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The role of visual short-term memory in object-based attentional selection

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The role of visual short-term memory in object-based attentional selection

by

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ABSTRACT

The present study investigated the relationship between object-based attention and visual short-term memory (VSTM). Three claims were investigated: (a) spatial attention and spatial STM share similar processing resources; (b) object-based attention and object STM share similar processing resources; and (c) both sets of processing resources are dissociable. Although the first claim is well established, the latter two claims are less established due to limited empirical evidence in the literature. Specifically, studies that provided evidence for the latter two claims (Matsukura & Vecera, 2008; Tan, 2008) employed an object-based attention task (Duncan, 1984) with no spatial component that heavily engaged object STM. These issues were addressed in the present study using a dual-task paradigm with different combinations of attention tasks and memory tasks. The different attention tasks used could engage spatial attention, object-based attention, or both. Similarly, the different memory tasks used could engage spatial STM, object STM or both. Experiment 1 was designed to address the issue of a lack of spatial component in the object-based attention task by including a spatial version of the object-based attention task used in previous studies. The results in Experiment 1 were consistent with all three claims that were investigated. Experiment 2 was designed to address the issue of heavy engagement of object STM by the object-based attention task by using a different object-based attention task (Egly et al., 1994). The results in Experiment 2 were not entirely consistent with all three claims. Specifically, while there was some support for the first two claims, the third claim was not supported. Overall, the findings in the present study suggest that the interaction between object-based attention and VSTM is complex and further studies are required to fully describe the relationship.

CHAPTER 1: INTRODUCTION

When one engages the environment to perform a task, the visual system usually needs to select the task relevant visual information over the task irrelevant visual information. This is because the amount of visual information that is available to an individual at any moment of time is more than what the visual system can handle (Tsotsos, 1990). Hence, in order to prevent the visual system from becoming overloaded, it is crucial that the system selects task relevant information. The cognitive mechanism responsible for the selection of task relevant visual information over task irrelevant information is visual selective attention (e.g., Johnston & Dark, 1986; Pashler, 1998).

When the task in question is complex and requires several stages, it is common for visual information selected at an earlier stage of the task to be employed in the later stage of the task. Hence, it is necessary for the cognitive system to maintain the relevant visual information temporarily in a highly accessible state in order for the information to be stored and processed simultaneously, which will allow the manipulation of visual information for the completion of the concurrent task. For example, when one is trying to locate one’s current position on a map, one needs to temporarily maintain visual and spatial information of the surrounding environment (e.g., surrounding landmarks and their spatial relationship), and then manipulate and transform this visual information such that it can be matched to the symbols on the map in order for one to read the map correctly. The cognitive mechanism that is responsible for keeping visual information in a highly accessible state such that it can be manipulated and transformed for the concurrent task is visual working memory (VWM) (e.g., Baddeley, 1986; Logie, 1995).

In the current study, I shall explore the interaction between different subcomponents of visual selective attention (i.e., spatial attention and object-based attention) and two subcomponents of VWM (i.e., spatial short-term memory (STM) and object STM). In the following sections, I shall review studies in the literature to demonstrate that there are at least these two distinct types of visual selective attention and that a similar distinction exists in VWM. I shall also review studies to demonstrate that visual attention and working memory (WM) are closely related, including studies that have demonstrated that spatial attention and spatial WM engage similar processing resources. Finally, I shall review several recent studies to suggest that object-based attention and object WM also engage similar processing resources. The research question of the current study will be built on these lines of research.

Visual Aspects of Selective Attention

Although William James (1890/1950, pp. 403-404) claimed that “everyone knows what attention is”, several attention researchers (e.g., Pashler, 1998; Wright & Ward, 1998) have pointed out that attention is a complex and multi-component concept, and that there has been little agreement amongst attention researchers in the definition of the term. For example, Pashler (1998) pointed out that one’s everyday notion of attention might include the properties of selectivity (i.e., the ability to process some stimuli over others), limited capacity (i.e., inability to perform simultaneous processing) and effort (i.e., exertion is required for sustained processing). Wright and Ward (1998) also pointed out that there are several aspects of attention, including selectivity, control, capacity, and relation to arousal and consciousness that are highly related but not necessarily similar to each other.

As attention is a theoretically loaded term and might have different meanings amongst different researchers within the literature, it is necessary to be explicit on the definition of the term 'attention' as it is used in the current study. Previous researchers have described attention as a filter (Broadbent, 1957), or a type of mental resource or capacity (Kahneman, 1973), or a selective attenuator (Treisman, 1964), or a type of "glue" that binds features together (Treisman & Gelade, 1980), or as an emergent property of a competitive interaction (Desimone & Duncan, 1995). While the conceptualization of how attention works might differ for these different metaphors of attention, one common thread is that an important function of attention is to select relevant information over irrelevant information. Within the context of the current study, the term visual attention refers to a selective process, in which task relevant visual information receives more processing than task irrelevant visual information. This definition of visual attention emphasizes the selectivity aspect of attention over other aspects such as control, capacity and relationship to arousal and consciousness. The emphasis on the selectivity aspect of attention does not suggest that the other aspects of attention do not exist, or that selectivity is diametrically opposite and distinct from the other aspects of attention. It is possible that aspects such as control and capacity operate in tandem for the selection of relevant stimuli over irrelevant ones (e.g., Johnston & Heniz, 1978). For example, processing resources (i.e., capacity) might be required in order to initiate a selection episode, or a control mechanism may be required to shift the selection episode from one stimulus to another stimulus.

In terms of the cognitive conceptualization of attention, the current paper adopts the ‘cause’ metaphor of attention (e.g., Fernandez-Duque & Johnson, 1999, 2002), in which it is assumed that there is a controller for the attentional selection process (Posner & Peterson, 1990; Posner, Snyder & Davidson, 1980), as opposed to an ‘effect’ metaphor of attention (Desimone & Duncan, 1995), in which attention is conceptualized as an emergent effect with no explicit control mechanism. In other words, the current paper leans towards the theoretical suggestion that the neural implementation of the selection process is probably implemented by specialized underlying neural modules (e.g., Posner & Peterson, 1990) rather than from an interactive biased neural competition (Desimone & Duncan, 1995). However, it is noted that this is an emphasis rather than an assertion, in that it is possible that both ‘cause’ and ‘effect’ theories of attention are not necessarily contradictory, and the adoption of either conceptualization depends on how attentional metaphors are framed (Fernandez- Duque & Johnson, 1999, 2002). The ‘cause’ metaphor of attention is adopted for the current paper primarily for ease of description and because the metaphor ‘fits’ better with the concept of the central executive in the WM framework of Baddeley (1986, 2007) adopted for the current paper.

A further assumption made in the current study is that the selective process of visual attention is not unitary, but can be fractionated into different types of selective processes. Specifically, I will argue that there are at least two types of visual attention, namely spatial based attention, in which spatial locations are the units of selection, and object-based attention, in which discrete objects are the units of selection. In the following sections, I shall review past studies that provided evidence for both types of attentional selection.

