as continuous, a correspondence process may sample and store the image of the man at one point in time. At a later point in time, when the man is at a different position, visual information is sampled again and then matched to the image of the man stored in memory. A successful match could lead to the integration of the newly sampled information to the existing image in memory, effectively updating that image. Kahneman et al. (1992) called this integration of old and new information impletion, and it was the means of perceiving the changing states of a single object. This concept of a dynamic object representation requires the use of attention for the accrual of new information and memory for storage of older information. The finding of a shared capacity for object representation in attention and memory supports this view.

Alternative sources of overlap between attention and memory

The conclusion of this chapter is that attention and memory share the capacity for object representation. Are there alternative interpretations of this overlap? Cowan (2001) considered the source of short-term memory limitations to be the focus of attention. In other words, short-term memory and attention shared a common capacity.

Fougnie and Marois (2006) directly examined this possibility in visual attention and memory, and showed that there was some distinction in their respective capacities. However, there was an amount of task overlap observed, and the current study replicated their results. Fougnie and Marois (2006) concluded that although attention and memory have distinct capacities, they primarily share central executive resources. If the central executive is defined as functions such as mental set-shifting, updating, and inhibition (Miyake, Friedman, Emerson, Witzki & Howerter, 2000), then the same-object advantage observed here cannot be explained by differences in executive processing. The demands on these executive functions were the same across the Same- and Different-objects conditions. However, if another function of the central executive is the formation and maintenance of objects, then the same-object advantage observed in the current study can be considered to stem from a central executive resource. However, the dual-task cost observed in the current experiments was not completely eliminated by the same-object advantage, suggesting that there is more to the distinction of attention and memory than object representations.

Another way to view the current results is that VSTM is an important part of the tracking process. The specific mechanism supporting attentional tracking is still under debate (Cavanagh & Alvarez, 2005), but some researchers have modeled tracking as a cycle of sampling and encoding target information into VSTM, and comparing them to the stimulus at the next sample (Allen, McGeorge, Pearson & Milne, 2006; Oksama & Hyönä, 2008). Under this view, VSTM is a crucial component of a tracking process. In the next chapter, I will examine this possibility.

Conclusion of Chapter II

The experiments of this chapter investigated whether attention and memory shared a common resource of object representations. Using a dual-task requiring the use of attention and memory, this problem was addressed by manipulating whether attention and memory targeted the same set of objects or a different set of objects. If attention and memory used the same object representations, dual-task performance should be higher when tasks using attention and memory target the same objects compared to when they target different objects. The results of four experiments agreed with this prediction. It is concluded that attention and memory share a common capacity for representing objects.

CHAPTER III

HOW DOES ATTENTION PRESERVE OBJECT CONTINUITY?

Introduction

This chapter will examine the process by which objects are perceived to be continuous. The conclusion of the previous chapter was that attention and memory share a capacity for object representation. Another way to view this conclusion is to say that attention and memory are both required in preserving an object representation. This experiments reported in this chapter examined how attention and memory could both be involved in preserving object continuity.

Information from the visual world is constantly changing. One fundamental component of human cognition is to provide a sense of stability despite changes in information. Objects must be perceived as the same enduring entities, or as continuous, over time in the face of changes to location and appearance. For example, if you see a person crossing the road, how do you know it is the same person that arrives on the other side? Object continuity must also be preserved when information about the object is temporarily discontinued. For example, if the person walks behind a truck, how do you know that the person emerging from behind the truck is the same person? One way that the person could be perceived as continuous is by sampling an image of the person prior to disappearing, and comparing a memory of the image to a new sample taken after the person emerges from behind the truck. The purpose of this study was to investigate whether attention mediates object tracking by comparing discretely sampled information to representations in memory.

The preservation of object continuity is important in the multiple-object tracking (MOT) task, where participants are required to discriminate moving targets from non-targets. Despite the continual change in objects' positions, participants must perceive the targets as the same enduring entities throughout the tracking period. Some theories of how MOT is accomplished was discussed in the previous chapter, including visual index theory Pylyshyn (2000, 2001), grouping strategies (Yantis, 1992), and multi-focal attention (Cavanagh & Alvarez, 2005).

More recently, some researchers have proposed that MOT involves sampling and memory. Allen, McGeorge, Pearson and Milne (2006) proposed that the locations of targets are sampled by visual indices and stored in visual short-term memory (VSTM). While the target locations are stored in VSTM, the indices take another sample at the next distinct time interval. Importantly, changes occurring between these sampling intervals do not affect the process. A central control mechanism compares the stored targets to the newly indexed objects, and if the two groups have similar attributes, the newly indexed objects are stored and become the current representation of the targets. This process is repeated throughout the motion period. Oksama and Hyönä (2008) also incorporated memory into a model of tracking objects with unique visual identities. Their model involves the attentional updating of target objects in a serial manner. The locations of objects not currently under the focus of attention are stored in VSTM. Memorized locations and the visual identity are compared to current visual input with a central control mechanism. Successful target tracking depends on minimal discrepancy between memorized and perceived object information. A mechanism that takes discrete samples can maintain object continuity even if an object disappears for a period of time. Storing the information for comparison to the next sample suggests that object continuity depends on the consistency of information between samples.

The results of the target recovery (TR) task suggest that a sampling mechanism could facilitate object tracking. TR is similar to MOT, in that participants track the positions of multiple moving targets, but it differs from MOT because the display briefly disappears while participants are tracking. Alvarez, Horowitz, Arsenio, DiMase and Wolfe (2005) first showed that, surprisingly, participants were able to maintain high tracking performance despite the inclusion of this brief blank period. Do participants continue tracking through the blank, or do they memorize the information necessary to recover targets after the blank? Horowitz, Birnkrant, Fencsik, Tran and Wolfe (2006) proposed that participants treated the blank like an occlusion and continued to track objects while they were invisible. This predicted that providing occlusion cues just before the blank and making the objects disappear one at a time would result in better performance than if occlusion cues were absent and objects all disappeared at once. Instead, they found that occlusion cues and asynchronous disappearance resulted in worse performance than when occlusion cues were present and objects disappeared simultaneously. They suggested that recovery of targets was accomplished by storing information prior to the blank to compare it with information across the blank.

How does behavior related to TR suggest a sampling mechanism? Keane and Pylyshyn (2006) manipulated the blank duration and the post-blank object positions in a TR task. In some trials, the objects paused during the blank, so that the pre-blank object positions matched the post-blank positions. In other trials, the objects moved during the blank, so that the pre-blank and post-blank positions became increasingly discrepant as the blank duration increased. Performance was high when objects paused during the blank, and remained high across all blank durations. However, performance declined when objects moved during the blank, and became more impaired as the blank duration increased. These results showed that accuracy declined as the spatial discrepancy increased between the object locations prior to and after the blank. These results support the memory-based account by Horowitz and colleagues (2006). However, these results similarly support sampling models of the MOT process. As the duration of the blank increases, so does the discrepancy between pre- and post-blank positions, and so it would degrade the match between the stored location and the newly indexed location. The sampling account of TR is also appealing because performance is not impaired by the blank in the display, but by the consistency of information across the blank.

A memory-based sampling mechanism may account for TR performance, but does it apply to multiple-object tracking without a blank? One way to examine this is by testing whether behavior related to MOT and TR is similarly affected by consistency of the same kind of target information. In this chapter, we examined whether the consistency of surface features, specifically color, affected behavior related to MOT and TR. The role of surface features in MOT has been controversial (Bahrami, 2003; Horowitz, Klieger, Fencsik, Yang, Alvarez & Wolfe, 2007), but there is a facilitative effect of surface features on MOT (Makovski & Jiang, 2009a, 2009b). The results showed that consistent colors facilitated performance in both MOT and TR. These results supported predictions of a proposed tracking process based on sampling object information for storage into memory, and matching it to currently viewed objects.

Experiment 3.1: Consistent colors facilitate target recovery

In Experiment 3.1, we examined whether consistent color could facilitate the recovery of targets after the blank. Participants tracked objects appearing in different task-irrelevant colors. At a random point during motion, the all the objects disappeared, and during this blank the objects could pause or move. Color consistency was manipulated so that, in half of the trials, color was the same across the blank, while in the other half the color was different. Additionally, we divided the time of object motion into several discrete periods, and manipulated the consistency of object colors across these periods. This manipulation resulted in the appearance of moving objects having visibly consistent colors or periodically changing colors.

Method

Participants

All participants in this chapter were recruited through the Psychology Research Sign-up System at Vanderbilt University, and participated in exchange for credit toward requirements of undergraduate psychology classes. All participants were tested in accordance with Vanderbilt University's Policy for the Protection of Human Subjects and the APA 2002 Code of Ethics. Participants in Experiment 3.1 were 16 Vanderbilt undergraduate students, including 13 females, with a mean age of 19.75 (s = 1.24).

Apparatus and Stimuli

All stimuli were presented in MATLAB using the Psychophysics Toolbox extension (Brainerd, 1997; Pelli, 1997) and administered on an eMac G4 with a CRT monitor at 1024 x 768 pixel resolution and 89 Hz refresh rate. Participants were positioned approximately 57 centimeters (cm) from the computer monitor. Each dot was 0.8 degrees of visual angle (°) in diameter, and they appeared in a square, white frame spanning 19° x 19°, appearing on a black background. The motion algorithm used in the experiments of this chapter was identical to the one described in Chapter II. The average speed was 9.15 degrees per second (°/s). Nine unique colors were randomly chosen and assigned to each dot at the beginning of each trial. The colors were randomly chosen without replacement from a set of 12 equidistant color coordinates on an imaginary circle centered on the white spot in 1976 CIE $L^*u^*v^*$ color space (CIE, 1986). The radius of the circle was 0.09 *u'v'* units. The mean luminance of the colors was 29.88 cd/m^2 (s = 0.88). This color set is depicted in Figure 3.1.

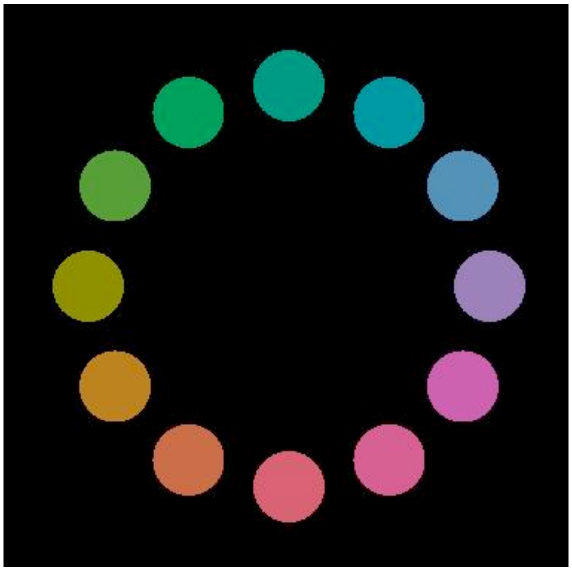


FIGURE 3.1
The 12 colors used for stimuli are depicted to the left. These colors are drawn from 1976 CIE $L^*u^*v^*$ space. The color space coordinates of each color are preserved in this figure, so that neighboring colors are harder to perceptually discriminate than colors that are further apart. Each color is most easily discriminated from the color directly across from it. The perceptual discriminability between the colors was verified by psychophysics (data not shown).

Procedure

Nine colored dots appeared for 500 ms, followed by the appearance of circle cues around the 3 target dots for an additional 2000 ms. Participants were instructed to track the circled dots. The cues disappeared, and after 250 ms, the dots began moving randomly for 6000 ms. The appearance of the dots was manipulated with a 5x2x2 within-subjects factorial design. The first factor in this experiment was color consistency across periods. The entire 6000 ms duration of motion was divided into discrete periods. The dot colors were made inconsistent across periods by swapping colors between randomly selected pairs of dots. Target dots could swap colors with either targets or non-targets. Color swaps occurred at a random point within each period so that the rate of swapping was not perfectly regular and predictable. Period duration was manipulated across trials to be 125, 250, 500, or 1000 ms, so that there were 48, 24, 12 or 6 swaps in a trial, respectively. In the remaining one fifth of the trials, the dot colors were consistent across all periods; in other words, dots retained their colors for the entire 6000 ms motion duration. The second factor in this experiment was the motion of the dots during the blank. At 1, 2, 3, or 4 seconds after the dots started to move, all the dots disappeared for 350 ms. During this blank, the dots either paused so that they were in the same position before and after the blank, or continued to move such that they were in a different position before and after the blank. Color swaps across periods were constrained prior to and after the blank to occur at least half of a period length before and after the blank. The third factor in this experiment was the color consistency across the blank. In half of the trials, dot colors were consistent prior to and just after the blank, while in the other half, the dot colors were swapped during the blank so that they were inconsistent prior to and just after the blank. At the end of the trial, the dots stopped moving and turned white. Removing the colors for the response period eliminated the possibility that participants were responding only based on the memorized colors of the targets in the trials in which the colors were always consistent. Participants were instructed to use the mouse to select their targets. At each selection, either a high or low tone was sounded depending on whether a target or non-target, respectively, was selected. Participants completed 8 trials for each condition, resulting in 160 trials in total.

Results

The data were scored as proportion of accurately selected targets, that is the number of correctly selected targets divided by number of targets. An analysis of variance (ANOVA) examined the effects of color consistency across motion periods (125 ms, 250 ms, 500 ms, 1000 ms period duration, consistent), color consistency across the blank (inconsistent, consistent) and position during the blank (pause, move). There was no main effect of consistency across motion periods, $F(4,60) = 2.04$, $p = 0.099$ (partial eta squared, $\eta_p^2 = 0.12$), but there were main effects of consistency across the blank, $F(1,15) = 26.55$, $p < 0.001$ ($\eta_p^2 = 0.64$), and position, $F(1,15) = 132.94$, $p < 0.001$ ($\eta_p^2 = 0.898$). There were two-way interactions between consistency across motion periods and consistency across the blank, $F(4,60) = 7.22$, $p < 0.001$ ($\eta_p^2 = 0.325$), as well as consistency across the blank and position, $F(1,15) = 7.13$, $p < 0.05$ ($\eta_p^2 = 0.322$), but the interaction between consistency across motion periods and position was not significant, $F(4,60) = 0.45$, $p = 0.77$ ($\eta_p^2 = 0.029$). The three-way interaction was significant, $F(4,60) = 4.72$, $p < 0.01$ ($\eta_p^2 = 0.24$).

Simple effect analyses were conducted to find the source of the three-way interaction. We first examined trials when colors were inconsistent across motion periods. We averaged across the levels of motion period duration and submitted the data to examine effects of consistency across the blank (inconsistent, consistent) and position (pause, move). This revealed main effects of color consistency, $F(1,15) = 7.94$, $p < 0.05$ ($\eta_p^2 = 0.34$), and position, $F(1,15) = 111.89$, $p < 0.001$ ($\eta_p^2 = 0.88$), but no interaction, $F(1,15) = 0.39$, $p = 0.54$ ($\eta_p^2 = 0.02$). When averaged across the levels of position, there was a modest, but significant, increase in accuracy when colors were consistent across the blank ($\overline{X} = 0.74$, $SEM = 0.26$) compared to when they were inconsistent across the blank ($\overline{X} = 0.71$, $SEM = 0.027$), $t(15) = 2.82$, $p < 0.05$ ($d = 0.28$). This confirmed that the main effect of consistency was driven by a consistent color benefit. Then, trials with consistent colors across motion periods were submitted to a simple effects ANOVA to examine the factors of color consistency across the blank (inconsistent, consistent) and position (pause, move). There were main effects of consistency, $F(1,15) = 42.21$, $p < 0.001$ ($\eta_p^2 = 0.74$), and position, $F(1,15) = 67.48$, $p < 0.001$ ($\eta_p^2 = 0.82$), and the interaction was significant, $F(1,15) = 20.27$, $p < 0.001$ ($\eta_p^2 = 0.57$). Paired comparisons showed higher performance when the color across the blank was consistent compared to inconsistent in both the pause, $t(15) = 2.52$, $p < 0.05$ ($d = 0.53$), and the move trials, $t(15) = 6.89$, $p < 0.001$ ($d = 1.7$). As shown on the right side of Figure 3.2, there was a larger benefit from color consistency across the blank when the dots moved compared to than when they paused. This was confirmed by taking the difference between consistent and inconsistent color trials and comparing these differences across move and pause trials.

This contrast revealed a significant larger difference in the move trials compared to the pause trials, $t(15) = 4.5$, $p < 0.001$ ($d = 1.44$).

Discussion

These results clearly showed facilitated target recovery when colors were consistent across the blank. However, this consistent-color benefit was much stronger when the colors of the objects were visibly consistent across motion periods. Further results showed a greater consistent-color benefit when the dots moved compared to when they paused during the blank. These results suggest that appearance information is relied on more when other types of information, such as object position, are insufficient to create a correspondence across a discontinuity. We conclude that appearance information is important in preserving the continuity of dynamic objects tracked across a blank. These observations are consistent with the sampling account in that the success of tracking was dependent the consistency of object position and color. These results can be explained by a mechanism that samples information about the targets before the blank and compares that to information after the blank to successfully recover the targets. We also found that consistent colors across periods facilitated performance, suggesting perhaps that people used color to sustain target representations during tracking.

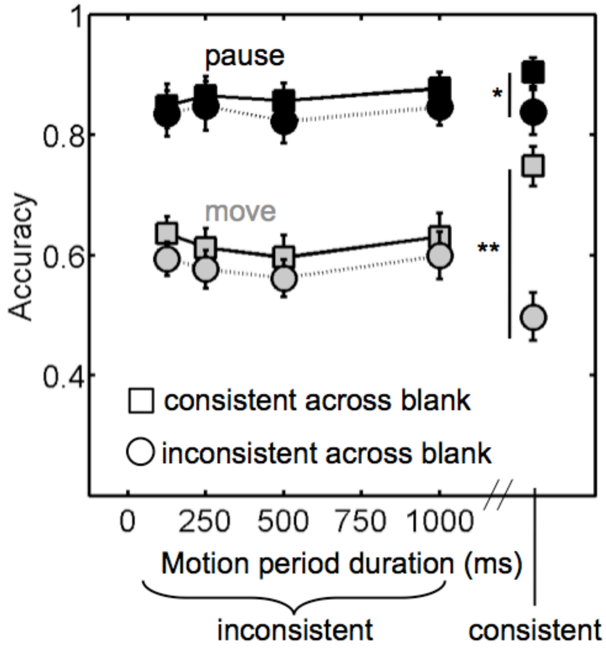


FIGURE 3.2
The results of Experiment 3.1 are depicted to the left. When colors were inconsistent across periods, they changed once per period. Higher performance was found when dots paused during the blank (black) versus moved (gray). There was better performance when colors were the consistent across the blank (squares) compared to when they were inconsistent across the blank (circles). When colors were inconsistent across periods, there was a modest consistent color benefit ($p < 0.05$). Consistent color benefits were more evident when the colors were consistent across periods in both pause (black) and move (gray) conditions. * $p < 0.05$, ** $p < 0.001$. The error bars represent the standard error of the mean.

Experiment 3.2: Color consistency in object tracking and target recovery

In Experiment 3.1, we demonstrated that consistent colors facilitated TR. Does consistent color have a similar effect on MOT? In the current experiment, MOT and TR tasks were mixed, as the absence or presence of a blank varied randomly across trials. Importantly, the consistency of colors was manipulated differently to examine the effects of consistency on behavior related to MOT and TR. In MOT trials (blank absent), the effect of color consistency was assessed by manipulating whether the colors consistent across motion periods. In TR trials (blank present), the effect of color consistency was assessed by manipulating whether the object colors were consistent or inconsistent across the blank. It is proposed that if a common process mediates both MOT and TR, then the effect of color consistency should be the same in both tasks. Alternatively, if distinct processes mediate both MOT and TR, then the effect of color consistency should be different across tasks. A secondary purpose of Experiment 3.2 was to investigate whether the use of appearance information in TR is mediated by VSTM. Participants performed an articulatory suppression task to discourage verbal encoding of the colors.

Method

Participants were 12 Vanderbilt undergraduate students, including 4 females, with a mean age of 18.58 (*s* = 0.9). The apparatus was identical to that of Experiment 3.1, except that vocal responses to the articulatory suppression task were recorded with an InSync gooseneck microphone, connected with a Griffin iMic USB convertor. The stimuli were identical to that of Experiment 3.1.

Procedure

As shown in Figure 3.3, participants viewed 2 vertically aligned digits for 500 ms and were instructed to repeatedly recite these digits aloud into a microphone until the end of the dot motion. A 200 ms interstimulus interval (ISI) followed. The square white frame then appeared for 500 ms, followed by nine dots, including the 3 circled targets, for 2000 ms. The circle cues disappeared, and after 200 ms, the dots randomly moved for 6000 ms. The blank was absent in half of the trials and present in the other half of the trials, indicating MOT and TR trials, respectively. In order to find conditions under which MOT and TR could be equated for task difficulty, the average speed of the dots' motion was varied to be 9.38, 12.42, 15.49, or 18.56°/s. In half of all the trials, the dot colors were consistent across motion periods, while in the other half they were made inconsistent across periods by swapping at a random point in each period. Of the trials with colors that were inconsistent across motion periods, only a 500 ms period duration was used. In the TR trials, all of the dots disappeared at 1, 2, 3 or 4 seconds after the start of the dot motion for 200 ms. The dots continued to move during the blank in all trials. The dot colors were inconsistent across the blank in half of the TR trials, and consistent across the blank in the other half of TR trials. In MOT trials, the manipulation of consistency across the blank was coded as a dummy variable since there was no blank. For both MOT and TR, the dots stopped moving and turned white after moving for 6000 ms. Participants selected targets by controlling a box on the display with the computer mouse. To avoid feedback effects on each response, the tone accompanying each selection was uninformative. After participants selected three objects, the targets appeared red for 200 ms before the blank intertrial interval (ITI), so that feedback was not available until all selections were made. There were 8 trials per condition, resulting in a total of 256 trials.

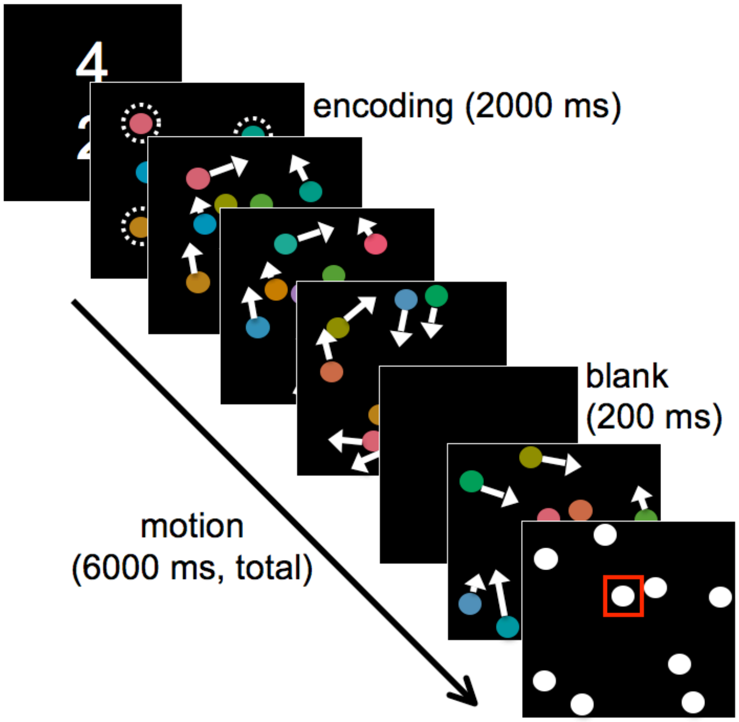


FIGURE 3.3
A schematic of the procedure for target recovery (TR) trials when colors were inconsistent across periods in Experiment 3.2. First, participants were shown two digits for the articulatory suppression task. Next, different colored dots appeared for 2000 ms with the targets cued by circles. Next, the dots started to move and change colors. The mask and blank appeared at 1, 2, 3 or 4 seconds from the beginning of the 6000 ms motion period. Multiple-object tracking (MOT) trials were similar except that the mask and blank were absent.

Results

We directly compared the consistent color benefits in MOT and TR by examining the difference in accuracy between trials when color was consistent and inconsistent. For MOT, trials with consistent colors across periods were categorized as consistent, while trials with inconsistent colors across periods, averaged across all period durations, were categorized as inconsistent. In TR, trials with consistent colors across the blank were categorized as consistent, while trials with inconsistent colors across the blank were categorized as inconsistent. For TR, only trials with consistent colors across motion periods were considered for analysis. Results from earlier experiments had shown that the effects of consistency across the blank in TR were only effective when the colors were consistent across motion periods (data not shown). The data were submitted to a 3-way ANOVA to examine the effects of Speed (9.38, 12.42, 15.49, 18.56°/s) x Task (MOT, TR) x Consistency (inconsistent, consistent). There were main effects of Speed, $F(3,33) = 98.4$, $p < 0.001$ ($\eta_p^2 = 0.899$), Task, $F(1,11) = 168.5$, $p < 0.001$ ($\eta_p^2 = 0.94$), and Consistency, $F(1,11) = 39.08$, $p < 0.001$ ($\eta_p^2 = 0.78$). There was no Speed x Consistency interaction, $F(3,33) = 1.27$, $p = 0.3$. However, there was a Speed x Task interaction, $F(3,33) = 5.5$, $p < 0.01$ ($\eta_p^2 = 0.33$), as well as a Task x Consistency interaction, $F(1,11) = 26.96$, $p < 0.001$ ($\eta_p^2 = 0.71$). The three-way interaction was significant, $F(3,33) = 3.19$, $p < 0.05$, $\eta_p^2 = 0.22$ (see Figure 3.4A).

The goal of the speed manipulation was to observe the effects of color consistency in both MOT and TR under conditions in which MOT performance was below ceiling. To do this, we examined the MOT trials and TR trials when the colors were consistent. On average, MOT performance ($\overline{X} = 0.77$, $SEM = 0.03$) when the object speed was 18.56°/s was similar to TR performance ($\overline{X}$ = 0.72, *SEM* = 0.04) when the object speed was 15.49°/s, $t(11) = 1.06$, $p = 0.31$. Importantly, this MOT performance was not at ceiling, as it was significantly lower than to MOT performance in color-consistent trials when the object speed was 9.38°/s, $t(11) = 3.78$, $p < 0.001$ (d = 1.44). We then examined the effects of Task and Consistency for MOT at 18.56°/s and TR at 15.49 °/s. These data showed main effects of Task, $F(1,11) = 14.93$, $p = 0.01$ (η_p^2 = 0.58), and Consistency, $F(1,11) = 27.62$, $p < 0.001$ (η_p^2 = 0.72), but no interaction, $F(1,11) = 3.47$, $p = 0.09$ (η_p^2 = 0.24). Paired comparisons showed superior performance in consistent trials compared to inconsistent trials for both MOT, $t(11) = 3.27$, $p < 0.01$ (d = 1.14), and TR, $t(11) = 4.9$, $p < 0.001$ (d = 2.08). The lack of interaction observed in this analysis suggests a similar use of surface features in both tasks (Figure 3.4B).

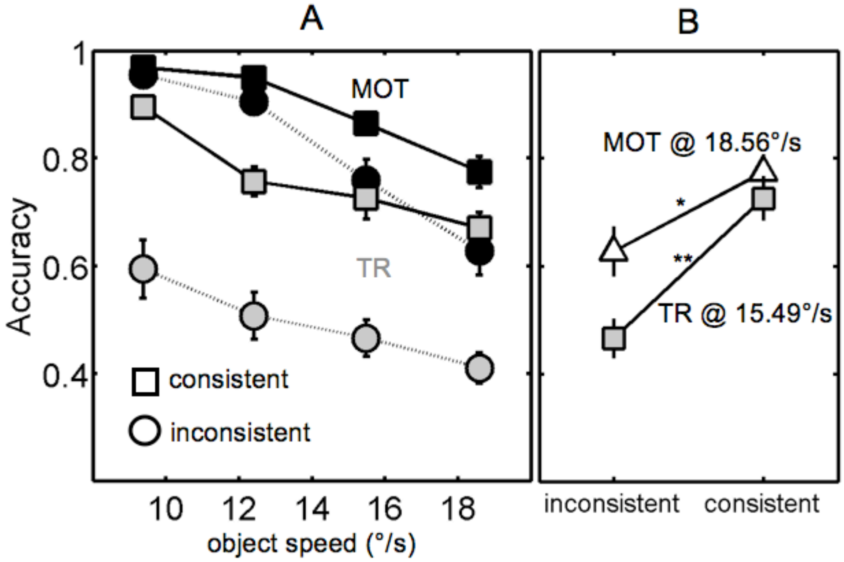


FIGURE 3.4 The results of Experiment 3.2 are depicted above. (A) Accuracy is plotted as a function of object speed in terms of degrees per second (°/s). The results of MOT trials are depicted as black symbols, while the results of TR are depicted as gray symbols. The results of trials with consistent colors are depicted as squares, while those with inconsistent colors are depicted as circles. (B) A direct comparison between MOT trials brought below ceiling performance and TR is depicted, using data from Experiment 2B. MOT performance at the fastest object speed (18.56°/s) was shown to be comparable to that of TR at a slower speed (15.49°/s) when object color was consistent ($p = 0.31$). Consistent-color benefits were observed for both MOT (* $p < 0.01$) and TR (** $p < 0.001$). Error bars show standard error of the mean for each condition.

Discussion

The results of Experiment 3.2 showed that consistent object colors facilitated performance in both MOT and TR. In relation to the predictions, these results support the hypothesis that a common process mediates both MOT and TR. These results accord with a sampling model of object continuity, which predicts that performance is determined the consistency of information related to the target objects (Allen McGeorge, Pearson & Milne, 2006; Oksama & Hyönä, 2008). In the current study, the decrease in accuracy due to inconsistent colors can be accounted for if the mismatch between the memory of the target colors and new input impaired object correspondence. Observing the same effect of color consistency in both MOT and TR suggests that the same mechanism is common to both tasks.

The consistent-color benefit was observed despite the use of a concurrent articulatory suppression task in both MOT and TR. This is some evidence to suggest that the information about colors was not stored as a verbal code, but instead stored in VSTM. The results of a previous experiment showed the same effects of consistency across the blank in TR, even when the blank was preceded by a full-screen mask (data not shown). This supported the idea that VSTM was used to represent color in TR. The consistent-color benefit observed in the MOT task with concurrent articulatory suppression suggests that color information in MOT may also be maintained in VSTM, which agrees with previous research (Makovski & Jiang, 2009b). However, unlike TR, the objects in MOT are always visible, so it is possible that the color representation is sustained in the visual system without relying on VSTM. The next experiment directly examined the difference in color representation for MOT and TR.

Experiment 3.3: Color representation in object tracking and target recovery

What kind of memory mediates the use of colors in TR and MOT? The results from Experiment 3.2 suggest that VSTM may play a role. VSTM capacity for perceptually distinguishable stimuli belonging to the same category is reduced to about one object (Olsson & Poom, 2005). Awh, Barton and Vogel (2007) showed that change detection accuracy was better when objects changed to a different category, (e.g. Chinese characters and random polygons), compared to when objects changed to another exemplar of the same category. Together, these studies indicate that VSTM represents color with relatively low resolution. Based on these studies, we predicted that a low-resolution representation in VSTM would enable participants to detect large changes in color, but less able to detect small changes in color. Trials with large color changes would lead to a higher probability of mismatch during a sample-to-comparison process, leading to a greater decrease in accuracy. In further testing the idea that VSTM mediates color representation in TR, a full-screen mask appeared just prior to the blank in TR trials. VSTM representations are known to be robust to effects of visual masking (Vogel, Woodman & Luck, 2006). In summary, if color is represented solely by VSTM, the degree of accuracy impairment related to inconsistent colors should be affected by whether the magnitude of change is small or large.