Spatial Visual Attention

Previous research in visual selective attention has demonstrated at least two types of selection units, namely spatial location (e.g., Downing & Pinker, 1985; Posner, Snyder & Davidson, 1980; Eriksen & Yeh, 1985) and objects (e.g., Duncan, 1984; Egly, Driver & Rafal, 1994; Vecera & Farah, 1994). The early research in visual selective attention centered on spatial locations as the unit of selection, which resulted in the dominant 'spotlight' and 'zoom lens' metaphors of spatial attention. Evidence for the attentional selection of spatial location comes from spatial cueing studies. For example, Posner et al. (1980) demonstrated that a valid cue (i.e., a cue that occurred at the same location as the target on 80% of the trials) decreased reaction time (RT) to the target, and an invalid cue (i.e., one that occurred at a different location from the target on 20% of the trials) increased RT. This finding supported a 'spotlight' metaphor of visual selective attention, which states that attention moves through spatial locations akin to a spotlight beam and only visual information illuminated by this beam is selected. Eriksen and Yeh (1985) conducted a similar experiment, in which the target could appear in four possible locations and the percentage of cue validity was manipulated. It was demonstrated that reaction time to both the validly cued and invalidly cued targets varied as a function of the percentage of cue validity. Eriksen and Yeh interpreted this finding as supporting a 'zoom lens' model, in which attentional resources can be distributed over the visual field with low resolving power, or constricted to small portions of the visual field with a concomitant increase in processing power.

Object-based Visual Attention

Despite theoretical differences between the ‘spotlight’ and ‘zoom lens’ model (e.g., Cave and Bichot, 1999), both models implicitly assume that attention selects spatial location for further processing. However, several researchers (e.g., Duncan, 1984; Egly et al., 1994; Pylyshyn, 2003; Scholl, 2001; Vecera, 1998) proposed that the selection unit of attention could be discrete objects rather than spatial locations. A study by Neisser and Becklen (1975) provided some early evidence for object-based selection. Subjects viewed two optically superimposed movie scenes at the same spatial location and were required to perform a ‘selective looking’ task in which they had to attend to one of the superimposed scenes (e.g., a ‘ball-game’, in which subjects counted the number of times three players passed a ball amongst themselves) and ignored another (e.g., a ‘hand-game’, in which two sets of hands hit each other). When subjects were engaged in the ‘selective-looking’ task, they were unaware of unexpected events that occurred in the unattended scene (e.g., the two sets of hands stopped and shook hands). As both the scenes were spatially superimposed, the selection of the attended scene could not be spatially mediated. If the attention spotlight or zoom lens had focused on one of the scenes, it would have included a substantial portion of the ignored scene, including the unexpected event as well. This early study provided some evidence that a unitary region of spatial selection as described by both the ‘spotlight’ and ‘zoom lens’ models cannot account for all forms of attentional selection. However, Scholl (2001) pointed out that the stimuli employed in Neisser and Becklen’s study were naturalistic and dynamic displays, and that it is unclear whether a movie scene constituted a single object rather than a perceptual group or an extended event. As such, while Neisser and Becklen provided some evidence to suggest the attentional selection in their study was not spatially mediated, it is unclear whether it was object-based.

A study by Rock and Gutman (1981) provided similar evidence as Neisser and Becklen (1975) with better-controlled stimuli. Subjects were asked to attend to one of two overlapping novel figures in a series of such overlapping figures. The novel figures were either red or green outlines and subjects were asked to attend to either the red or the green novel figures. It was found that subjects could recognize the attended novel figures in a later recognition task, but recognition for the unattended novel figures was virtually nonexistent. When a familiar figure (e.g., a Christmas tree) was inserted into the series of overlapping figures, subjects immediately recognized it when it was in the attended color, but could not recognize it when it was it the unattended color. This was despite the fact that the familiar figure in the unattended color was presented 1 second before the recognition test, demonstrating that failure to recognize the familiar figure when it was in the unattended color was a perceptual effect rather than a memory effect. Although one experiment did provide evidence that some of the general features of the unattended figures were recognized, the overall findings suggested that the form of the unattended figures were not recognized. Similar to the Neisser and Becklen study, neither the ‘spotlight’ nor the ‘zoom lens’ model would be able to account for the findings in the Rock and Gutman study. The fact the forms of the unattended figures were not recognized provided some evidence that the selection was object-based.

While both the Neisser and Becklen (1975) and the Rock and Gutman (1981) studies provided evidence of object-based selection with spatially overlapping stimuli in a focused attention task paradigm, Duncan (1984) used spatially overlapping stimuli with discrete objects in a seminal study using a divided attention paradigm. Subjects viewed briefly presented masked displays, consisting of a box and a line overlapping in the same spatial location. Each object had two varying properties: the height of the box could be tall or short, and the box had a gap that was located on the left or right of the box; the texture of the line could be dotted or dashed, and the line could either be tilted to the left or right. Subjects were instructed to report two of the four properties, either from the same object (e.g., line's texture and line's tilt direction) or from different objects (e.g., line's texture and box's height). Subjects were less accurate when reporting properties from different objects than from same objects. Similar to the Neisser and Becklen and the Rock and Gutman studies, it would be difficult for spatial attention to account for this finding because the objects were spatially overlapping and hence would be subsumed under the same attention 'spotlight' or 'zoom lens'. However, if the units of selection were discrete objects rather than spatial locations, an additional selection would be required when subjects reported properties from different objects, which would then result in the same object benefit (or different-object cost) that was observed. The findings of Duncan's study have since been replicated when the box and the line were located in different locations (Vecera & Farah, 1994), or when both objects were identical in form and hence had similar varying properties (Awh, Dhaliwal, Christensen & Matsukura, 2001), or when the objects were defined by perceptual set (Baylis & Driver, 1993), or when the objects were defined by transparent motion (Valdes-Sosa, Cobo & Pinilla, 1998, 2000; Valdes-Sosa, Bobes, Rodriguez & Pinilla, 1998).

The evidence for object-based attention extends beyond divided attention studies. Adopting a spatial cueing paradigm similar to Posner et al. (1980) in which spatial effects were clearly demonstrated, Egly et al. (1994) modified the paradigm to demonstrate both spatial and object-based selection effects within a single task. Egly et al. employed a display in which two rectangle outlines were placed on the sides of an imaginary square. The end of one of the rectangles was cued by brightening it (i.e., its color changed from gray to white) on each trial with cues that were 75% valid. Subjects were instructed to detect a luminance decrement, which would occur at one end of one rectangle immediately after the cue. The luminance decrement target could appear in the same location as the cue (i.e., valid cue), or in a different location from the cue (i.e., invalid cue). When the targets was invalidly cued, it could appear at the uncued end of the cued rectangle (i.e., same-object condition) or the equidistant end of the uncued rectangle (i.e., different-object condition). Subjects were fastest to detect a target when it was validly cued. When targets were invalidly cued, subjects were faster to detect targets in the same-object condition compared to the different-object condition. Because the distance between the two target locations and the cue location for the invalid cue trials was identical, the faster RT in the same-object condition was interpreted as a 'same-object advantage'. The findings of Egly et al. have since been replicated with objects defined by illusionary contours (Moore, Yantis & Vaughan, 1998) and objects defined by amodal completion due to an occluding object (Behrmann, Zemel & Mozer, 1998; Moore et al., 1998). Recent findings have identified several conditions in which the 'same-object advantage' in the spatial cueing paradigm could be modulated. For example, Shomstein and Behrmann (2008) demonstrated that when the presentation time of the two rectangles was increased, a larger same-object advantage was elicited. Hecht and Vecera (2007) demonstrated that the same-object advantage was eliminated when the surface outline of the rectangles were non-uniform (i.e., multi-colored). If one assumes that increasing the presentation time of the rectangles increases the perceptual strength of the rectangle as an object, and that the perceptual strength of rectangles with non-uniform surfaces is decreased compared to rectangles with uniform surfaces according to the principle of uniformed-connectedness (Palmer & Rock, 1994), then one can interpret the findings of Shomstein and Behrmann and of Hecht and Vecera as providing further support to the notion of object-based attentional selection within the Egly et al. paradigm; that is, the same-object advantage in the Egly et al. object task is modulated by the perceptual strength of the objects.

The just reviewed studies provide ample evidence for both spatial and object-based attentional selection. While some researchers advocate a strong object-based selection position that states that attention selects discrete objects by default (e.g., Pylyshyn, 2001) or a strong spatial selection position that states that attention selects a spatial location prior to accessing any features or objects within that location (e.g., Anllo-Vento & Hillyard, 1996; Huang & Pashler, 2007a), the general position in the literature is that whether selection is spatially mediated or object-based depends on the visual task engaged (e.g., Lavie & Driver, 1996; Vecera & Farah, 1994). Hence, describing attentional selection as both spatial and object-based is not necessarily contradictory. For the purpose of the present study, I assume that the selection unit of attention, spatial locations or discrete objects, is task dependent and remain agnostic towards whether attention selects spatial locations or discrete objects by default.

Visual Working Memory or Visual Short-Term Memory?

Just as the term attention has many meanings, WM is also a term that is theoretically loaded and might have different meanings amongst different researchers. For example, Logie

(1996) pointed out that in the history of memory research, the term WM referred to different cognitive constructs, such as primary memory, short-term memory, language comprehension constraint, a processor, activation, attention and expertise. Because researchers investigating WM hold differing views on what constitutes as WM (see Miyake and Shah, 1999 for a review), it is necessary to explicitly define the WM model employed in the current paper. The current paper generally adopts Baddeley's (1986, 2007) view of a multicomponent WM model. According to Baddeley and Logie (1999), this multicomponent WM model is non-unitary, in that WM is fractionated into different subcomponents. Although WM can be influenced by information from long-term memory, it is distinct from long-term memory and not an activated portion of long-term memory as posited by some models (e.g., Cowan, 1995, 1999; Engle, Kane & Tuholski, 1999).

In the initial formulation of his working memory model, Baddeley (1986; Baddeley & Hitch, 1974) proposed three components for the architecture of the WM system: (1) a central executive with control and supervisory functions, also involved in complex cognitive tasks like reasoning and comprehending, (2) an articulatory loop for the maintenance and rehearsal of verbal information, and (3) a visuo-spatial sketchpad for maintaining visuo-spatial information. Baddeley (2000, 2007) added a fourth component to the model called the episodic buffer, a limited capacity system that provides temporary storage of information held in multimodal code. The episodic buffer is also thought to be capable of binding information from the other components, and also from long-term memory, into a unitary episodic representation. As the emphasis of the current study will be on the visual aspects of WM, the visuo-spatial sketchpad will be the focus of the study.

Within the context of the Baddeley WM model, different types of WM tasks have been used (see Baddeley, 1986 for a review) with different emphasis on either the storage or the manipulation aspects of WM. Hence, the term WM is ambiguous because different researchers might use the term WM to refer to tasks that might have different emphasis. For example, one set of tasks that are described as WM tasks are ‘span tasks’ used by Engle and colleagues (e.g., Engle, Kane et al., 1999; Engle, Tuholski, Laughlin & Conway, 1999; Kane, Hambrick, Tuholski, Wilhelm, Payne & Engle, 2004) in which subjects are required to continuously switch between two tasks, one of which is a maintenance task and the other of which is a task that requires some sort of verbal or visual judgment. For example, in the symmetry span task (Kane et al., 2004), subjects were required to recall a sequence of locations that were presented on a square matrix. Subjects were required to judge whether a pattern presented on the square matrix was symmetrical in between presentations of locations in the sequence. Subjects continued switching between both tasks until subjects could no longer recall the sequence of the locations on the matrix. The number of locations that could be recalled by the subject is known as the ‘span’ score. Tasks such as these, which are employed by Engle and colleagues focus on both the temporary maintenance of visual information and attentional switching between different tasks.

Luck and colleagues (e.g., Luck & Vogel, 1997; Vogel, Woodman & Luck, 2001) used the term WM to refer to a set of tasks that require the temporary maintenance of information while engaging in another concurrent task. The general methodology is such that subjects are presented with an array of objects, which they have to remember in order to indicate whether a later probe is identical to one of the objects in the array. The probed memory task is employed by itself to provide a memory baseline, but often is also employed in a dual-task paradigm. In the case of the latter, the object array is usually presented in the beginning of the trial and the probe is presented at the end of the trial, with the concurrent task performed in between the presentation of the object array and the probe. Tasks such as these, which are employed by Luck and colleagues, concentrate on the maintenance of visual information while a concurrent task is being performed.

In the current paper, the task employed to engage the memory component of the visual system is more similar to that employed by Luck and colleagues than that employed by Engle and colleagues. In other words, the task emphasizes the maintenance of visual information without the continuous switching or shifting of attention on the visual information being maintained. Although Luck and colleagues used the term ‘visual working memory (VWM)’ to refer to these maintenance tasks (e.g., Luck & Vogel, 1997; Vogel et al., 2001), others in the literature have used the term ‘visual short-term memory (VSTM)’ (e.g., Logie, Zucco & Baddeley, 1990; Klauer & Zhao, 2004) to describe the memory component engaged by the memory task employed in the current paper. Shah and Miyake (1999) argued that the term STM refers to a more storage-oriented notion in which information is temporarily stored, while WM refers to a process-oriented construct akin to a mental ‘workspace’ in which the active processing and temporary storage of task-relevant information dynamically take place. In the context of Baddeley’s multicomponent WM model, STM would probably engage the appropriate subcomponents (i.e., phonological loop, visuo-spatial sketchpad) maximally and the central executive and episodic buffer minimally, while WM would probably engage all components of the model, especially the central executive. This is a view espoused by other researchers. For example, Cowan (1995, 1999) defined STM as a subset of WM, while Engle, Kane et al. (1999) suggested that WM contains the activated traces of STM plus controlled attention.

In order to address whether STM and WM were dissociable constructs, Engle, Tuholski et al. (1999) tested subjects on two types of memory tasks. One set of memory tasks thought to reflect WM were the tasks that required the switching of tasks during the maintenance of the sequence, similar to the symmetry span task described above. Another set of memory tasks thought to reflect STM required subjects to maintain a sequence of information without the need for task switching. Using both confirmatory factors analysis and structural equation modeling, Engle, Tuholski et al. demonstrated that both STM and WM reflected separate but highly correlated constructs. The early studies by Engle and colleagues (Engle, Kane et al., 1999; Engle, Tuholski et al., 1999) employed tasks that mainly involved verbal WM and verbal STM tasks and did not involve VWM and VSTM tasks. Hence, one could argue that these studies demonstrated the distinction between WM and STM in the verbal aspects of memory but not the visual aspects. However, Kane et al. (2004) extended this distinction to VWM and VSTM by applying similar statistical analysis to sets of VWM and VSTM tasks.