Method

Participants were 16 Vanderbilt undergraduate students, including 6 females, with a mean age of 19.4 (*s* = 1.18). The apparatus and stimuli were identical to that of Experiment 3.2, except that the blank was preceded by a full screen mask composed of

36 discs, each spanning 2.3° in diameter and positioned on points of a grid spanning the entire tracking frame. Each grid position was jittered by ±0.76° to degrade the appearance of a grid. These discs appeared in randomly selected colors drawn from the same color set described above. The procedure was identical to that of Experiment 3.2, with the following modifications. The color changes were either small or large in magnitude both when the colors were inconsistent across motion periods and when the colors were inconsistent across the blank. Small color changes involved changing the color of a dot to one of two 2nd neighbors in our set of 12 colors, such as between two shades of blue. Large color changes involved changing the current color to one of two 5th neighbors in our color set, such as between blue and red. In addition, we only used the 500 ms motion period duration. We added a factor of speed to equate task difficulty between MOT and TR, so that the dots moved at a rate of 9.5°/s or 18.36°/s. Participants completed 8 trials for each condition for a total of 256 trials.

Results and Discussion

The trials were sorted as inconsistent or consistent, just as in Experiment 3.2. The data were then submitted to a 4-way ANOVA to examine the effects of Speed (9.5, 18.36°/s) x Magnitude (Small, Large) x Task (MOT, TR) x Consistency (consistent, inconsistent). The results revealed main effects of Speed, $F(1,15) = 114.01$, $p < 0.001$ ($\eta_p^2 = 0.88$), Magnitude, $F(1,15) = 14.23$, $p < 0.01$ ($\eta_p^2 = 0.49$), Task, $F(1,15) = 154.71$, $p < 0.0001$ ($\eta_p^2 = 0.91$), and Consistency, $F(1,15) = 114.9$, $p < 0.0001$ ($\eta_p^2 = 0.906$). There were two-way interactions between Speed x Task, $F(1,15) = 5.92$, $p < 0.05$ ($\eta_p^2 = 0.28$), Magnitude x Task, $F(1,15) = 9.42$, $p < 0.01$ ($\eta_p^2 = 0.386$), Task x Consistency,

$F(1,15) = 27.23$, $p < 0.001$ ($\eta_p^2 = 0.64$), and Magnitude x Consistency, $F(1,15) = 8.29$, $p < 0.05$ ($\eta_p^2 = 0.36$). The other interactions were not significant (F's < 1). The only significant three-way interaction was Speed x Task x Consistency, $F(1,15) = 11.97$, $p < 0.01$ ($\eta_p^2 = 0.44$). While the Speed x Magnitude x Task interaction was approaching significance, $F(1,15) = 3.9$, $p = 0.067$ ($\eta_p^2 = 0.206$), the others were not close to significance (F's < 2.3). The 4-way interaction was also significant, $F(1,15) = 8.92$, $p < 0.01$ ($\eta_p^2 = 0.37$). We investigated the source of this interaction with simple effects ANOVAs and planned comparisons.

The results of performance at 9.5°/s showed that the magnitude of color change modulated performance in TR, but MOT performance was potentially at ceiling. For MOT at 9.5°/s, a simple effects analysis revealed no main effect of Magnitude, $F((1,15) = 0.27$, $p = 0.6$ ($\eta_p^2 = 0.018$), however there was an effect of Consistency, $F(1,15) = 4.73$, $p < 0.05$ ($\eta_p^2 = 0.24$), which revealed higher performance when colors were consistent ($\overline{X} = 0.94$, $SEM = 0.015$) compared to when they were inconsistent ($\overline{X} = 0.87$, $SEM = 0.04$). There was no Magnitude x Consistency interaction, $F(1,15) = 0.72$, $p = 0.41$ ($\eta_p^2 = 0.045$). For TR at 9.5°/s, there were main effects of Magnitude, $F(1,15) = 18.58$, $p < 0.001$ ($\eta_p^2 = 0.55$), and Consistency, $F(1,15) = 110.99$, $p < 0.001$ ($\eta_p^2 = 0.88$), and a significant interaction, $F(1,15) = 13.76$, $p < 0.01$ ($\eta_p^2 = 0.48$). This interaction was confirmed with difference scores, constructed by subtracting performance in the inconsistent trials from the consistent trials, showed a larger difference for large color changes compared to small color changes in TR, $t(15) = 3.71$, $p < 0.01$ ($d = 1.08$). The results are depicted in Figure 3.5A.

The purpose of the speed manipulation was to examine whether the magnitude of color change affected MOT performance once it was brought down from ceiling. To confirm this, we contrasted MOT performance at 9.5°/s to 18.36°/s, averaging across all other trial types. This revealed significantly higher performance at 9.5°/s, $t(15) = 8.99$, $p < 0.001$ ($d = 1.66$), confirming that MOT performance was lower than ceiling at the faster speed. For MOT at 18.36°/s, a simple effects analysis revealed a main effect of Consistency, $F(1,15) = 36.1$, $p < 0.001$ ($\eta_p^2 = 0.71$), which showed higher performance when colors were consistent ($\overline{X} = 0.76$, $SEM = 0.03$) compared to when they were inconsistent ($\overline{X} = 0.62$, $SEM = 0.05$). However, there was no effect of Magnitude, $F(1,15) = 3.87$, $p = 0.068$ ($\eta_p^2 = 0.20$), and no interaction, $F(1,15) = 0.7$, $p = 0.42$ ($\eta_p^2 = 0.04$). For TR at 18.36°/s, a simple effects analysis revealed a main effect of Consistency, $F(1,15) = 77.82$, $p < 0.001$ ($\eta_p^2 = 0.84$), which showed higher performance when colors were consistent ($\overline{X} = 0.54$, $SEM = 0.02$) compared to when they were inconsistent ($\overline{X} = 0.33$, $SEM = 0.016$). There was no effect of Magnitude, $F(1,15) = 4.0$, $p = 0.06$ ($\eta_p^2 = 0.21$), and no interaction, $F(1,15) = 0.3$, $p = 0.59$ ($\eta_p^2 = 0.02$). When speed was 18.36°/s, we still did not observe an effect of color change magnitude in MOT, even though MOT performance was brought down from ceiling. We also did not observe effects of color change magnitude in TR at this speed, but this may have been because performance in the inconsistent trials was at floor. Together, it seems that color representation in TR can be sensitive to the magnitude of change, while color representation in MOT is not (Figure 3.5B).

These results showed that while the color consistency effect in MOT was not sensitive to the magnitude of color change, the color consistency effect in TR was sensitive to the magnitude of change. This may indicate that color representations in TR are mediated by VSTM, but are represented differently in MOT. It is possible that VSTM mediates color representation in MOT (Makovski & Jiang, 2009b), but it can be buttressed by other systems, such as iconic memory or sensory persistence, which were not eliminated in the MOT task. Extra precision in the representation of color afforded by iconic memory may provide greater sensitivity to the small color changes during MOT. In summary, the results support the notion that color is represented differently in TR and MOT.

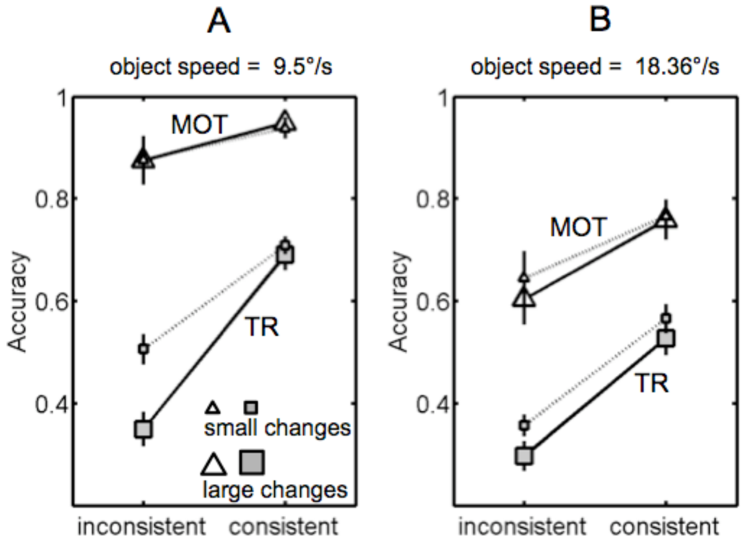


FIGURE 3.5
The results of Experiment 3.3 are depicted to the left. (A) At 9.5°/s, TR performance was modulated by the magnitude of color change, while ceiling performance in MOT may have obscured effects of magnitude. (B) At 18.36°/s, MOT performance was brought down from ceiling (see text for analysis), but no effect of color change magnitude was observed. Error bars show standard error of the mean for each condition.

Experiment 3.4: Color correspondence in target recovery is not object-specific

In this experiment, we examined whether the process of matching colors between each sample was specific to each object. An alternative account is that participants stored a list of the target colors without remembering which color belonged to which object. We contrasted these accounts by manipulating whether the targets swapped colors with other targets or with non-targets. The object-specific account predicts that task performance would drop in both conditions, because each specific object's color would be inconsistent. The alternative account predicts that task performance would only drop in the latter condition. If participants remembered target colors without making a correspondence to each object, then the matching process would not consider swaps between targets to be inconsistent, but it would consider swaps with non-targets to be inconsistent.

Method

Participants were 11 Vanderbilt undergraduates, including 5 females (mean age = 18.63, *s* = 1.02). The apparatus and stimuli were identical to that of Experiment 3.3. The procedure was identical to that of Experiment 3.3, except that we did not manipulate the magnitude of the color change or object speed. Instead, we manipulated how the colors were swapped in the inconsistent trials. In half of the trials, targets swapped colors with other targets, while non-targets swapped colors with other non-targets. In other words, the colors were swapped within groups. In the other half, the targets swapped colors with non-targets, so that colors were swapped across groups. Finally, participants tracked four out of eight objects. There were 8 trials per condition, resulting in 128 trials in total.

Results and Discussion

The data were categorized as consistent or inconsistent, as in Experiment 3.2, and submitted to a 3-way ANOVA to examine the effects of Group (within, across) x Task (MOT, TR) x Consistency (inconsistent, consistent). This revealed main effects of

Group, $F(1,10) = 7.18$, $p < 0.05$ ($\eta_p^2 = 0.42$), Task, $F(1,10) = 269.05$, $p < 0.001$ ($\eta_p^2 = 0.96$), and Consistency, $F(1,10) = 19.67$, $p < 0.01$ ($\eta_p^2 = 0.66$). There was no Group x Task interaction, $F(1,10) = 2.28$, $p = 0.16$. However, there was a significant Group x Consistency interaction, $F(1,10) = 13.93$, $p < 0.01$ ($\eta_p^2 = 0.58$), and a Task x Consistency interaction, $F(1,10) = 9.06$, $p < 0.05$ ($\eta_p^2 = 0.47$). The three-way interaction was significant, $F(1,10) = 10.14$, $p < 0.01$ ($\eta_p^2 = 0.5$). The results of the three-way interaction suggested that consistency effects were observed when the changes were made across groups rather than within groups. This was confirmed by paired comparisons made between inconsistent and consistent trials for each task and each level of the grouping manipulation. Of these four *t*-tests, a significant effect was found only in TR when changes were made across groups, $t(10) = 5.77$, $p < 0.001$ (all other *t*'s < 1.3).

Color-based errors. We conducted further analyses to pursue the possibility that participants are using a color-based strategy involving memorizing a list of target colors and using it for recovery when a target is lost. We examined the number of response errors made in TR trials when colors were consistent across motion periods, across levels of Group (Within, Across) and consistency across the blank (inconsistent, consistent). A 2-way ANOVA revealed main effects of Group, $F(1,10) = 5.36$, $p < 0.05$ ($\eta_p^2 = 0.35$), and Consistency, $F(1,10) = 17.78$, $p < 0.01$ ($\eta_p^2 = 0.64$), and a significant interaction, $F(1,10) = 16.42$, $p < 0.01$ ($\eta_p^2 = 0.62$). Paired comparisons revealed that more errors were made in inconsistent trials compared to consistent trials Across Groups, $t(10) = 5.77$, $p < 0.001$, but not Within Groups, $t(10) = 0.55$, $p = 0.59$. Of the errors made in the inconsistent trials of the Across Groups condition, we calculated how often participants selected a non-target whose post-blank color matched that of a pre-blank color of a missing target. These errors accounted for 57% of the errors in that condition.

These results show that the consistent-color benefits that we observed in previous experiments are not object-specific. That is, a one-to-one object correspondence is not necessary to maintain consistency. At a glance, these results seem to support the idea that participants strategically remember a list of target colors. If the targets are lost, as in target recovery, they simply recover objects appearing colors belonging to that list, regardless of the objects' positions. In trials where targets swap colors with other targets, selection errors would be less likely since participants using this strategy would recovery other targets. In trials where targets swap colors with other targets, participants using this strategy would mistakenly recovery non-targets, leading to more selection errors. This predicts no performance impairment in within-group trials, but does predict impairment in across-group trials. However, this idea is not supported by the error analysis in TR, which showed that mistakenly recovering non-targets that appeared in the same colors as targets prior to the blank only accounted for a little over half of the total errors. There could be other kinds of information, such as motion or position, which contribute to object correspondence along with color. An alternative account is that due to attention being divided between several targets, some target colors were mistakenly bound to targets other than the ones the colors were originally assigned. In other words, participants could have formed illusory conjunctions (Treisman & Schmidt, 1982), and misbind target relevant information.

General Discussion of Chapter III

The experiments in this study were designed to explore the idea that a sampling process mediates the ability to track objects. The idea of a sampling mechanism makes two general predictions. First, objects can be tracked across a visual discontinuity. This is because no information is processed between samples, and this is supported by findings in TR (Alvarez et al., 2005; Horowitz et al., 2006). Second, preservation of object continuity is dependent upon the consistency of information between samples. This has been shown in the TR task in one study in which performance was dependent on the consistency of position across the blank (Keane & Pylyshyn, 2006).

We examined whether performance related to two tasks, multiple object tracking (MOT) and target recovery (TR), was similarly affected by the consistency of objects' colors. The sampling mechanism predicts that performance would be facilitated by consistent object information, and impaired by inconsistent object information. The results demonstrated a consistent color benefit in both the MOT and TR tasks. In the first experiment, we observed that consistent colors across the blank in TR facilitated performance. Color provided a strong cue to relate the objects across a discontinuity and it was used more when other information, namely object position, was not completely reliable. Experiment 3.2 directly compared the effects of color consistency in MOT and TR. It was hypothesized that if a common process mediated MOT and TR, then there would be similar effects of color consistency across both tasks. If distinct processes mediated MOT and TR, there would be different effects of color consistency across both tasks. The results of Experiment 3.2 showed a consistent-color benefit in both MOT as well as TR, which agreed with the prediction of the common process hypothesis. The results of Experiments 3.3 showed the consistent-color benefits were modulated by the magnitude of the color change in TR, but not MOT. Finally, the results of Experiment 3.4 showed that the consistent color benefit was not object-specific. Accurate tracking did not depend on there being a one-to-one correspondence between the target objects and their colors. Instead, target recovery was successful and object continuity was maintained if any target appeared in any target color.

Together, these results suggest that object continuity is preserved by a process that is sensitive to the consistency of object color for both objects that remain continuously visible, as in MOT, and objects that briefly disappear, as in TR. This could be a process that periodically samples information and compares it to other samples across discrete time intervals. We offer the observation that both MOT and TR are similarly affected by the consistency of color information as evidence that the object correspondence process is uses a sampling mechanism. Furthermore, our results suggest that different representations of color may be used for visible and invisible objects. Our results suggest that colors may be represented with higher resolution for visible objects than invisible objects. This may be because in addition to the use of VSTM, color representation for visible objects may be buttressed by iconic memory or another kind of sensory memory.

Does a common process mediate both MOT and TR?

The results of this chapter suggest that a common process could support the preservation of object continuity for both MOT and TR, and that this process may involve a periodic sampling mechanism. Previous work using MOT had suggested that location information about the targets was sampled and compared in an iterative process (Allen et al., 2006; Oksama & Hyönä, 2008). Not only does this account for the effects of speed on MOT performance (Oksama & Hyönä, 2008), but it also accounts for the results of TR (Keane & Pylyshyn, 2006). The current results extend this theory by suggesting that the sampling process is sensitive to color. Manipulating the consistency of object colors in our tasks affected behavior, such that inconsistent colors impaired performance of both MOT and TR. These results support the idea that color information is sampled from objects during tracking and stored for comparison during the next interval of sampling. The goal of this comparison is to find a match based on position and color – matches preserve object continuity, while mismatches impair object continuity.

The idea of periodically sampling information is not restricted to tracking tasks such as MOT and TR. Research on visual attention has demonstrated that information is not apprehended in a continuous manner. Transient attention can be drawn to a spatial location, but not be held there indefinitely (Nakayama & Mackeben, 1989). Van Rullen, Carlson and Cavanagh (2007) provided some psychophysical evidence that attention processes information in a periodic manner, even when only one object is attended. Observers viewed four discs of random noise, and were cued to one or more locations where a brief change in contrast was likely to occur. The derived psychometric functions were compared against computational models that assumed continuous accrual of information or periodic sampling of information. When stimuli had a lower overall contrast, the prediction error for the sampling model was significantly lower than that of the continuous model. This suggested that visual attention operated in a periodic sampling manner under some viewing conditions. Also, Van Rullen, Reddy and Koch (2005) showed that visual attention enhanced motion direction ambiguity in stimuli resembling the wagon-wheel illusion. The wagon-wheel illusion refers to the misperception of a wheel's spokes rotating in the opposite direction to that of the wheel. This has been attributed to a mechanism that discretely samples position information of a moving object and computes motion based on the smallest spatial displacements in the display. The illusion arises because the mechanism samples at a sub-optimal rate, so that the smallest displacements between samples are not in the wheel's direction of motion, but in the opposite direction of motion. They showed that this misperception occurred when the elements of a stimulus cycled around 10 Hertz. However, this misperception was eliminated when observers concurrently engaged in an attentive task, in a rare demonstration that attention could impair psychophysical performance. This suggested that visual attention was the source of discrete sampling of information in this illusion.

How is sampled information stored? The storage of sampled information may be mediated by VSTM, as suggested by Allen et al. (2006) and Oksama and Hyönä (2008). The storage of position information can account for previous results of TR studies (Keane & Pylyshyn, 2006), as well as findings of how speed affects MOT (Oksama & Hyönä, 2008). Our results extend this account by suggesting that color information may also be stored in VSTM. Makovski and Jiang (2009b) showed that color information, when used to facilitate MOT performance, was stored in VSTM. Tracking performance benefited when the objects were uniquely colored compared to when they were homogenously colored, but this benefit was not observed when participants concurrently performed a one-back color memory task during tracking. The results of the current study suggested that the color representation used during MOT was of higher resolution than what is expected of VSTM. However, they do not refute the results of Makovski and Jiang (2009b), since it is possible that color representation for visible objects may benefit from additional types of memory, like iconic memory. Another possibility is that VSTM could store color at a higher resolution than previously assumed.

Could the attentional sampling mechanism account for the observation that color correspondence is not object-specific? It is possible that attention to the multiple objects stems from a single, common resource. Divided attention could have resulted in binding errors that produced illusory conjunctions (Treisman & Schmidt, 1982). All of the target colors and locations could have been sampled and accurately retained, but improperly matched to information in memory. The comparison mechanism would recognize a match for any previously retained color, regardless of what object previously appeared in that color. The conditions of the task could have increased the probability for illusory conjunctions, because the colors were not task relevant, unlike the results of Chapter II, which showed accurate object-specific color memory when the colors were task relevant.

The role of spatiotemporal and surface features in object continuity

Object continuity depends on making a correspondence between different states with some form of information. What kind of information mediates object continuity? In its original form, object file theory proposed that correspondence is based on spatiotemporal continuity, while appearance is allowed to vary greatly (Kahneman, Treisman & Gibbs, 1992). In other words, the way an object is considered to be the same object even when the visual information changes is determined by its place in space and time, not by its appearance. In accordance with the original version of object file theory, some research has shown that object continuity is based primarily on spatial and temporal information, rather than appearance (Scholl, 2001; Mitroff & Alvarez, 2007; Flombaum, Scholl & Santos, 2009). For example, motion of a single object can be perceived between two spatially- and temporally-distinct events, even when the object changes appearance (Cavanagh, Arguin & von Grunau, 1989; Kolers & Pomerantz, 1971; Kolers & von Grunau, 1976). Visual masking occurring on the level of object representations may reflect the integration of two differently appearing objects into a single representation (Enns & Di Lollo, 1997; Lleras & Moore, 2003). Also, an object passing through a tunnel in a smooth motion path is perceived as a single object, even if it appears dramatically different between entering and exiting the tunnel (Flombaum, Kundey, Santos & Scholl, 2004).

However, other studies have shown that appearance can have an important role in preserving object continuity. Memory for appearance can be important for preserving object continuity across saccades (Hollingworth, Richard & Luck, 2008). Apparent motion perception can be facilitated with consistent spatial frequency (Green, 1986; Ramachandran, Ginsburg & Anstis, 1983) or color (Green, 1989; Dobkins & Albright, 1993). Appearance information is also crucial in determining the perception of an object's motion path when spatiotemporal information is made ambiguous; Feldman & Tremoulet, 2006). A moving object changing in appearance can be perceived as multiple objects rather than different states of the same object (Moore & Enns, 2004; Moore, Mordkoff & Enns, 2007).

The results of the current study do not speak to whether spatiotemporal information or surface features are dominant in preserving object continuity, but they do support the idea that both play a role. Tracking tasks like MOT and TR are inherently spatial, but the results of the current study as well as others (Horowitz et al., 2007; Oksama & Hyönä 2004, 2008; Makovski & Jiang, 2009a, 2009b) have provided evidence that surface features facilitate tracking, and can play a role in successful object correspondence processes.

Conclusion of Chapter III

The results of this chapter suggest that object tracking could be mediated by periodically sampling information, and this process is sensitive to the consistency of object color. Color representation is different across the tasks, in that color for visible objects in MOT may be of higher resolution than in TR, suggesting that additional memory systems could buttress color representation in MOT, but not TR. Finally, the consistent color benefit observed was not object-specific. This could have stemmed from illusory conjunctions formed due to attention being divided across several target objects.

One important feature of a matching process is that some perceptual change must be detected even when a match between corresponding pieces of information is made. This is the hallmark of updating an object representation. Updating will be examined more closely in the following chapter.

CHAPTER IV

UPDATING OBJECTS IN VISUAL SHORT-TERM MEMORY

Introduction

In the previous chapter, I presented research suggesting that a periodic process preserves the continuity objects of attention and memory. Part of this process entails matching new information to previous features of the object. It is important for a correspondence process to tolerate a degree of change in any feature while still computing a match between the different object states. This would update the object, so it is perceived to have changed but still considered the same continuous entity. In this chapter, I present research examining the nature of updating visual object representations in memory. Parts of this research were published by Ko and Seiffert (2009).

Updating refers to the modification of short-term memory by adding new information and/or replacing old information. This is an important ability in daily life, for example when creating a mental list and revising it as new priorities arise. If, while at the grocery store, you get a call telling you that you should also buy milk but not buy butter, you can modify your working memory to incorporate this new information and end up with a new mental list. Updating is an executive function, and is not constrained by the limits of short-term memory capacity (Morris & Jones, 1990). Some research suggests updating is functionally distinct from other executive functions, such as inhibition and task-switching (Miyake, Friedman, Emerson, Witzki & Howerter, 2000), and is the only one of these functions related to intelligence measures (Friedman, Miyake, Corley, Young, DeFries & Hewitt, 2005). Here, we will use the term updating to refer to any modification to the contents of working memory that necessitates combining new information with stored information, including modifying the memory of the attributes of an object. Updating tasks have been useful in examining other cognitive processes (Garavan, 1998; Oberauer, 2002), but few studies have examined the updating process itself (Bao, Li & Zhang, 2007; Kessler & Meiran, 2006; Morris & Jones, 1990). In this chapter, we examined whether updating VSTM is an object-based process.

Luck and Vogel (1997) provided the first evidence suggesting that object representations were the units of storage in VSTM, as described in previous chapters. Following these findings of object-based storage in VSTM, the purpose of the current study was to examine whether another use of VSTM, specifically updating, was also object-based. We asked whether updating memory would lead to reprocessing of all the features of a target object. In other words, does updating one feature of an object in memory automatically refresh all other features of the same object? If VSTM stores information as object representations, then one might expect that any process, such as updating, affecting one feature of the object representation would also affect on the other features.

The motivation for predicting object-based updating in VSTM stems from the object-based attention literature. As described in the Introduction, the seminal work on object-based attention came from studies of divided attention. These results showed that the cost of divided attention was attenuated when two attended features appeared on one object instead of across two objects, suggesting that the units of attentional selection was an object (Duncan, 1984; Baylis & Driver, 1993; Vecera & Farah, 1994; Watson & Kramer, 1999; Awh et al., 2001).

Another important branch of research in object-based attention has examined the spread of attention within an object. Egly, Driver and Rafal (1994) presented participants with two vertical rectangles and cued them to one corner of one rectangle. Detection of a probe at the cued location was significantly faster compared to when the probe appeared at uncued locations, replicating Posner's (1980) famous findings of spatial attention. However, probe detection at an uncued location within the same object as the cued location was significantly faster than uncued locations in a different object, even when these locations were equidistant from the cued location. This indicated the automatic spread of attention throughout an object once it was attended. Lamy and Tsal (2000) conducted a similar study, except that the appearance of the two objects was different in color and shape. In one experiment, participants were told that if a cue appeared inside an object, the target was likely to appear inside an object of the same color and shape, regardless of location. The results showed a facilitated detection when the target appeared inside an object of the same color and shape, even if it had changed locations. Importantly, there was still some benefit for the cue to appear in the original object location even if a differently appearing object now occupied that location. In other words, when attention was directed to an object's features, it automatically spread to its location. One primary finding of these cueing studies is that the effect of cueing spread to the task-irrelevant aspects of the display. Egly et al. (1994) showed that attention spread to the uncued locations of the same object. Lamy and Tsal (2000) showed that attention to object features spread to the object's location. In other words, the processing of an object representation seems to occur in a unitary fashion, in that processing one aspect of an object representation leads to processing of its other aspects.

The experiments in this chapter examined whether object representations in memory followed this same principle. Participants engaged in a task that required the processing of one feature of an object in memory, and I observed whether the effect of this processing had a similar effect on its other features. In regards to the broader question of whether the object representations in attention and memory are the same, the strategy I adopted in this chapter was to examine whether object representations in memory exhibited the same properties as those of object representations in attention.

Experiment 4.1: Updating visual short-term memory is feature selective

The purpose of Experiment 4.1 was to examine whether updating proceeded in an object-based manner. We employed a change detection task, typically used to assess VSTM, with an additional procedural step. Participants viewed a sample array of multiple bars with unique colors and orientations, followed by a delay, and a probe display consisting of a single object. In addition, between the sample and the probe, another stimulus appeared at one of the object locations to cue participants to modify their memory of the corresponding object. We called this stimulus a *recurrence cue*, which refers to the idea that the new stimulus is to be considered part of the corresponding object, if it was to appear again. If the recurrence cue was a colored dot, they were to modify their memory of the object that had previously appeared in the same location as the recurrence cue so that its color matched that of the recurrence cue. If it was a white bar, they were to modify the orientation of the object to match that of the recurrence cue (Figure 4.1A). If memory updating is object-based, then the updating process should affect all features of the object indicated by the recurrence cue. To test the memory for both features of the objects, changes were applied to either the same or different feature dimension as the recurrence cue. For example, if the recurrence cue indicated updating the color of the object, then either the color of the probed object could be changed or the orientation of the probed object could be changed. These trials were referred to as the updated feature (UF) or non-updated feature (NUF) trials, respectively (Figure 4.1B).

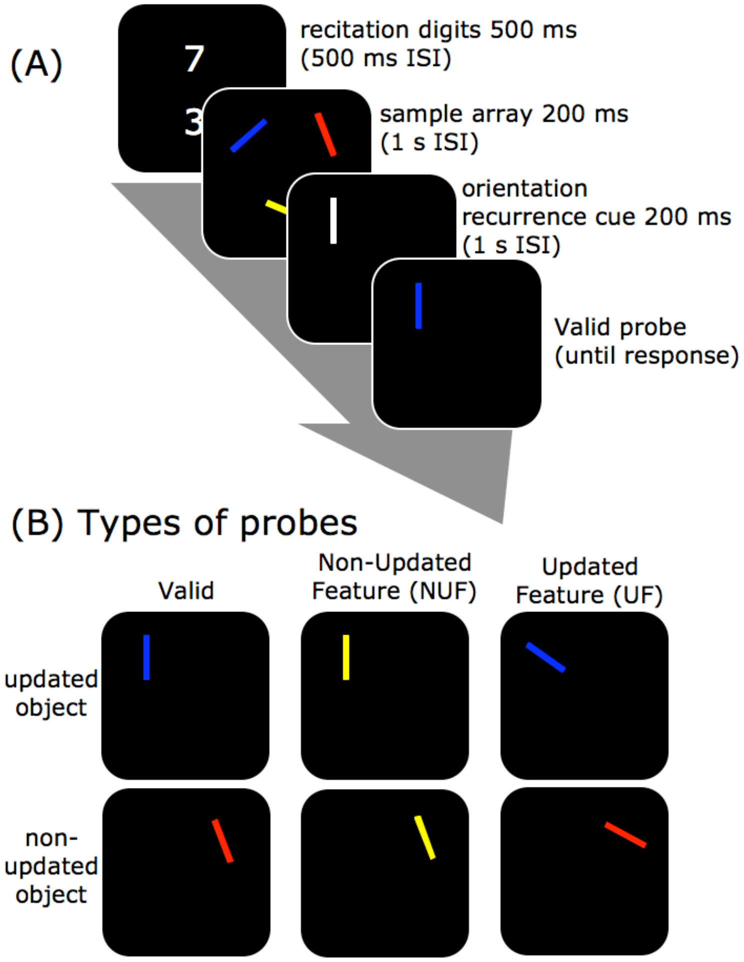


FIGURE 4.1
A schematic of the general methodology is depicted to the left. (A) The top half of the figure depicts one trial. For this example, participants would have been instructed to update their memory by changing the orientation of the blue tilted bar to be a blue vertical bar. The probe appeared at the end of the trial was valid if it matched the updated information as in this example. (B) The bottom half of the figure depicts examples of probes that could follow the trial depicted in (A). Types of probes for the updated objects are shown in the top row and for the non-updated objects in the bottom row. Valid probes of updated objects were the combination of features from the sample and recurrence cue (e.g. a blue vertical bar). Invalid probes either changed the non-updated feature of the object (NUF), which was color in this example, or the updated feature (UF), which was orientation.

The experiment was designed to examine three hypotheses, all of which shared the following assumption. It was assumed that memory for information indicated by the recurrence cue would be facilitated. Recent studies have shown that shifts of attention to information in memory result in an enhanced representation or prioritization of the item (Griffin & Nobre, 2003; Landman, Spekreijse & Lamme, 2003; Makovski & Jiang, 2007; Makovski, Sussman & Jiang, 2008). The object-based hypothesis proposes that the effect of updating one feature of an object should spread to all of its features. This predicts performance benefit for both the updated feature and non-updated feature in the updated object (Figure 4.2A). This result could come about if, when updating the memory of one feature, the memory of the other feature of the object is refreshed, so both features share facilitation of memory performance. The feature-based hypothesis proposes that the effect of updating one feature results in sensitivity to all values of that feature dimension in memory. This predicts superior change detection for the updated feature, regardless of whether an updated or non-updated object was probed (Figure 4.2B). Finally, the feature-selective hypothesis proposes that the facilitative effect of updating will be restricted to only the updated feature and object (Figure 4.2C). This contrasts with the object-based hypothesis in that it predicts the effect of updating will not spread to all features of the updated object. It contrasts with the feature-based hypothesis in that it predicts the effect of updating will not spread to all objects.