Mohr and Linden (2005) provided further evidence demonstrating a similar distinction for visual information. Using a dual-task paradigm, Mohr and Linden presented subjects with colored shapes and required them either to maintain the visual information or to actively manipulate the visual information while concurrently performing either a random number generation task or a phonological task. The maintenance task is thought to engage VSTM, while the manipulation task is thought to engage VWM. Because the random number generation task engages the central executive, it would affect performance on the manipulation task but not the maintenance task if the distinction between WM and STM also applied to visual information. Because the phonological task is thought to engage only the phonological loop and not the central executive or visuo-spatial sketchpad, it should affect neither the visual maintenance nor manipulation tasks. Mohr and Linden found that while the concurrent phonological task did not interfere with either task, the random number generation task interfered with the manipulation task. The phonological task served as a control task, ruling out the explanation that the interference to the visual manipulation task was due to a lack of processing resources (i.e., the visual manipulation task was more difficult). Hence, the finding suggested that VWM and VSTM engage different cognitive functions.

As mentioned, the current study will use a task involving the temporary maintenance of visual information without either active manipulation of the information or a requirement for subjects to switch repeatedly between different tasks. According to the distinction proposed by Shah and Miyake (1999), Cowan (1999) and Engle, Kane et al. (1999), the task employed in the current study does not engage VWM but does engage VSTM. Hence, I will follow the distinction proposed by Shah and Miyake and define the maintenance task as a VSTM task rather than a VWM task. In the rest of the paper, when describing previous research, I will use the term VSTM to denote visual maintenance tasks and the term VWM to denote visual manipulation tasks or task that requires constant task switching (e.g., Kane et al., 2004), even though the researchers in the original studies might have named them otherwise (e.g. Luck & Vogel, 1997; Vogel et al., 2001). However, it is noted that both VSTM and VWM are closely related in that most VWM tasks probably also require the cognitive functions associated with VSTM. For example, if one were asked to mentally rotate an image, it would be almost impossible to perform this task without temporarily maintaining some visual information of the manipulated image. In other words, the difference between VSTM and VWM could be a matter of the degree of central executive engagement rather a discrete difference. This point will be further elaborated in the section ‘Visual Attention and VSTM’.

Visual Aspects of Working Memory

Due to the lack of empirical data, the internal functions and structure of the visuo-spatial sketchpad were not articulated as well as the articulatory loop in Baddeley’s earlier models of WM (Baddeley, 1986). However, by examining empirical studies dealing with the manipulation and maintenance of visual and spatial information (e.g., Logie, 1986; Logie & Marchetti, 1991; Logie et al., 1990; Smyth & Pendleton, 1989), Logie (1995) articulated the visuo-spatial sketchpad in further detail. He proposed two subcomponents for the visuo-spatial sketchpad, namely (1) the inner scribe, which is a spatial subcomponent that deals with spatial and movement information, and (2) the visual cache, which is an object subcomponent that deals with visual information pertaining to an object (e.g. color, form, texture). It must be noted that while most researchers consistently name the first subcomponent as either spatial WM or spatial VSTM, there is less consensus with regards to the term used to describe the second subcomponent. Some researchers have used the term ‘object WM’ or ‘object STM’, while others have used the term ‘visual WM’ or ‘visual STM’. In the current paper, I will use the terminology ‘object STM’ when describing the second subcomponent (i.e., the object subcomponent) and will reserve the term ‘VSTM’ as a reference to both subcomponents. Also, when the central executive is used in tandem with the both subcomponents for the manipulation of visual information, the term ‘VWM’ will be used. Similarly, the terms ‘object WM’ and ‘spatial WM’ will be used when either the first subcomponent or the second subcomponent is used in tandem with the central executive.

Evidence for the spatial subcomponent was derived from studies that demonstrated the interference effect of concurrent movements on the retention of spatial patterns (e.g., Logie et al., 1990; Smyth & Pendleton, 1989). For example, Logie et al. (1990) employed a dual-task paradigm in which subjects performed a memory span task either for spatial locations in a visual matrix pattern or for a visually presented letter sequence. In the first experiment, these two span tasks were combined concurrently either with an arithmetic task or with a task that involved manipulation of visuo-spatial material. In the second experiment, the two span tasks were combined with two established tasks developed by Brooks (1967) that controlled for difficulty in a visuo-spatial task and a verbal task. The findings from both experiments indicated that while the arithmetic and the verbal tasks disrupted the letter span more than the visual span, the visuo-spatial tasks disrupted the visual span more than the letter span. Because the visual span task required subjects to maintain the spatial locations presented in a visual matrix, Logie et al. proposed that the findings were consistent with a subsystem of VSTM that deals with spatial information and that could be dissociable from verbal VSTM. Evidence for the object subcomponent comes from studies parallel to the one described above. For example, Logie (1986) asked subjects to memorize a list of concrete words using either verbal rote rehearsal or a visual imagery mnemonic. Subjects were concurrently presented with either visual images or auditory speech that they were told to ignore. The presentation of unattended visual images interfered with the use of the visual mnemonic but not the verbal rote rehearsal, while the unattended auditory speech interfered with the use of the verbal rote rehearsal but not the visual mnemonic. Logie (1986) interpreted this finding as demonstrating a subsystem of VSTM that deals with visual information pertaining to an object and that is dissociable from verbal VSTM.

Logie and Marchetti (1991) provided evidence that the spatial and object subcomponents within the visuo-spatial sketchpad were dissociable. They showed that arm movements concurrent with a retention interval interfered with the retention of spatial patterns, but not object information (i.e., color), whereas a concurrent visual interference task disrupted the retention of object information, but not spatial patterns. A similar study by Tresch, Sinnamont and Seamon (1993) also revealed a double dissociation between spatial and object STM. Subjects were asked to perform either a movement discrimination spatial task or a color discrimination object task while remembering either the location of a dot (a spatial memory task) or the shape of an object (an object memory task). Spatial STM was selectively impaired by the movement discrimination spatial task, while object STM was selectively impaired by the color discrimination object task.

Further evidence for distinct components in VSTM comes from research in neuroscience. Smith et al. (1995) measured subjects’ brain activity using positron emission topography (PET) while they engaged in either a spatial memory task (i.e., retaining the position of three dots for 3 seconds) or an object memory task (i.e., retaining the identity of two objects for 3 seconds). The PET measures revealed that different parts of the brain were activated for the maintenance of visual and spatial information respectively. The spatial memory task activated only the right hemisphere regions, while the object memory task activated primarily left hemisphere regions. This suggested that different biological substrates were involved in the maintenance of spatial and object information respectively. Further research with PET measures by Smith and Jonides (1997) replicated the above findings and demonstrated that the biological substrates associated with both the object and spatial STM subcomponents can be dissociated from the biological substrates associated with verbal STM.

While the studies described above provide evidence for an object and a spatial subcomponent in VWM, it must be noted that not every WM model supports such a distinction. On the one hand, certain models propose a WM model that is unitary in nature (e.g., Cowan, 1995, 1999) or domain free (e.g., Conway & Engle, 1994; Engle, Conway, Tuholski & Shisler, 1995). On the other hand, several researchers have proposed a finer distinction among subcomponents of VWM (e.g. see Cornoldi & Vecchi, 2003, for a review). In the current paper, I shall adopt the visuo-spatial sketchpad component of the WM model proposed by Baddeley (1986) and Logie (1995) as my definition of VWM and I shall concentrate on just maintenance of information. Thus, VWM has both an object STM and a spatial STM subcomponent. Although it is possible that the visuo-spatial sketchpad might not be an accurate or precise model of VWM, it should not affect the interpretation of the findings of the current study. For example, while Cowan (1995) noted that a unitary WM model makes no differentiation between WM and long-term memory representations, the representations in question could be multi-modal in nature. Hence, one can be agnostic towards the assumption of whether WM is differentiated from long-term memory and still assume that different modes of WM representation affect attention differentially. Similarly, if the subcomponents of WM were more finely differentiated (Cornoldi & Vecchi, 2003), it would mean the findings in the current study might be incomplete because only two subcomponents of visual WM were investigated, but not necessarily incorrect.