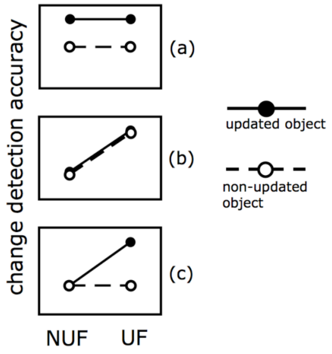


FIGURE 4.2
Depicted on the left are predictions made by (a) object-based hypothesis, (b) feature-based hypothesis, and (c) feature-selective hypothesis.

Method

Participants

Participants were 11 adult volunteers (4 males) with a mean age of 25.45 (*s* = 4.82) recruited from the Nashville community through the Psychology Research Sign-up System at Vanderbilt University. They all participated in exchange for $10 per hour. They were tested in accordance with Vanderbilt University's Policy for the Protection of Human Subjects and the APA 2002 Code of Ethics.

Apparatus and Stimuli

Stimuli were presented in MATLAB using the Psychophysics Toolbox extension (Brainerd, 1997; Pelli, 1997) on an eMac G4 with a CRT monitor at 1024 x 768 pixel resolution and 89 Hz refresh rate. Participants used a headrest, which positioned them at approximately 57 centimeters (cm) from the monitor. Vocal utterances were recorded with an InSync gooseneck microphone, connected with a Griffin iMic USB convertor.

Stimuli were colored bars subtending 0.5 x 2 degrees of visual angle (°). These objects were positioned on three equidistant points of an imaginary circle with a diameter of 8.5°, such that the overall spatial configuration resembled an inverted triangle. A set of 12 colors that was described in the previous chapter was used. Only 2nd neighbor colors from this set appeared in a given trial of this experiment. Orientations were eight angles increasing from 0 to 157.5 degrees in 22.5 degree increments to, and only 2nd neighbor orientations appeared in a given trial.

Procedure

At the beginning of every trial, two vertically aligned digits appeared in the center of the screen for 500 milliseconds (ms), followed by a blank 500 ms ISI. Participants recited these numbers aloud into the microphone for the duration of the trial. Concurrent performance of this articulatory suppression task likely reduced verbal encoding strategies. Next the sample array appeared for 200 ms, followed by a blank, 1-second interstimulus interval (ISI). Objects in the sample array were three colored bars each with unique colors and orientations (see Stimuli). Then, the recurrence cue appeared for 200 ms in the same location as a randomly selected object in the sample array, followed by a blank, 1-second ISI. On half of the trials, the recurrence cue was a white bar at an orientation that was not shown in the sample array. On the other trials, the recurrence cue was a dot (subtending 0.7 degrees of visual angle in diameter) in a color that was not shown in the sample array. Participants were instructed to update their memory of the orientation or color of the object in the corresponding location (Figure 4.1A).

A single bar was randomly selected to appear in the probe display. On half of the trials, the probe was valid. Valid probes of updated objects appeared with the updated feature modified to match that of the recurrence cue (Figure 4.1A). Valid probes of non-updated objects appeared as they did in the sample display (Figure 4.1B, bottom row, left). On the other half of the trials, the probe was invalid with the change applied in one of two ways. In non-updated feature (NUF) trials, the change was applied to the feature dimension different than that of the recurrence cue. In updated-feature (UF) trials, the change was applied to the same feature dimension as that of the recurrence cue. Changes applied on invalid trials were features from non-corresponding objects, i.e. a feature swap. Invalid probes of the updated objects were never the same as the objects in the sample array. Participants were instructed to press a key labeled "correct" if the probe was valid, and a key labeled "incorrect" if the probe was invalid. To prevent correlation between which object was updated and which object was probed for memory, the selection of the object to be updated was made randomly, such that each object had equal probability of being probed. This resulted in an uneven number of trials in which updated- or non-updated objects were probed, but the variation in the number of trials for each condition remained relatively low across participants. From a total of 480 trials, non-updated objects were probed in a mean of 318.9 trials ($s = 6.59$) and updated objects were probed in a mean of 161.09 trials ($s = 6.59$).

Results and Discussion

The alpha level was set to 0.05 for all analyses in this study, and was Bonferroni corrected for multiple comparisons. Change detection data were scored as proportion accurate across trial repetitions. The accuracy data were submitted to a 2 x 3 within-subjects ANOVA to examine the effects of Object (non-updated, updated) x Probe (valid, NUF, UF). The results showed main effects of Object, $F(1,10) = 29.7$, $p < 0.001$ ($\eta_p^2 = 0.75$), and Probe, $F(2,20) = 6.04$, $p < 0.01$ ($\eta_p^2 = 0.37$), and a significant Object x Probe interaction, $F(2,20) = 5.43$, $p < 0.05$ ($\eta_p^2 = 0.35$). This significant interaction fit the prediction from the feature-selective hypothesis, but did not fit the other hypotheses. Paired comparisons showed that in valid trials, there was no significant difference in change detection accuracy between updated objects (80%) and non-updated objects (71%), $t(10) = 1.78$, $p = 0.1$ ($d = 0.79$). Since our a priori hypotheses only made predictions based on the invalid trials (NUF and UF), the remaining analyses focused on these trials. In NUF trials, there was no significant difference between updated objects (57%) and non-updated objects (59%), $t(10) = 0.91$, $p = 0.38$ ($d = 0.12$). In UF trials, accuracy for updated objects (81%) was superior to that for non-updated objects (58%), $t(10) = 3.9$, $p < 0.01$ ($d = 1.69$). In updated objects, there was superior accuracy in the UF trials compared to NUF trials, $t(10) = 3.23$, $p < 0.01$ ($d = 1.39$), but in non-updated objects, there was no difference in the same contrast, $t(10) = 0.52$, $p = 0.61$($d = 0.06$) (see Figure 4.3).

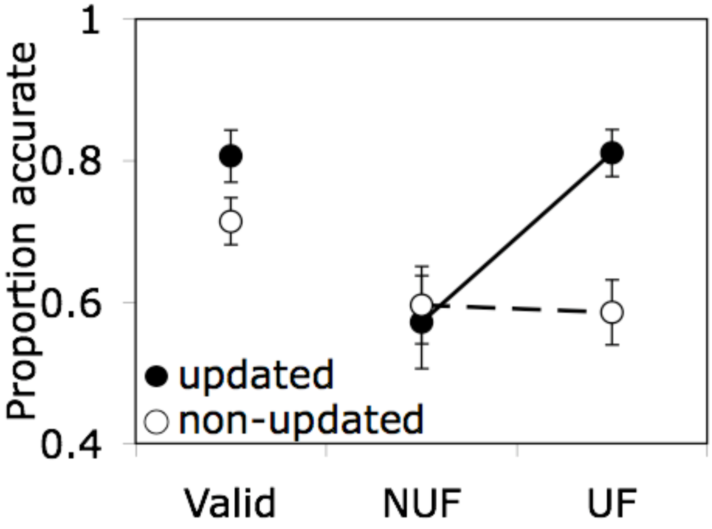


FIGURE 4.3
The accuracy data for Experiment 4.1 is depicted on the left. The error bars in all of the graphs represent the standard error of the mean.

These results clearly support the feature-selective hypothesis, and reject the feature-based and object-based hypotheses. Memory for the updated feature was facilitated, but only in the updated object, which rejects the feature-based hypothesis. Memory for the updated feature of the updated object was superior to that of its non-updated feature, indicating that the facilitative effect of updating was found only for the updated feature, rejecting the object-based hypothesis. Crucially, memory for the non-updated feature of the updated object was no better than memory for the non-updated objects. This result suggests that the facilitative effects of updating do not spread to the non-updated features of the object. However, there are at least two alternative accounts of this data. First, it is possible that participants did not memorize the visual stimuli as objects. Information may not have been stored in an object-based manner, which was addressed in Experiment 4.2. Alternatively, the updated object may not have been represented, which was addressed in Experiment 4.3.

Experiment 4.2: Updating is feature selective, but storage is object-based

One reason Experiment 4.1 may have shown feature-selective updating rather than an object-based effect was that information was not stored as objects in visual short-term memory (VSTM). There is evidence that participants could selectively encode separate features of the display (Woodman & Vogel, 2008). The purpose of Experiment 4.2 was to examine whether the object-based effect of storage and feature-selective updating could both be replicated. Object-based storage is reflected by similar capacity for simple features and more complex conjunctions of features (Luck & Vogel, 1997). In this experiment, participants engaged in two tasks: the updating task (modified from Experiment 4.1) and a standard change detection task. The change detection task evaluated object-based storage by manipulating the stimulus type and set-size (modified from Luck & Vogel, 1997). Participants performed the tasks in separate blocks, and task order was counterbalanced. This allowed us to observe whether visual memory was object-based at the same time as replicating Experiment 4.1 with different stimuli.

Method

Participants were 11 Vanderbilt undergraduate students, including 6 females, with a mean age of 18.72 (*s* = 1.01). All participants were recruited through the Psychology Research Sign-up System at Vanderbilt University, and participated in exchange for credits toward requirements of undergraduate psychology classes. The apparatus was identical to that of Experiment 4.1. The stimuli were colored squares, white oriented bars or colored oriented bars against a black background, constructed to be similar to stimuli used by Luck and Vogel (1997). Colored, oriented bars were used for the sample array in the updating task. Squares subtended 0.7° x 0.7°, and bars subtended 1.2° x 0.2°. The objects were centered on points of a 5 x 5 grid that spanned 10° x 7°. The points on the grid were equally spaced by 2.5° in the horizontal plane and 1.75° on the vertical plane. Positions were randomly jittered such that an object could be displaced by up to +/- 0.25° in the horizontal plane and +/- 0.175° in the vertical plane. The colors and orientations were identical to those used in Experiment 4.1.

Procedure

The change detection task proceeded as follows. Two vertically aligned digits appeared in the center of the screen for 500 ms, followed by a blank 500 ms ISI. Then, a sample array composed of either 2, 4, 6 or 8 objects appeared for 100 ms, followed by a 1 second blank ISI. The objects were colored squares, white oriented bars, or conjunctions of color and orientation. Objects could share the same color and/or orientation, but location was unique to each object (as in Vogel, Woodman & Luck, 2001). Then, another array of objects appeared until participants provided a response. On half of the trials, this test array was identical to the sample array, and on the other half of the trials, it was different by one object. On Different trials, a randomly chosen object appeared in a different feature value than the corresponding object in the sample array. The different feature value was directly opposite of the sample feature value in either color or orientation space, for example, a yellow color would be replaced by a blue and a vertical orientation would be replaced by horizontal. In the conjunction condition, there were an equal number of color and orientation changes to the changed object. The updating task was identical to Experiment 1 except for stimuli were the same as those used in the maintenance task. Tasks were blocked in the session, and task order was counterbalanced across participants.

Results and Discussion

Following Luck and Vogel (1997), the data for the change detection task were scored as capacity estimates (*K*) according to Cowan's formula (2001), in order to understand the results as they related to the number of objects in the display:

$$K = (\text{hits} + \text{correct rejection} - 1) \text{ x \# of objects in the display}$$

These data were submitted to a 3 x 4 within-subjects ANOVA to examine the effects of Stimulus (color, orientation, conjunction) x Set-size (2, 4, 6, 8). The results revealed a main effect of Stimulus, $F(2,20) = 30.29$, $p < 0.001$ ($\eta_p^2 = 0.75$), and Set-size, $F(3,30) = 5.58$, $p < 0.01$ ($\eta_p^2 = 0.36$), as well as a significant Stimulus x Set-size interaction, $F(6,60) = 4.3$, $p < 0.01$ ($\eta_p^2 = 0.3$).

These effects were driven by differences between the orientation trials compared to the other stimulus types. To confirm this, a separate ANOVA, that excluded the orientation data, was conducted to examine the effects of Stimulus (color, conjunction) x Set-size (2,4,6,8). This showed no effect of Stimulus, $F < 1$, $p = 0.98$ ($\eta_p^2 < 0.01$), but did show a main effect of Set-size, $F(3,30) = 3.19$, $p < 0.05$ ($\eta_p^2 = 0.24$). The interaction was not significant, $F < 1$, $p = 0.45$ ($\eta_p^2 < 0.1$). These results showed that capacity for conjunctions matched capacity for the most difficult feature, which was color (Figure 4.4A), indicating object-based storage. This replicated previous findings supporting the conclusion that VSTM has an object-based capacity (Luck & Vogel, 1997; Vogel, Woodman & Luck, 2001).

Results from the updating task replicated the feature-selective effect from Experiment 1. The data for the updating task (Figure 4.4B) were scored as proportion accurate. The accuracy data were submitted to a 2 x 3 ANOVA to examine the effects of Object (non-updated, updated) x Probe (valid, NUF, UF). The results revealed a non-significant effect of Object, $F(1,10) = 4.29$, $p = 0.06$ ($\eta_p^2 = 0.3$), a significant effect of Probe, $F(2,20) = 6.65$, $p < 0.01$ ($\eta_p^2 = 0.4$), and a significant Object x Probe interaction, $F(2,20) = 30.13$, $p < 0.001$ ($\eta_p^2 = 0.75$). Paired comparisons showed that in valid trials, there was no significant difference in change detection accuracy between updated (75%) and non-updated objects (79%) in valid trials, $t(10) = 1.05$, $p = 0.3$ ($d = 0.41$). In NUF trials, there was no significant difference between updated objects (64%) and non-updated objects (67%), $t(10) = 1.06$, $p = 0.3$ ($d = 0.19$). In UF trials, there was a significant advantage for updated objects (91%) compared to non-updated objects (69%), $t(10) = 6.97$, $p < 0.001$ ($d = 1.87$). For updated objects there was a significant difference between UF (91%) and NUF trials (64%), $t(10) = 7.06$, $p < 0.001$ ($d = 2.2$), but not for non-updated object, $t(10) = 1.19$, $p = 0.26$ ($d = 0.13$). Similarly to Experiment 4.1, these results demonstrated feature-selective updating. Together, these results provided evidence for object-based memory and feature-selective updating in the same participants.

An additional analysis examined possible effects of task order on the updating task. For example, performing the memory task first may have influenced participants to adopt an object-based strategy. The data were submitted to an Order (1st, 2nd) x Object (non-updated, updated) x Probe (valid, NUF, UF) mixed design ANOVA, which did not reveal a main effect of Order, $F(1,9) = 0.22$, $p = 0.65$ ($\eta_p^2 = 0.024$). Importantly, the three-way interaction was also not significant, $F(2,20) = 0.88$, $p = 0.43$ ($\eta_p^2 = 0.09$), indicating no effect of task order on performance of the updating task.

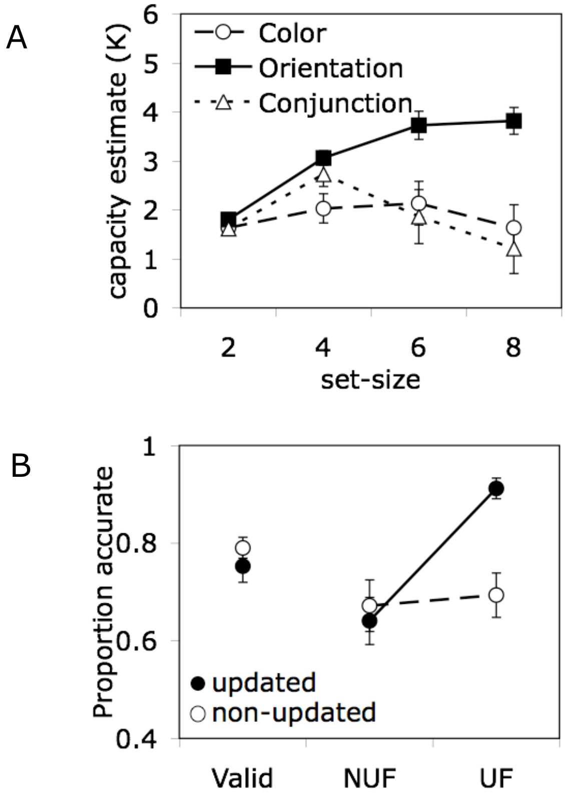


FIGURE 4.4
The results of Experiment 4.2 are depicted on the left. (A) The results of the change detection task are plotted as capacity (K) plotted as a function of display set-size. Similar capacities for conjunctions and the most difficult feature, in this case orientation, indicate object-based storage. (B) The results of the updating task, which was constructed with the same stimuli and performed by the same participants as the change detection task, is depicted. These results support predictions of feature-selective updating.

Experiment 4.3: Updated objects are represented in memory

Another alternative account of the feature-selective effect is that participants may not have represented the updated appearance of the updated object. Participants may have merely represented the sample array and the recurrence cue, but never integrated the two to form an updated representation. For example, if a trial consisted of updating a tilted blue bar into a vertical blue bar as in Figure 4.1A, participants may have only represented the tilted blue bar and the white vertical bar in memory and nothing more. This is in contrast to the task instructions that emphasized integrating the new feature value into the memory of the object to create a representation of the updated object, in this example, a vertical blue bar. While we do not doubt that participants encoded and represented the objects in the sample array and the recurrence cue during the trial, the purpose of Experiment 4.3 was to demonstrate that they also were representing the updated appearance of the updated object.

To find evidence for a representation of the updated version of the updated object, we devised a task with the assumption that information in memory guides visual selection, and that stronger representations have more influence on visual selection than weaker representations. Participants readily attend to visual information that appears while they are currently representing that information in working memory (Downing, 2000; Huang & Pashler, 2007; Soto, Heinke, Humphreys & Blanco, 2005) and this allocation of attention is automatic and can facilitate responses in an easy visual task (Olivers, Meijer & Theeuwes, 2006; Soto, Humphreys & Heinke, 2006; see Soto, Hodsoll, Rotshtein & Humphreys, 2008, for review). In Experiment 4.3, the trials proceed just as they did in the updating task (Experiment 4.1), except that on half of the trials, participants completed a different task. On these trials, a vertical line appeared with the probe. This cued participants to abandon the updating task and instead make a simple speeded response as to whether the probe appeared to the right or left of the line (Figure 6B). For our critical comparison, we added another type of invalid trial, which was the unaltered version of the updated object (Figure 4.5). The unaltered probe was identical to the object in the sample array. According to our hypothesis that the updated appearance of the updated object was represented in memory, we predicted that performance on the spatial task should be equivalent, or better, when the probe was the updated object compared to the unaltered object.

Method

Participants were 24 Vanderbilt undergraduate students, including 11 females, with a mean age of 18.83 (*s* = 0.81). Apparatus and stimuli were identical to that of Experiment 4.1, except for the following differences. Objects now appeared in three randomly selected locations for each trial. They were centered on 10 equidistant points of an imaginary circle that was 10° in diameter. The objects in a sample were separated by at least one point on this circle, and never appeared on the top or bottom location. This slight alteration was incorporated to accommodate the spatial task. The vertical line used in the spatial task subtended 1.5° x 10°. The horizontal position of the line was 2.5° to the left or right of the probe.

Procedure

The procedure was identical to Experiment 4.1, except for the following changes. On invalid trials, the applied changes were feature values from the opposite side of feature space as the valid values, to increase discriminability. There were three types of invalid trials, including NUF and UF trials previously described. In the third type, unaltered trials, if an updated object was probed, then the probe was identical to the object as it appeared in the sample display, as if it had never been updated. Alternatively, if a non-updated object was probed in this third type of trial, the probe appeared with the updated feature incorporated into its appearance.

Participants were cued to engage in either the change detection task or a speeded spatial task on equal number of trials (288 trials per task, 576 trials in total). As in the previous experiments, the probe appeared in the same location as its corresponding object in the sample. In the change detection task, the probe appeared alone, and participants reported whether the probe appeared correctly or incorrectly by pressing keys marked ‘correct’ or ‘incorrect’ with their right hand. Participants were told that the change detection task was unspeeded and to respond as accurately as possible. For the speeded spatial task, a thin, vertical white line appeared closely to left or right of the probe’s location. In other words, wherever the probe appeared on the screen, the line appeared close to the probe’s location, and was equally likely to appear to the left or right of that location. Participants reported whether the probe appeared to the right or left of the line by pressing keys marked ‘left’ or ‘right’ with their left hand. They were told to respond as quickly as possible without sacrificing accuracy. They were instructed to keep their responding fingers over the keys during the experiment (Figure 4.5).

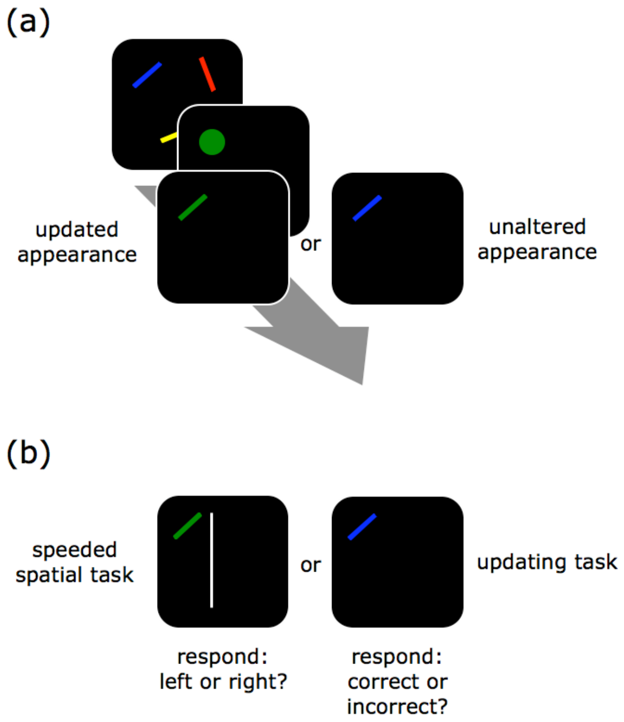


FIGURE 4.5
A schematic of the method of Experiment 4.3. (a) The upper half of the figure depicts one trial over time, ending with the updated object in its updated appearance on the left (to which participants would correctly respond "correct"), or with the unaltered appearance on the right (to which they would respond "incorrect"). (b) The lower half of the figure depicts the two different tasks in which participants might engage at the end of the trial. On the left, the appearance of a vertical line, randomly appearing on the left or right of the probed object, cues participants to perform a speeded spatial judgment task. On the right, they engage in the updating task (see text).

Results and Discussion

Responses were scored as proportion accurate for both the change detection and spatial tasks. The accuracy data for the change detection task were submitted to a 2 x 4 ANOVA to examine the effects of Object (updated, non-updated) x Probe (valid, NUF, UF, unaltered). The results showed main effects of Object, $F(1,23) = 26.5$, $p < 0.001$ ($\eta_p^2 = 0.54$), and Probe, $F(3,69) = 2.9$, $p < 0.05$ ($\eta_p^2 = 0.11$). The Object x Probe interaction was significant, $F(3,69) = 15.8$, $p < 0.001$ ($\eta_p^2 = 0.41$), once again supporting the feature-selective account of memory updating. There was no difference between updated- and non-updated objects in the valid trials, $t(23) = 1.36$, $p = 0.18$ ($d = 0.24$), or NUF trials, $t(23) = 1.12$, $p = 0.27$ ($d = 0.23$). For UF trials, change detection accuracy was superior for updated objects (80.9%) compared to non-updated objects (56%), $t(23) = 7.84$, $p < 0.001$ ($d = 1.71$). For updated objects, accuracy for UF trials (80.9%) was superior compared to NUF trials (57.3%), $t(23) = 5.38$, $p < 0.001$ ($d = 1.11$). For non-updated objects, there was no significant difference between NUF trials and UF trials (according to the Bonferroni-corrected alpha level of 0.007), $t(23) = 2.5$, $p = 0.02$ ($d = 0.37$). These results replicate the previous three experiments supporting feature-selective updating. Finally, analysis of the change detection task also involved the unaltered probe trials. Since the unaltered probes entailed a change to the updated feature, we predicted no difference between these and UF trials. This was confirmed by paired comparisons showing no significant differences in accuracy for unaltered probe trials compared to UF trials for both updated objects, $t(23) = 1.87$, $p = 0.07$ ($d = 0.38$), and non-updated objects, $t(23) = 1.42$, $p = 0.17$ ($d= 0.2$). These results are depicted in Figure 4.6A

For the spatial task, the reaction time for only correct trials were analyzed, and the remaining data were trimmed to exclude reaction times beyond 2.5 standard deviations of the individual participant's grand mean. This resulted in a mean of 3.64% of trials (s = 6.3%) being excluded. Accuracy and reaction time data were submitted to separate ANOVAs to examine effects of Object (updated, non-updated) x Probe (valid, NUF, UF, unaltered. Accuracy showed main effects of Object, $F(1,23) = 6.49$, $p < 0.05$ ($\eta_p^2 = 0.22$), and Probe, $F(3,69) = 3.06$, $p < 0.05$ ($\eta_p^2 = 0.12$), and the Object x Probe interaction was significant, $F(3,69) = 3.31$, $p < 0.05$ ($\eta_p^2 = 0.16$). The reaction time data showed a main effect of Object, $F(1,23) = 10.98$, $p < 0.01$ ($\eta_p^2 = 0.32$), but no main effect of Probe, $F(3,69) = 0.87$, $p = 0.46$ ($\eta_p^2 = 0.04$). Although the Object x Probe interaction was not significant, $F(3,69) = 2.58$, $p = 0.06$ ($\eta_p^2 = 0.1$), it approached significance, suggesting that the variance in the reaction time data may have obscured underlying effects.

The primary contrast of interest was between the updated and unaltered probes of the updated object. We hypothesized that if participants represented the updated appearance of the updated object, then their spatial task performance to that updated probe should be equal to, or perhaps better than, the unaltered probe. Accuracy data showed superior performance for updated probes (96%) compared to unaltered probes (92%), $t(23) = 2.17$, $p < 0.05$ ($d = 0.36$). Reaction times showed no difference between updated and unaltered probes, $t(23) = 1.7$, $p = 0.1$ ($d = 0.25$). However, the trend in the means was for *faster* reaction times with the updated form ($\bar{X} = 774$ ms, $SE = 28$) compared to the unaltered form ($\bar{X} = 820$ ms, $SE = 47$), suggesting that reaction time behavior reflected the same effect found in accuracy, and not a speed/accuracy trade-off (Figure 4.6B). These results confirmed our prediction that task performance for the updated object probe was at least as good, if not better, than performance with the unaltered probe, suggesting that the updated appearance of the object was represented at least as well as the unaltered appearance. Responses to the spatial task were consistent with the idea that participants were integrating the information about the recurrence cue with the sample array to create a memory representation of the updated object.

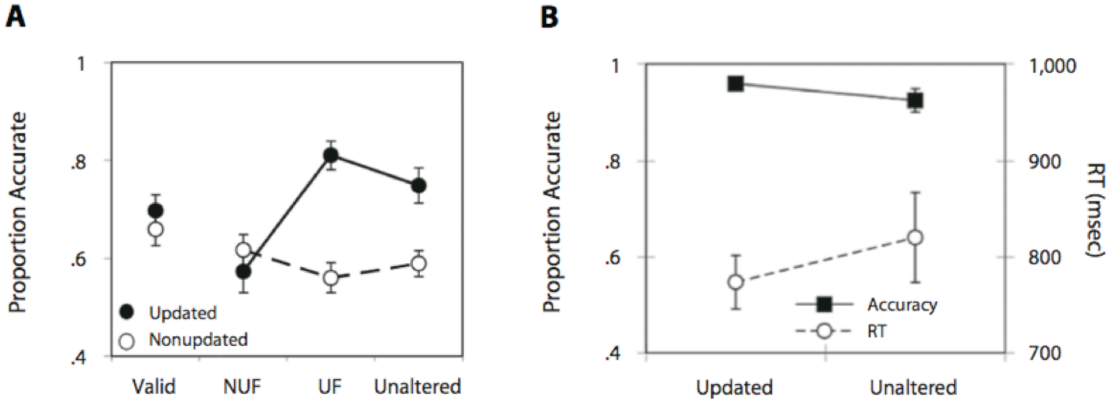


FIGURE 4.6
The results of Experiment 4.3 are depicted above. (A) The accuracy data for the updating task replicates results that support the feature-selective updating hypothesis. (B) The critical contrasts for the speeded spatial judgment. The results show significantly higher accuracy when object involved in the spatial judgment is the updated object compared to the unaltered object ($p < 0.05$), suggesting that the updated object was represented in memory.

General Discussion of Chapter IV

This study investigated whether updating visual short-term memory (VSTM) was an object-based process. The experiments examined whether updating a single feature of an object in memory would lead to refreshing of all the features of that object. The main finding was that the effects of updating were restricted to the updated feature, and did not spread to any other features of the updated object (Experiment 4.1). This effect was not due to failure to store information as objects (Experiment 4.2). Finally, the results of Experiment 4.3 suggested that feature-selective updating was unlikely to be due to a poor representation of the updated object. In summary, it is concluded that that updating VSTM is feature-selective and not object-based. Feature-selective updating might indicate that representations in VSTM are not objects, but features. Alternatively, updating and storage mechanisms of VSTM may have different bases. Both of these possibilities will be discussed.

Are there object-based representations in VSTM?

The current result showing feature-selective updating calls into question the type of representations used in VSTM, and may suggest that information in VSTM is represented as features rather than objects. The theory that object-based representations are the basis for the storage of information in VSTM has been intensely debated. The groundbreaking discovery of object-based representations, by Luck and Vogel (1997), demonstrated that two features of an object can be stored in VSTM with the same memory load as a single feature. The result could be accounted for by strong associations between the memory for the different features that make up an object, such that remembering one feature automatically gives rise to the other at no cost. More recent results showing costs related to the number of features are particularly detrimental to this strong version of the theory. For example, Olson and Jiang (2002) showed that storing color and orientation features as unified objects provided a modest benefit over storing the exact same features as separate items. Storing the information as objects did not cut the cost of storage in half evidencing a memory cost to the number of features. Similarly, Xu (2002) showed storage costs related to the multiple parts of objects. Alvarez and Cavanagh (2004) showed VSTM storage capacity to decrease as stimulus complexity increased (but see Eng, Chen & Jiang, 2005). If objects in memory are associations formed between its component features, then such results indicate the associations are not perfect, because increasing the number of features also increases the memory load. However, all of this research on memory storage finds at least *some* benefit of object organization of features, even if it is imperfect. Given the wealth of evidence supporting object-based benefit to storage of information in VSTM, it is unlikely that our findings of feature-selective updating indicate that object-based storage does not exist. It is more likely that our findings reflect the possibility that storage and updating processes in VSTM do not necessarily share a common basis of representation. In other words, VSTM storage may be object-based, while VSTM updating could be feature-based. In the next section, we discuss possible ways that this could be implemented.

Different bases for updating and storage

It is possible that while working memory storage is object-based, updating is instead feature-based. One way this could be possible is if the selection of a single feature of an object for updating breaks the associations between features formed at encoding and maintained in storage. Previous research has shown that features of perceived objects can be selectively encoded into VSTM according to the task instructions (Woodman & Vogel, 2008), and it remains plausible that similar feature-selective behavior can occur when the objects are already stored in memory. In addition to the current study, others have suggested that updating to be mediated by distinct, feature-specific systems (Mohr & Linden, 2005; Mohr, Goebel & Linden, 2006). Mohr and Linden (2005) examined updating of visual memory by presenting participants with two objects, each with a unique color and orientation, and instructing them to imagine a mix of the colors or the average of the two orientations or both. Their results showed no dual-task cost between tasks requiring both color- and orientation-updating compared to when they only performed one updating task, but there was a dual-task cost when two orientation-updating tasks were performed. Further, they showed that updating depended on central executive resources, while maintenance did not. Together, these results suggest that updating of visual memory is mediated by independent, feature-specific systems, and may engage additional executive functions. These executive functions may allow the updating process to ignore or break associations between features formed at encoding and maintained in memory.