Visual Attention and VSTM

Two conclusions can be drawn from the review thus far. First, there are at least two types of visual selective attention, namely spatial attention and object-based attention. Second, there are at least two subcomponents of STM, namely spatial STM and object STM. On the surface, one cannot help but notice the similarities between visual selective attention and VSTM, in that both consist of a spatial and object component. Given what is known about how visual information is processed by the brain, this similarity may not be coincidental. Ungerleider and Mishkin (1982) established that two distinct cortical visual pathways exists in the non-human primate visual system, namely the ventral pathway that is thought to be associated with recognizing an object and understanding what it is (i.e., the 'what' of an object) and the dorsal pathway that is thought to be associated with analyzing the spatial location of an object (i.e., the 'where' of an object). Subsequent research has suggested that a similar organization could be present in humans (Haxby, Grady, Horwitz, Ungerleider et al., 1991; Ungerleider & Haxby, 1994). Hence, it would not be surprising if a similar distinction were to be found in both visual selective attention and VSTM. As first reviewed, there is evidence for both object-based and spatial components of visual attention and VSTM. What is not established is evidence that both cognitive components are highly related. In the following paragraphs, I shall review studies to present the case that visual attention and VSTM are highly related cognitive components.

Role of Attention in WM Models

From a theoretical perspective, several WM models regard attention as an important component in their model. For example, in Baddeley’s (1986) multi-component model, attention is thought to be an important aspect of the central executive component that facilitates its control and supervisory functions. In line with this view, Baddeley (1996) provided some preliminary data to suggest that the capacity for focused selective attention provides a promising further component of a complete specification of the central executive. Another WM model in which attention plays an important role is the embedded-processes WM model proposed by Cowan (1995). According to Cowan, attention is required to activate a subset of long-term memory, which then becomes ‘working memory’. Hence, any information that is in the focus of attention would be in working memory, though the inverse is not true. Another WM model proposed by Engle and colleagues (e.g., Conway & Engle, 1994; Engle et al., 1995) also included attention as an important component. In fact, Engle, Kane et al. (1999) defined WM as STM (activated portion of long-term memory) plus controlled attention. For example, Kane, Bleckley, Conway and Engle (2001) demonstrated that individual differences in performances on an antisaccade task, in which controlled attention is required, correlate highly with WM capacity, such that individuals who performed better on the antisaccade task had a higher WM capacity. However, it must be noted that most of the empirical data that support the above WM models come from investigation on verbal WM rather than visual WM.

A study by Schmidt, Vogel, Woodman and Luck (2002) investigated the role of visual attention in the transfer of perceptual representations into VSTM. Subjects were required to remember an array of six colored squares. Prior to the presentation of the array, a cue appeared at the location of one of the squares in the array. After the array was presented, there was a delay interval before a probe square was presented at the location of one of the squares in the previous array. Subjects were required to indicate whether the color of the probe was the same as the color of the square that was at that location in the previous array. Subjects were more accurate on this VSTM task when the probe appeared in a previously cued location, even when the cue was not predictive of the probe location. This finding suggested that the deployment of visual attention could influence the transfer of perceptual representations into VSTM.

Role of WM in Attention Models

Even though most theories of attention do not explicitly describe the role of VWM, its role is usually implied in the models. For example, most spatial attention theories based on studies in visual search postulate that the visual system creates an internal template of the target for matching items in the search array (e.g., Duncan & Humphreys, 1989; Wolfe, 1994). Hence, WM is probably required to maintain the internal template while the system engages in the search process. Recent studies have also shown that the contents of WM can direct attentional deployment. For example, several studies have demonstrated attentional capture by objects that were stored in WM (e.g., Downing, 2000; Huang & Pashler, 2007b; Olivers, Meijer & Theeuwes, 2006; Pashler & Shiu, 1999; Soto, Heinke, Humphreys & Blanco, 2005; but see Downing and Dodds, 2004; Woodman & Luck, 2007). The standard paradigm was that subjects were asked to remember an object, for a test at the end of each trial, while searching for a target in an array. RT was faster when the object in WM matched the target, but slower when the object in WM matched a distractor. While the mechanism involved in the presumed capture of attention by the object in WM is still under debate, the finding suggests that WM also has a role in the determining the deployment of attention, similar to the role that visual selective attention has in determining the type of information that enters visual WM.

The role of attention in the described WM models (Cowan, 1999; Engle, Kane et al., 1999) is to act mainly as a controller, in that it allows the switching of processing resources between concurrent tasks while maintaining or manipulating task relevant information in a temporary workspace. However, most of the discussed studies did not directly employ a visual attention task that required subjects to select a specific visual target over other distractors while maintaining relevant visual information in VSTM. In a paper reviewing studies that demonstrated the possible functions of the central executive, Baddeley (1996) pointed out while there are numerous studies that investigated the role of the central executive as a ‘controller’ while information was being maintained or manipulated, there was a general lack of empirical data investigating the role of the central executive as a ‘selector’ or ‘inhibitor’ (i.e., attentional selection) in similar situation. For example, in the Mohr and Linden (2005) study in which a difference was found between maintaining and manipulating information, the task employed to engage central executive was the random number generation task, which taps into the ‘controller’ role of attention. Thus, the finding that the maintenance task, in which only VSTM was engaged, was not affected by engaging the central executive, has not been demonstrated when the role of the central executive is a ‘selector’. Also, in the Kane et al. (2004) study in which a distinction was found between

VWM and VSTM using both confirmatory factor analysis and structural equation modeling, the role of attention was to control the switching of the maintenance task and the visual task rather than to select information. In the following paragraphs, recent studies are described in which attention acts as a ‘selector’ in dual-task interference paradigms involving the engagement of VSTM. The general finding in these studies is that when the role of attention (i.e., the central executive) is that of a ‘selector’ rather than a ‘controller’, VSTM performance is affected when the central executive is engaged.

Relationship between VSTM and Visual Attention

In terms of the relationship between visual attention and VSTM, Awh and colleagues (e.g., Awh & Jonides, 2001; Awh, Vogel & Oh, 2006) have proposed that VSTM and visual attention are closely related. Most of the evidence for such a claim comes from findings in spatial attention and spatial STM. Awh, Jonides and Reuter-Lonrez (1998) conducted a series of experiments to demonstrate that spatial attention is required for the maintenance of spatial locations in STM. Subjects were instructed to maintain the location or the identity of a letter that appeared in a specific location. While holding the information in VSTM, they had to make a speeded response to a target that appeared on the screen. RT was faster when the target appeared in the same location as the memory cue only when subjects maintained location information in VSTM. This suggested that the subjects deployed attention spatially to the locations that they were trying to maintain in STM. In another experiment, Awh et al. (1998) asked subjects to maintain the spatial location of an object in VSTM. During the retention period, subjects were asked to perform a color discrimination task. The critical manipulation was that on half of the trials, the color task required a shift of attention because of the size and eccentricity of the stimuli (the shifting-attention condition), while on the other half of the trials, the stimuli were large enough to occlude all potential memorized locations and no attention shifts were required (the static-attention condition). Subjects were less accurate on the memory task in the shifting-attention condition compared to the static-attention condition. Again, this finding suggested that spatial attention is required for the maintenance of spatial location in VSTM.

Further evidence for the close relationship between spatial attention and spatial VSTM comes from research in neuroscience. Using functional magnetic resonance imaging (fMRI), Awh et al. (1999) measured brain activity of subjects engaged in a spatial STM task and found that maintenance of spatial information led to enhanced activation in the early visual areas contralateral to the memorized locations. This is similar to the finding in which spatial attention leads to the modulation of activity in similar areas (e.g., Gratton, 1997; Heinze, Mangun, Burchert & Hinrichs et al., 1994). This finding was corroborated by Awh, Anllo-Vento and Hillyard (2000), in which subjects were asked to perform a spatial STM task and a spatial attention task that employed identical stimulus displays. During the delay of the spatial STM task, behaviorally irrelevant probe stimuli were flashed at both memorized and non-memorized locations. Event-related potential (ERP) measures were used to assess the visual processing of the probes. Early ERP components were enlarged in response to a probe that appeared at memorized locations. These visual modulations were similar in latency and topography to those observed in the spatial attention task, again suggesting that spatial attention and spatial STM activate similar brain regions.

The studies of Awh and colleagues just described claimed that spatial attention and spatial STM engage similar processing resources by demonstrating that both spatial attention and spatial STM tasks activate similar brain regions (Awh et al., 1999; Awh et al., 2000), or that the engagement of spatial STM inevitably leads to spatial attention being engaged onto the maintained spatial locations (Awh et al., 1998), or that directing spatial attention away from maintained spatial locations decreased VSTM performance (Awh et al., 1998). Another line of studies employing a dual-task paradigm reached similar conclusions (Oh & Kim, 2004; Woodman & Luck, 2004). Subjects were asked to maintain either spatial information or object information such as color (Oh & Kim, 2004) or shape (Woodman, Luck & Vogel, 2001) in VSTM. They were tested on this information at the end of each trial. During the delay between initial encoding and the test at the end of the trial, subjects were asked to perform a visual search task, a task in which spatial attention is thought to be engaged. There was no difference in search slopes for the visual task when subjects remembered object information (color, shape) compared to the baseline control condition (visual search task without maintaining any visual information in VSTM), but search slopes were steeper when subjects maintained spatial information in VSTM. This suggested that maintaining spatial information in VSTM interfered with the visual search task, providing more evidence for the claim that spatial attention and spatial STM engage similar processing resources.

Another inference from the findings of Oh and Kim (2004) and Woodman, Luck and Vogel (2001) was that object STM does not interfere with spatial attention. Tan (2008) pointed out that there were two possible explanations for the non-interference of maintaining object information in STM on spatial attention. First, many theories of visual attention (e.g., Treisman, 1988; Treisman & Gormican, 1998) claim that spatial location is a ‘special feature' compared to other visual features. For example, in Treisman's Feature Integration Theory (Treisman & Gelade, 1980), attention is required to bind visual features to a spatial location to form a coherent object. If spatial features are special, it is possible that spatial STM is accessed whenever any form of visual attention is engaged. Hence, the loading of spatial STM would affect all forms of visual attention and not just spatial attention. The alternative explanation is that the interference is specific, such that loading spatial STM affects spatial attention more than other forms of visual attention. While neither explanations necessarily contradicts the assumption that spatial attention and spatial STM engage similar processing resources (e.g., Awh et al., 2006; Oh & Kim, 2004; Woodman & Luck, 2004), the former explanation implicitly posits a hierarchical relationship between spatial STM and attention not inherently obvious in the explanation posited by either Oh and Kim or Luck and Vogel.

Tan (2008) attempted to distinguish between these two alternatives by adopting a dual-task paradigm similar to Oh and Kim (2004). Subjects were asked to maintain in VSTM either spatial locations or the colors of objects in a visual array. However, instead of performing a visual search task concurrently, subjects performed a version of the Duncan (1984) task, which as noted earlier, is presumed to tap into object-based attention. In the first experiment, the Duncan task was modified such that only a single speeded response was required (unlike the original Duncan task which required two unspeeded response), making it similar to the visual search task employed in Oh and Kim (in which only a single speeded response was required). There were two conditions in the Duncan task: subjects monitored (and reported) properties either from the same object or from different objects. When compared to the baseline object-based attention task in which subjects' VSTM was not loaded, the different-object cost (i.e., the difference in mean accuracy of same object and different objects conditions) did not differ significantly when subjects remembered color, but was significantly larger when subjects remembered spatial locations, despite the fact that subjects found it more difficult to remember spatial locations than color (i.e., they showed higher RT and lower mean accuracy). These results suggested that maintaining object information, but not spatial information, in VSTM interfered with object-based attention and that object-based attention and object STM engaged similar processing resources. Also, the results suggested that the interference effect of loading spatial STM on spatial attention was specific, that is loading spatial STM did not affect all forms of visual attention.

In Tan's (2008) second experiment, the original version of the Duncan (1984) task with two unspeeded responses was employed. While there was no difference in performance on the Duncan task regardless of whether subjects remembered spatial or color information, there was more interference on the mean accuracy in the VSTM task in the dual-task condition relative to the baseline condition when subjects remembered color, despite the fact that the spatial STM task was more difficult. This finding is consistent with the claim that object-based attention and object STM engage similar processing resources. Matsukura and Vecera (2008) also found that when subjects performed the Duncan task, mean accuracy in the VSTM task in the dual-task condition was lower relative to the baseline when subjects remembered color than when they remembered spatial locations. Furthermore, Matsukura and Vecera also demonstrated that when subjects performed a visual search task, the mean accuracy in the VSTM task in the dual-task condition was lower relative to the baseline when subjects remembered spatial locations than when they remembered color. In other words, Matsukura and Vecera demonstrated a double dissociation of the interference effect of loading both spatial and object STM on spatial and object-based attention. This is consistent with the claims proposed earlier, in that object STM and object-based attention engaged similar processing resources (Tan, 2008), as did spatial STM and spatial attention (Oh & Kim, 2004; Woodman & Luck, 2004).

Based on the numerous studies cited above (Awh et al., 1998; Awh et al., 1999; Awh et al., 2000; Matsukura & Vecera, 2008; Oh & Kim, 2004; Tan, 2008; Woodman & Luck, 2004; Woodman et al., 2001), the relationship between spatial and object-based attention with spatial STM and object STM can be summarized by the model depicted in Figure 1. There are three claims that can be derived from the model. First, spatial attention and spatial STM share similar processing resources. Second, object-based attention and object STM share similar processing resources. Third, these two sets of resources are dissociable from each other. As shown in Figure 1, the first claim is substantiated by numerous studies in the literature, while the second and third claims are less substantiated by existing studies.

The main purpose of the present study was to test the three claims derived from the model depicted in Figure 1 (bottom), especially the claim that that object-based attention and object STM engage similar processing resources. Although the findings in Tan (2008) and Matsukura and Vecera (2008) support this claim, there are limitations to those findings. First, the stimuli employed in the object-based attention task in both studies were overlapping in the same spatial location and hence no spatial selection was required. Thus, it is not surprising that loading spatial STM did not affect the task. Second, both studies demonstrated the interference effect of object STM on object-based attention with the Duncan (1984) task. The claim that object-based attention and object STM engage similar resources would be stronger if the findings could be extended to other object-based attention tasks, such as that used by Egly et al., (1994).