A useful way to speculate further how updating could break object representations is to consider known theories of object-based processing. Object file theory (Kahneman, Treisman & Gibbs, 1992) proposes that updating an object consists of three components: (1) *correspondence*, in which a perceived object is considered a new or previously viewed object; (2) *reviewing*, in which, once correspondence is established, older information regarding the perceived object is retrieved; and (3) *impletion*, where the old and new information are integrated to generate the percept of one object changing, rather than two different objects. In our paradigm, we assumed that object correspondence between the sample object and the recurrence cue could easily be established by a common location. That all participants were able to understand and accomplish the memory updating task at greater than chance levels, supports this assumption. The second stage, reviewing, may have been impaired. Notice that this is another way of saying that the feature information in the recurrence cue was not successfully integrated with the information from the sample array. It is possible that the nature of the recurrence cue interfered with appropriate reviewing of all the features of the object in memory because the recurrence cue was a surface feature, such as color or orientation. In classic object file studies, the reviewing process has been typically shown to retrieve a single instance of an object, whether it is a letter (Kahneman, Treisman & Gibbs, 1992), an abstract identity (Gordon & Irwin, 2000), or a single face (Mitroff, Scholl & Noles, 2007). The information about the object was, in this previous work, to be integrated across multiple spatial locations. In the current study, however, the task required integration of multiple instances of feature information (color or orientation) to be integrated within a single spatial location. Perhaps reviewing previous states of an object is best guided by integrating across previous locations, but not surface features, such as color and orientation. Or, in other words, the memory for non-updated surface features is not refreshed. This was reflected in our results, which showed no impairment in change detection for the non-updated feature of the updated object, as compared to that of the non-updated objects.

Feature integration theory proposes that objects are represented by the binding of their features with attention (Treisman & Gelade, 1980). Each feature is represented within a feature map of other values in its domain, i.e. color. Spatial attention acts to bind the activated features from each map to a single location, resulting in accurate perception of the object. Failure of attention results in the miscombination of features when forming object representations, or illusory conjunctions (Treisman & Schmidt, 1982). In the current study, it is possible that a portion of change detection variability was determined by binding failures, since change trials involved swapping features between objects. Also, attention was divided to multiple objects at encoding, increasing the probability of binding failures. Ashby, Prinzmetal, Ivry and Maddox (1996) proposed that there is a degree of uncertainty about the location of each feature from a perceived image, and that this uncertainty is independent for each feature, regardless of whether it belongs to a target object or non-target object. A correct binding is highly probable when the distance between sampled locations of target features is less than the distance between the sampled location of a target feature and that of a non-target feature. While feature integration theory proposes that features are free floating prior to attention, location uncertainty theory proposes that the locations of features are instead coarsely coded. The dynamic field model of feature binding by Johnson, Spencer and Schoner (2009) also makes this distinction from feature integration theory. In the current study, it is possible that features of the multiple objects encoded in the initial sample were each encoded with a degree of location uncertainty. However, the location uncertainty of the feature in the recurrence cue could have been much lower than that of the other features, since it may have been the only attended feature upon its appearance. This would have resulted in superior change detection of the updated feature independently of all other features in the display.

One mechanism of memory updating could be attentional selection. Oberauer (2002) proposed that information in working memory existed in three states: (1) an activated portion of long-term memory that represented the passive storage of information, (2) a smaller region of direct access in which information was readily accessible for retrieval, and (3) the focus of attention, which holds just the chunk of information that is immediately available for processing. Although it was proposed that the focus of attention would be object-based in updating (Egly et al., 1994), it is possible that other modes of attention could have mediated updating. Whether object-based attention or another mode of attention is used to select relevant parts of memory for updating is an empirical question. Our results suggest that updating memory does not necessarily involve object-based attention, but may be performed with attention to specific features.

Conclusion of Chapter IV

This study in this chapter examined one important aspect of object continuity, which is updating. Object continuity processes must allow new information to be integrated with the object representation in order to perceive a single, continuous representation to be changing. In this way, an object representation can be updated. The results of this chapter showed that updating one feature of an object in VSTM did not lead to the automatic refreshing of the memory of its non-updated features. These findings can be accounted for by some theories of object representation, as will be discussed in the next chapter.

CHAPTER V

GENERAL DISCUSSION

In this dissertation, I examined whether the same object representations were used by both visual attention and memory. In the first chapter, I reviewed the literature on object representations in attention and memory, and proposed that attention and memory used the same object representations. Then, I presented the results of three empirical studies designed to examine different aspects of this problem. In Chapter II, I presented results showing that attention and memory shared a common capacity for object representation, supporting a view of shared object representations in attention and memory. In Chapter III, I presented results suggesting that a process involving both attention and memory was used to preserve object continuity. Finally, in Chapter IV, I conducted experiments that closely examined updating of object representations, revealing that the effects of updating are restricted to only the updated information, and does not spread to other parts of the same object. In this chapter, I will summarize the primary findings of each study, and then fit them into an integrative theory of visual cognition for objects.

In Chapter II, an object was viewed as a source of capacity limitation in attention and memory. A dual-task method was used to examine whether attention and memory shared this limited capacity for representing objects. The dual-task demanded the simultaneous use of attention and memory to objects. The primary finding was superior dual-task performance when each component task targeted the same objects rather than different sets of objects. This is consistent with the view that attention and memory draw from the same capacity to represent objects.

In Chapter III, I examined object representations as entities that remained continuous despite changes during its history. It was proposed that object continuity was preserved by an attentive process of sampling information and storing it in memory for comparison to subsequently sampled information. This sampling process predicts that object continuity is dependent on the consistency of object information, such as location and color, between samples. First, I showed that performance on target recovery (TR) was facilitated by consistent object location and color. Since TR involves tracking moving objects across a blank display of several hundred milliseconds, it must involve some process that stores information prior to the blank for comparison to information after the blank. I hypothesized that if the same sampling process mediated both MOT and TR, behavior related to each task would be similarly affected by consistency of the same kind of object information. The consistency of object colors was used to test this hypothesis. The results confirmed that consistent colors facilitated performance in both tasks. This supported the idea that a sampling process, which is sensitive to the consistency of object color, mediates object continuity. Importantly, this process entails coordination between attention and memory to result in successful continuity.

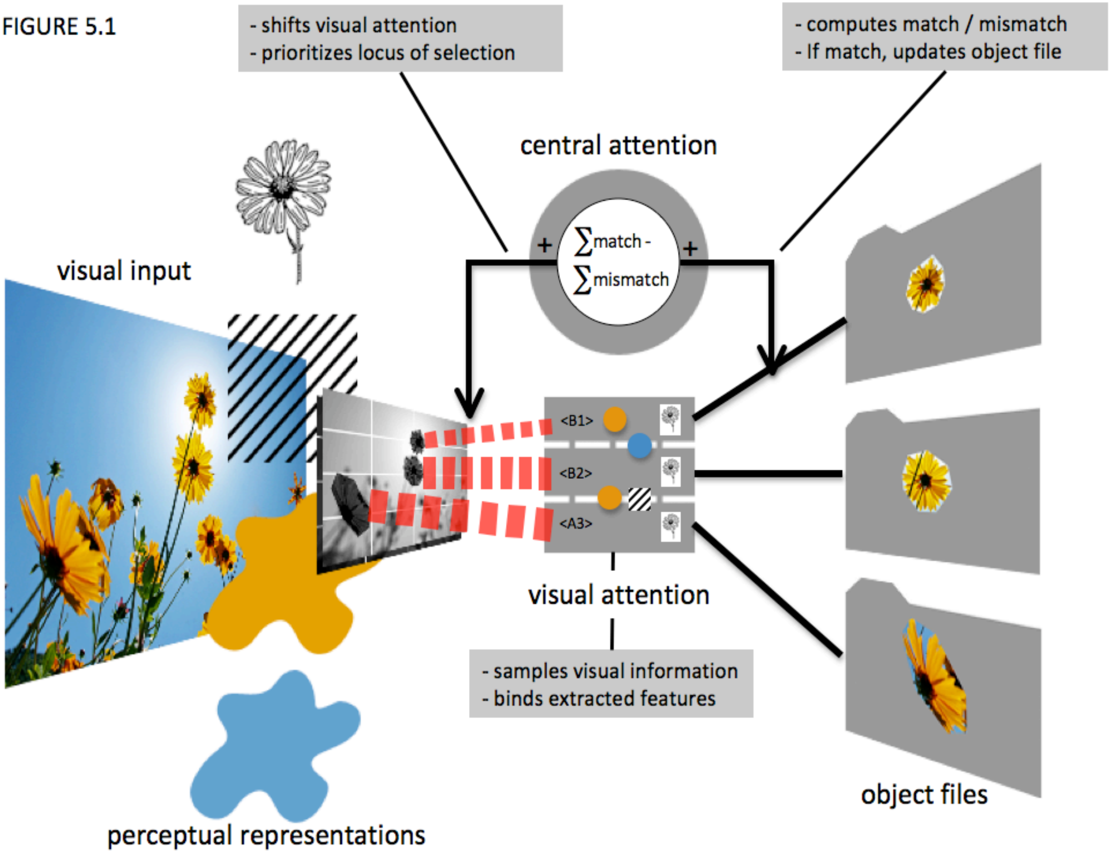
Finally, the experiments in Chapter IV took a closer look at the object updating process. An object is a representation that could be processed in a unitary fashion. In other words, what happens to one part of the object happens to the rest of it. It was hypothesized that updating a single feature of an object would result in refreshing the entire representation. Instead, we discovered that the effects of updating an object were restricted to its updated feature, and did not affect its other features. Further experiments showed that this process did not fail to represent an object in its updated form, but rather the resolution of its constituent features became differentiated. Did this suggest that the objects of attention and memory were not the same, since the expected results were no shown? In the next section I will outline a theoretical model of visual object continuity, and I will discuss some ways that the results of Chapter IV could fit within existing theories of object representation.

A model of visual object continuity

How do these results fit into the broader picture of visual cognition? What follows is an attempt to integrate the current findings into a model of object representation, continuity, and updating. The components of the model are informed by previous research as well as the current findings. I will first outline the theoretical process, and then provide a rationale for each stage, citing previous research and emphasizing how the current research contributes to its understanding. In this model, the process of visual object continuity can be described as four major stages:

(1) Visual information is selected and undergoes a binding process.
(2) A demand for continuity results in object files stored in memory.
(3) Divided attention to multiple objects results in imperfect object representations.
(4) Attention preserves continuity by periodically sampling information and matching it to object files stored in memory.

FIGURE 5.1



These stages are illustrated in Figure 5.1, shown above. In this figure, the visual input depicted on the far left side consists of several flowers to which the observer will attend. Several different representations emerge from the visual input. In the example, blue and yellow colors, one value of orientation and a long-term memory representation of a flower are depicted as being activated in parallel (Treisman & Gelade, 1980). Another representation is a spatial representation of visual information that has been grouped in some locations (Vecera & Farah, 1994). These groups can be formed according to any of several Gestalt principles, such as closure, uniformity, or good continuation. In this example, the groups are the heads of the flowers. It is proposed that, in the tasks used in this research, attention selects from a spatial array of grouped information. The task relevance of this selection mode is depicted by the grouped array being shifted to the right of the other representations. The selection of visual information by attention is depicted as red bars transferring information from the perceptual representations to the central gray box. A different channel is dedicated to each selected group (Cavanagh & Alvarez, 2005). Each channel is depicted as discrete red bars representing a discrete sample taken from the perceptual representations (Allen et al., 2006; Oksama & Hyönä, 2008).

Other information available within the selected group is extracted and undergoes a binding process. In Figure 5.1, binding processes are depicted as taking place inside the gray box. It is proposed that the purpose of visual attention is to perform at least two kinds of binding process. First, it binds the other features within the selected groups, resulting in their proper arrangement for more accurate perception (Treisman & Gelade, 1980). For example, one flower's head forms one group. It consists of the shape of the flower and the color of the petals. These features are bound together to enable a more accurate perception of the flower. Second, it relates the information extracted from the selected group to any long-term representations that have been activated, such as letters, well known object identities, or faces (Chun & Potter, 1995). In this example, the flower activates a representation in long-term memory, and this representation is matched to information extracted from the selected group. A third type of binding integrates the different instances of the object across time, resulting in the perception of a single, continuous entity (Kahneman, Treisman & Gibbs, 1992). This involves visual attention, but also requires memory and central attention. This kind of binding leads to a perception of object continuity, which will be discussed below.

Attention is viewed as a binding process. It is a single, limited resource that can be divided if multiple objects need to be represented. This limited resource is depicted in Figure 5.1 as a gray box containing samples of the perceptual representations. The boundaries between divisions become thinner and more permeable with each division. In the figure, this permeation is depicted as white lines formed with the gray box. The dashes in the lines represent permeability. Increased permeability leads to binding errors due to features slipping from one division to another. When multiple objects are represented, some kinds of information can be prioritized over others, and this priority prevents that information from slipping through divisions (Richard, Luck & Hollingworth, 2008). In Figure 5.1, an orientation feature and the colors are depicted as slipping through the lines, which will lead to misbinding of those features. Locations are depicted as coordinates from an alphanumeric coordinate system, as on some maps (e.g., A3, B1). Since the grouped array is prioritized, the locations will not leak through the permeable division.

Object files are created in memory when the task demands object continuity (Kahneman, Treisman & Gibbs, 1992). These are depicted as gray file folders on the right side of Figure 5.1. Object files can be viewed as a perpetuation of the mapping created by the attentional binding process. In this way, attention and memory share the same capacity for representing objects.

The preservation of object continuity is an active process resembling a circuit between visual attention, memory and central attention. Attention periodically samples information from the visual grouping currently under its scope. This information is compared to the information stored in an object file. The results of the matching process determine whether the object file is updated and whether attention should shift according to the update. Both operations proceed after a decision process. An executive process, mediated by central attention, could subtract the sum of all mismatches from the sum of all matches. A positive value from this operation would trigger updating of memory and shifting of attention, while a negative value would not trigger these processes. Failure to update a file or shifting attention results in the loss of object continuity. In Figure 5.1, central attention is depicted as a gray circle. The sum of detected mismatches is subtracted from the sum of detected matches, as illustrated within the circle. Arrows leading to the object files on the right, and attention to visual information on the left indicate that updating object files and shifts of attention rely solely on the outcome of this simple operation. Plus-signs are illustrated above the arrows indicate that the triggering of these processes depends on a positive value from the comparison process.

In the following sections, I will support each of these steps with previous research as well as the current findings. Many of the ideas have been drawn from previous research, but more emphasis will be placed on aspects supported by the current data.

Selection and binding

Attentional selection could be based on different types of information, such as a visual feature, an activated semantic category, or visual space. This idea is borrowed from Feature Integration Theory (Treisman & Gelade, 1980), which proposed that visual input activated several feature maps in parallel. The representation to be used as the primary input for selection could be determined by task demands. The selection cue could be a semantic category. For example, Duncan (1983) showed that selection from an early “iconic” representation could be based on semantic information, indicating that information was categorized prior to attentional selection. This idea was supported by several studies of iconic memory (Allport, 1978; Mewhart, Campbell, Marchetti & Campbell, 1981; for a review, see Coltheart, 1983), and more recently incorporated into models of temporal attention, such as Chun and Potter’s (1995) two-stage model. For this reason, visual and semantic information are among the perceptual representations depicted in Figure 5.1.

It is proposed that in the primary task used, MOT, attention selects visual information that has already been grouped by early visual processing. These groupings have been called proto-objects (Wolfe & Bennet, 1997) or object tokens (Pylyshyn, 2000). Duncan (1984) showed that the cost of attention could be object-based, and this suggested the formation of visual groupings prior to attention. Further research suggested that these visual groupings seemed to be embedded upon a spatial representation, so that attention selects groupings in specific locations (Kramer, Weber & Watson, 1997; Kramer & Jacobson, 1991; Egly, Driver & Rafal, 1994). This results in a hierarchical representation of parts, objects, and space that drives attentional selection (Baylis & Driver, 1993). Alternatively, attention could parse visual information into groups, and then select the groups. Some support for this comes from a study that showed no awareness for changes to groupings outside the focus of attention (Mack, Tang, Tuma, Kahn, & Rock, 1992). However, Moore and Egeth (1997) suggested that their results reflected a failure in memory, not of pre-attentive grouping. Their study showed that attentional behavior could be significantly affected by changes to grouping in the unattended background. Several other studies have shown similar results (Driver, Davis, Russell, Turatto, & Freeman, 2001; Russell & Driver, 2005; Lamy, Segal & Ruderman, 2006; Kimchi & Peterson, 2008).