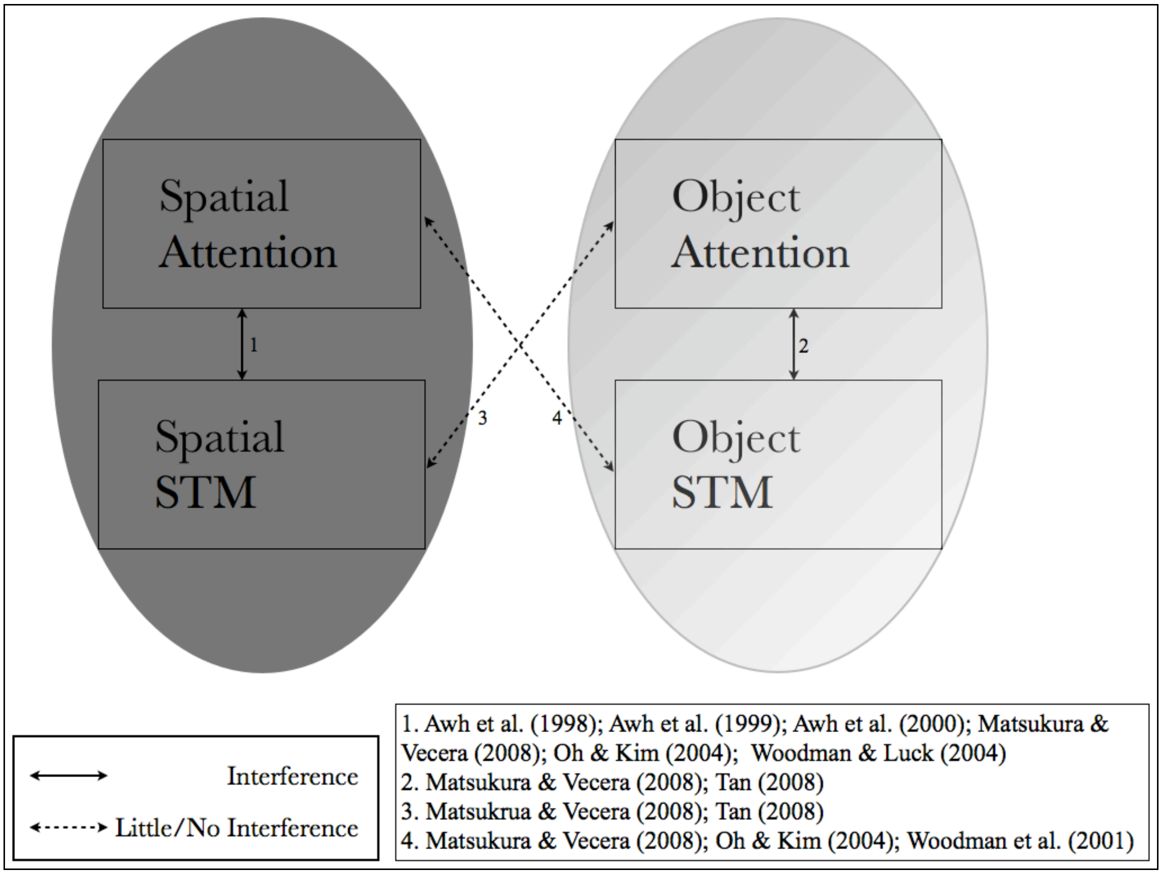

Figure 1. Proposed relationship between visual attention and VSTM. It is proposed that spatial attention and spatial STM share similar processing resources, that object-based attention and object attention also share similar processing resources, and that these two sets of processing resources are dissociable from each other. These claims are supported by studies showing interference effects when spatial attention and spatial STM were concurrently engaged (arrow 1), studies showing interference effects when object-based attention and object STM were concurrently engaged (arrow 2), studies showing that engaging object-based attention and spatial STM concurrently led to little or no interference effects (arrow 3), and studies showing that engaging spatial attention and object STM concurrently led to little or no interference effects (arrow 4). The list of studies supporting each arrow is shown in the box on the bottom right corner of the figure.

In the current study, these two limitations are addressed. The first limitation was addressed in Experiment 1, in which a spatial component was included in the Duncan (1984) object task used in Tan (2008) and Matsukura and Vecera (2008). The second limitation was addressed in Experiment 2, in which the Egly et al. (1994) object task was used to test the claim that object-based attention and object STM share similar processing resources.

CHAPTER 2: EXPERIMENT 1

Tan (2008) and Matsukura and Vecera (2008) demonstrated that performing the Duncan object task (Duncan, 1984) interfered with the object STM task more than the spatial STM task and suggested that object-based attention and object STM engage similar processing resources. However, the stimuli used in these studies did not have a spatial component, in that both the line and the box were spatially overlapped in the same location. Hence, it is possible that interference on the spatial STM task was less than on the object STM task because no spatial selection was required by the task. In the current experiment, I explored whether performing an object-based attention task with a spatial component would still result in the same interference effect on object STM.

One obvious candidate for the exploration of this issue would be to modify the object task used in Tan (2008) and Matsukura and Vecera (2008) so as to include a spatial component. Previous studies in which a spatial component was included in such a task found mixed results (e.g. Awh et al., 2001; Kramer, Weber & Watson, 1997; Vecera & Farah, 1994). For example, Vecera and Farah employed procedures and stimuli that were similar to Duncan (1984), but on half of the trials, the box and the line were spatially separated instead of spatially overlapping. Vecera and Farah found that the different-object cost was similar whether the box and the line were spatially overlapping or separated. This suggested that the object-based attention effect was spatially invariant because selection was engaged onto a spatially invariant representation of the stimuli.

Their view was challenged by Kramer et al. (1997), who employed procedures and stimuli similar to Vecera and Farah (1994), with the exception that the stimuli in the spatial overlapping condition were presented in the same position as those in the spatially separated condition (i.e., in the periphery) rather than in the center of the screen (i.e., in the fovea). Additionally, on 25% of the trials, subjects also had to make a speeded response to a post-display probe before reporting the two monitored properties. The probe could appear either at the same spatial location as the target object (ipsilateral) or on the opposite side (contralateral). Kramer et al. found that the different-object cost was larger when the box and the line were separated. Furthermore, the result of the post-display probe task suggested that attention was directed to the location of the target objects, such that RT for probes on the same side as the target object was faster. This suggested that the object-based attention effect was not spatially invariant. Kramer et al. suggested that as a result of increased metacontrast masking in the periphery (Breitmeyer, 1984), there was increased interference between the box and the line when they were presented overlapping in the periphery, which led to a decrease in the different-object cost. Indeed, the difference in the different-object cost between the spatial overlapping and separated conditions was eliminated when Kramer et al. presented the stimuli in the spatial overlapping condition in the fovea. Based on these results, Kramer et al. claimed that the object-based attention selection demonstrated by Vecera and Farah is not entirely spatially invariant and their results for the spatially separated condition could be obtained based on spatial selection without positing a spatially irrelevant object-based selection. When the object task employed separate stimuli, Kramer et al. suggested that attentional selection engaged on a grouped-array representation that has spatial dimensions.