Work described in previous sections showed that attention in MOT is not spread across a wide region of space (Sears & Pylyshyn, 2000), and does not just surround the region of space around each target (Scholl, Pylyshyn & Feldman, 2001). It selects the visual groupings to which the targets belong (Scholl, Pylyshyn & Feldman, 2001), but it may prefer rigid, closed figures rather than any arbitrary grouping (VanMarle & Scholl, 2003). MOT is used as the primary measure of attention and object continuity in Chapters II and III, so it is proposed that the grouped array is the precursor for object representations. The locations of selected groupings are prioritized, since MOT is an inherently spatial task, reducing the chance of being incorrectly bound to an object file. The modest same-object benefit observed in Experiment 2.3 might have been partially due to the fact that the objects were not spatially distinct in the Different-objects condition. This touches on the issue that the number of objects is often confounded by the amount of spatial processing involved. Duncan's (1984) original study of object-based attention demonstrated a cost of dividing attention even when the objects occupied the same space. The idea that these representations were spatially invariant was supported by Vecera and Farah (1994), who showed the same costs whether or not the objects were spatially overlapping or separate. This finding has been difficult to replicate (see Kramer, Weber & Watson, 1997), leading some researchers to propose that there are two kinds of object representations: an early grouped array, and a late, spatially invariant object representation in visual memory (Matsukura & Vecera, 2009). However, VSTM has also been shown to be represented spatially, especially at large object set-sizes (Jiang, Olson & Chun, 2000). At least one recent study has shown that, at longer retention intervals, objects in VSTM are less attached to their locations (Treisman & Zhang, 2006). For tasks such as MOT and the memory tasks used in this research, the grouped array is considered the primary basis of object representation. The distinction between these early groupings and object files is that the latter have been selected and must remain continuous for the task. In this way, the non-targets may also be represented in the grouped array, but cannot be tracked since they have not been selected for the task.

The selection of a visual group binds the features within that group (Treisman, 1982; Wolfe & Bennett, 1997). This kind of binding is borrowed from feature integration theory, as discussed in the introduction (Treisman & Gelade, 1980). This is distinct from other kinds of binding that is discussed in other models of visual cognition, such as the binding between type information and token information (Chun, 1997). However, these different forms of binding may all stem from a common limited capacity, such as the episodic buffer of Baddeley's component model of working memory (2000). Several other literatures have described similar bottlenecks of processing that may reflect binding between different kinds of information, including research in the psychological refractory period (Jolicoeur & Dell'Acqua, 1996) and visual working memory consolidation (Woodman, Vogel & Luck, 2006).

Evidence for this binding was demonstrated in Experiment 2.4. It was hypothesized that performance in the dual-task was determined by successful binding of features to specific objects, since the previous experiments used a memory task involving the swapping of features between objects. The memory task was manipulated, so that half of the invalid memory probes involved revealing a color on one object that had previously belonged to another object. In the other half, the probes involved revealing a new color not previously seen. Performance in the former condition had to have been determined by how well a color was bound to an object, while performance in the latter condition could be successful by remembering a list of colors, i.e. memory for features. Changes in dual-task performance, including the same-object advantage, was only observed in the condition requiring binding, not in the latter condition. This supported the idea that the shared capacity between attention and memory is of binding. Since objects are typically defined as the conjunction of multiple features (Luck & Vogel, 1997), this capacity for binding could be considered the same as capacity for objects.

This is supported by research showing that attention is necessary to maintain the bindings in memory (Wheeler & Treisman, 2002; Fougnie & Marois, 2008). Some researchers have argued that bindings in memory could be preserved even when attention is deployed during the maintenance period. Johnson, Hollingworth and Luck (2006) showed that visual search during memory retention did not differentially affect memory for features or conjunctions. Yeh, Yang and Chen (2005) showed no differential benefit of spatially cueing features or conjunctions during memory retention. Allen, Baddeley and Hitch (2006) showed that performance of a task demanding central attention did not differentially affect memory for features or conjunctions. However, Fougnie and Marois (2008) argued that the intervening tasks were not demanding enough or not did require visual attention. They showed impaired memory for binding when participants performed a MOT during the retention period, supporting the idea that visual attention is required for maintenance of feature binding in memory.

Object files in memory are required to preserve continuity

Kahneman, Treisman and Gibbs (1992) introduced the idea of an object file as a single representation responsible for the accrual, retrieval and updating of information related to a perceived object. The concept of the object file is incorporated in the current model as a crucial component. It is proposed that when the task demands continuity of information that is bound by attention, an object file is opened in memory to preserve this continuity. An object file is simply the preservation of the binding formed by attention, suggesting that the representation of objects in attention and memory reflect the same capacity. This capacity may be a general resource for binding (Baddeley, 2000), and may cause the same processing bottleneck observed in other paradigms (Jolicoeur & Dell'Acqua, 1996; Woodman et al., 2006).

The idea of this common capacity was supported by evidence from Chapter II. There were two tasks used in Chapter II that both required object continuity. In MOT, participants had to perceive the target objects as the same objects that were cued at the beginning of the trial, even as they randomly move across space. In the memory task, participants used VSTM to determine whether the features appearing on a specific object were the same or different than features previously viewed on that object. These were incorporated in a dual-task. Performance of this dual-task was facilitated when memory and attention was directed to the same objects. The source of the dual-task interference stemmed from the total number of object files required. In the Same-objects condition, the number of total number of object files was equal to that required in each of the Single-task trials, which resulted in the observation of no significant interference compared the estimate of ideal performance, reflected by performance in the Expected condition (Experiment 2.1, color group). In the Different-objects condition, having two different sets of objects exhausted the total number of objects files required to perform the dual-task, resulting in impaired dual-task performance. This impairment could have stemmed from either MOT or memory, and this trade-off could have changed from trial-to-trial, demanding the need to average across the tasks. If there were independent capacities to retain bound information, there should have been no difference in the dual-task cost between the Same- and Different-objects conditions.

The use of VSTM to preserve continuity was also observed in the experiments of Chapter III. TR performance was shown to be successful even with the presence of a full-screen mask just prior to the blank and the concurrent performance of articulatory suppression (Experiment 3.3). Representations in VSTM are known to survive these conditions (Woodman, Vogel & Luck, 2006), suggesting that information was retained in VSTM across the blank. The results of Experiment 3.3 showed that color representation was of relatively low resolution in TR, further suggesting the use of VSTM to retain information across the blank (Olsson & Poom, 2005; Awh, Barton & Vogel, 2007). This supports the view that a memory representation, like an object file, could be necessary in preserving object continuity in TR. The relationship between memory and MOT will be discussed in a later section.

Divided attention to multiple objects

In the proposed model, a single resource of attention is divided into "slots" to represent multiple objects. However, the boundaries between each slot become thinner or more permeable with each division. Some models of visual memory representation have proposed similar models of object representation, where object representation is determined by both the number of objects in memory and the content of each object. For example, Alvarez and Cavanagh (2004) described objects in visual memory as being slots that could each hold a minimal set of features. Olson and Jiang (2002) also showed that both the number of objects and the total number of features exerted a cost upon visual memory capacity. More recently, different methods have produced results that support the idea that visual memory stores discrete, fixed resolution "slots" (Zhang & Luck, 2008). These models predict that, when memorizing multiple objects, there would be high resolution for a subset of items, and no information for other items. In other words, there is no variability in the resolution of items in memory as the set-size increases. However, recently it was been noted that such analyses often fail to account for incorrect bindings of location and the memorized features (Bays, Catalao & Husain, 2009). When the incorrect bindings are accounted for, models based on visual memory as a single resource are better fit to behavioral data.

Similar to these resource models, attention, as defined by a capacity for binding is depicted as a single resource that could be divided. However, the accurate of binding for a given object is represented by the width of each division. The cost of attention is the loss of binding. Treisman and Schmidt (1982) supported this idea by showing that a lack of attention resulted in the misbinding of perceived information. Participants were briefly presented rows of five characters composed of three colored letters interleaved with two black digits. When report of the digits was emphasized, participants made errors on reporting the identity and color of the letters. Importantly, more errors involved miscombining the colors and identities, rather than erroneously reporting unseen features.

This indicated that when attention was diverted, features are still perceived, but they are miscombined or misbound, forming illusory conjunctions.

In Experiment 3.4, we showed that the consistency of object color was not object-specific in TR. Performance was no different if targets retained their original colors across the blank or swapped colors with each other. Performance was only impaired if the targets swapped colors with non-target across the blank. These results suggested that target colors were stored in VSTM during the blank, but since attention was divided between several targets, they could have been incorrectly bound in memory. This would result in a target match as long as the targets appeared in their pre-blank colors, regardless of which target had which color.

Could binding errors also help to explain the effects of feature-selective updating in Chapter IV? In these experiments, participants memorized conjunctions of color and orientation, and then updated the color or orientation of one object according to a recurrence cue. Then, their memory for one of the multiple objects was probed. The main finding was that updating resulted in a greater probability of change detection, but this effect was restricted to the updated feature. How does this effect fit into the proposed model? Ashby et al. (1996) proposed that the probability of successful binding was determined by the spatial uncertainty of perceived features, and this uncertainty is independent for each feature. It is possible that the encoding of multiple objects from the sample required divided attention, resulting in a relatively high level of spatial uncertainty for each feature. This was reflected in change detection performance that was below ceiling. In other words, imperfect memory for objects in the task resulted, for some degree, from a binding failure. However, only a single focus of attention was required to process the recurrence cue. The spatial uncertainty for this feature could have been much lower compared to the other features in memory, since attention was not divided during encoding. This would result in enhanced change detection for the updated feature compared to any other features in memory. Consistent with this view is that the changes involved in most of the experiments in Chapter IV are swaps between sampled objects. However, we observed similar results when changes involved the introduction of a new feature. This might imply that baseline change detection performance reflects both how well features are retained and how well they are bound to object files (Wheeler & Treisman, 2002).

Periodic sampling and object continuity

The preservation of object continuity is mediated by a correspondence process. The correspondence process involves attention taking a discrete sample of information from the visual group on which it is currently focused. This information is matched to an object file in memory. The outcome of this matching process determines whether the object file is updating, and whether attention is shifted according to the update.

Allen et al. (2006) proposed this kind of sampling process to explain how MOT was accomplished. Each target attracted a visual index, and the targets' location information was encoded into memory. At the next time interval, each target again attracted an index, and the target locations were consulted to match them against locations in memory. Matches are made based on the proximity between the sampled locations and those in memory. A similar memory-based component was used by Oksama and Hyönä (2008), but their model differs in an important way. Oksama and

Hyönä (2008) proposed that attention updated object representations in a serial manner. Spatial locations were preserved in memory because of this serial shifting. A single focus of attention shifted to the last memorized position of an object to be updated. Like Allen et al. (2006), tracking errors stemmed from the discrepancy between memorized and actual object location. Oksama and Hyönä (2008) proposed that the serial shifts of attention accounted for observed set-size effects in the tracking task, since more targets necessitate more shifts of attention within a certain amount of time. The results of Chapter III do not speak to whether there is a single focus of attention, or multiple foci of attention, since there was no set-size manipulation. I will adhere to Cavanagh and Alvarez's (2005) multi-focal attention for the purposes of the current theory.

There are two reasons to propose a sampling mechanism. First, it accounts for the preservation of object continuity, despite dramatic visual discontinuity. Second, it makes explicit predictions about the consistency of object features. As described in Chapter III, target recovery (TR) is a task similar to MOT, except that all objects temporarily disappear while participants are tracking them. It is possible that attention continually extracts target information for matching to representations in memory. However, the visual discontinuity introduced by the blank should result in a significant mismatch, causing the loss of the tracked targets. Keane and Pylyshyn (2006) showed that a blank of up to 450 ms still allowed high performance, as long as the pre- and post-blank positions were consistent with each other. This could be accounted for by a periodic sampling mechanism since the blank mimics the interval between samples. In Experiment 3.1, we showed that TR performance was not only dependent on consistent object position, but also consistent object colors. For each target, the sampling mechanism would extract object position and color and store that information in an object file. The mechanism would then take another sample of position and color and compare it to the object file already in memory. If there is enough of a match in position and color, the object file is updated according to the newly sampled information, and attention is shifted according to this update. Precise shifts of attention maintain accurate tracking.

Is sampling involved in MOT? Experiments 3.2 and 3.3 examined whether the sampling process was common to both MOT and TR. It was known from Experiment 3.1 that behavior related to TR was sensitive to the consistency of objects' colors. In Experiments 3.2 and 3.3, it was shown that color consistency similarly affected behavior in both MOT and TR. These results supported the hypothesis that a common process mediated both MOT and TR. Using color as a case study in the information that must be kept consistent to preserve object continuity, this process could involve the periodic sampling of information for comparison to representations in memory. It should be noted that the extent of support for the sampling mechanism is restricted to observed effects of informational consistency. The sampling mechanism is appealing because it makes specific predictions about how the consistency of information affects behavior, and is also helpful in accounting for TR related behavior. The results of Chapter III support the sampling mechanism by confirming its predictions about consistency, but they do not definitively rule out the alternative theory of continuous streaming of information. More research is required to elucidate this point.

How does the result of a matching operation lead to object continuity? It is possible that within an iteration of sampling, the total sum of matched features competes with the sum of mismatched features. This is easily modeled by subtracting the sum of mismatches from matches. A positive number from this operation could result in both the updating of an object file and the shifting of attention according to the updated information. A negative value, that is the sum of mismatches is larger than the sum of matches, does not signal the updating of the object file or shifting of attention, resulting in a failure to preserve continuity. In MOT, this would result in the loss of a target due to failure to shift attention. The matching process, decision-making and shifting of attention could be mediated by a central executive component (Baddeley & Hitch, 1974). This is supported by research showing a role of central attention in MOT (Tombu & Seiffert, 2008). This mechanism of tracking is similar to Cavanagh and Alvarez's (2005) model of multi-focal attention, which proposes that feature information extracted by attention is input to higher processes. The outcome of these higher processes signaled the shifting of attention to remain centered on the target object. In this way, object continuity could be thought of as a circuit between visual attention, visual memory and a central executive. Visual attention continues to sample information that is then compared to information in memory. A match in this comparison results in updating the object file and shifting attention according to that update to continue sampling information accurately. A mismatch does not lead to the updating and shifting operations, breaking the circuit.

It is important to allow perceptibly differing samples of information to satisfy a match in the matching operation. Without this tolerance for error, there is no way to perceive a single object changing. This was investigated extensively in Chapter IV, which showed evidence of feature selective updating. In regards to the sampling mechanism described in Chapter III, updating is important in MOT. For example, in matching locations across samples in MOT, there must be a degree of perceptible difference in location that is still considered to match. This difference could create vector information that could be used to update the object file and accordingly shift attention. In Experiment 3.3, we examined a similar property with object color. For both MOT and TR, we manipulated the degree to which colors changed in the inconsistent trials. In TR, the small color changes resulted in higher performance than large color changes. We interpret this to mean that smaller color changes reduced the probability of finding a mismatch between samples. However, no difference was found in the inconsistent trials of MOT, making the result difficult to interpret. If a sampling process mediates both tasks, as we suggest, it is possible that the duration between samples affects the resolution of color representation. Since the objects are continuously visible in MOT, there may be only very brief durations between samples, allowing other types of color representation, like iconic memory, to persist and facilitate the matching process.

Summary and Conclusion

The conclusion of this research is that the same object representations are used in visual attention and memory. The results of Chapter II showed that attention and memory share a common capacity of object representations. The experiments in Chapter III suggested that object tracking is mediated by a sampling mechanism that is sensitive to the consistency of object location and color. Finally, the experiments in Chapter IV investigated the effect of updating objects in visual memory. These results were integrated into a model of visual object continuity. Visual attention selects grouped information and binds the features within the group. The need for object continuity signals the establishment of an object file in memory, which perpetuates the binding formed by attention. Object continuity is conceptualized as a circuit between visual attention, visual memory, and central attention. Visual attention takes discrete samples of information in a periodic manner, and a process matches the sample to an object file in memory. The outcome of this matching process determines whether the object file is updated according to the newly sampled information, and whether attention is shifted according to the update.

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