Vecera (1997) acknowledged that the findings in Kramer et al. (1997) showed that spatial selection was involved in the spatially separated condition. However, he claimed that Kramer et al.'s findings did not necessarily rule out a spatially invariant object-based attention selection and proposed an alternative account for Kramer et al.'s results. Vecera argued that spatial selection or object-based section might interact with one another at different levels of the representations in the visual system, and that this would provide an alternative explanation for Kramer et al.'s results. Such an account posits that multiple forms of attentional selection might coexist in the visual system, and that the engagement of one selection mechanism over another might well depend on task conditions and properties of the stimuli (Vecera & Farah, 1994). Furthermore, Vecera also pointed out that Kramer et al. did not dispute the possibility that a spatially invariant object-based attention selection is in principle possible.

Awh et al. (2001) provided evidence for Vecera's (1997) claim when they demonstrated spatially invariant object-based attention effect using an object task. Awh et al. presented subjects two different colored lines (e.g., red, green) that varied on two properties (texture: dotted or dashed; gap: top or bottom). The lines were presented in the periphery, and the spatial distance between the lines was varied (near or far). Both spatial and object-based effects were found when the order of reporting was known in advance, but only an object-based effect was found when the reporting order could not be predicted. Awh et al. claimed that when the reporting order was known, subjects could spatially select one of the two objects in the initial presentation of the targets for the first report and hence this resulted in a spatial effect in that the report accuracy for the far condition was lower when subjects reported from different objects. However, when the reporting order was unknown, subjects had to select both targets in the initial presentation and this eliminated the spatial effect. Awh et al. suggested that when the reporting order was unknown, the process of selection operates on representations in object working memory (Luck & Vogel, 1997). Awh et al.'s findings were consistent with the claims of Vecera (1997; Vecera & Farah, 1994) that the engagement of one attentional mechanism over another might well depend on task conditions and properties of the stimuli.

Regardless of the type of representation on which the selection process operates, the just discussed studies (Awh et al., 2001; Kramer et al., 1997; Vecera & Farah, 1994; Vecera, 1997) demonstrated that two conditions are essential to elicit both a spatial and an object-based effect in the Duncan object task. First, the objects need to be presented in the periphery. Second, the response order of the monitored responses must be made known to the subjects. In the current set of experiments, these findings are exploited to explore how VSTM and object-based attention interact and interfere with each other using the Duncan object task with a spatial component.

Three different attention tasks were used. They included a visual search task adopted from Matsukura and Vecera (2008), the Duncan object task with overlapping stimuli (e.g., Duncan, 1984; Matsukura & Vecera, 2008; Tan, 2008) and the Duncan object task with separated stimuli (e.g., Awh et al., 2001;Vecera & Farah, 1994; Kramer, Weber & Watson, 1997). The role of the attention tasks was to engage the different types of processing resources and to determine whether there were differences in performance on the spatial and object STM tasks. In the visual search task, either 4 or 12 stimuli were presented in a circular array as shown in Figure 2 (bottom). The task was to indicate whether or not a target was present. The visual search task was expected to engage spatial attention. The assumption was that spatial attention would be more heavily engaged when there were 12 items than when there were 4 items.

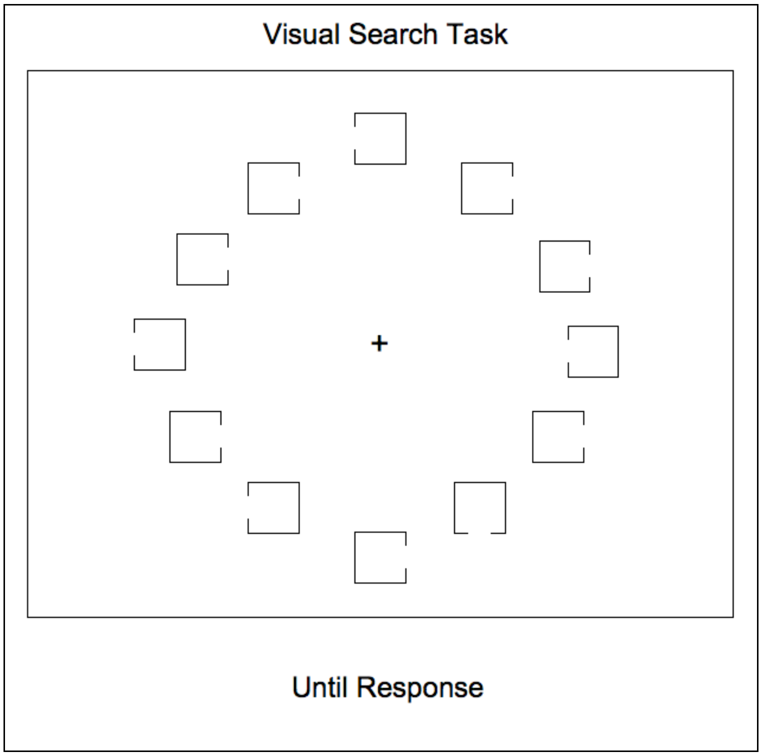

Figure 2. Sample of stimuli and procedure outline of the visual search task. Target had a gap in either the top or bottom. Subjects indicated whether or not a target was present. The example depicts a target with a bottom gap.

Figure 3 (bottom) illustrates the displays in the Duncan object task with overlapping stimuli (Duncan, 1984). Two overlapping objects were presented centered at fixation. Subjects answered two questions about one object (the same object condition) or one question about each object (the different object condition). The task was expected to engage object-based attention with the assumption being that object-attention was more heavily engaged in the different object condition.

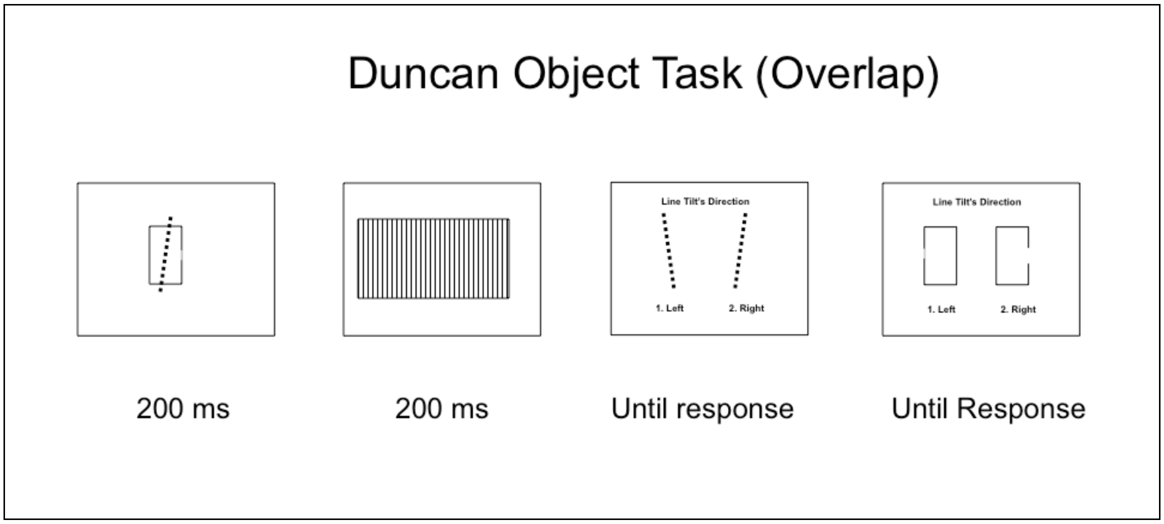

Figure 3. Sample of stimuli and procedure outline of the overlap version of the Duncan object task. The example depicts a different-object condition where subjects were required to report the line tilt first, followed by the box gap.

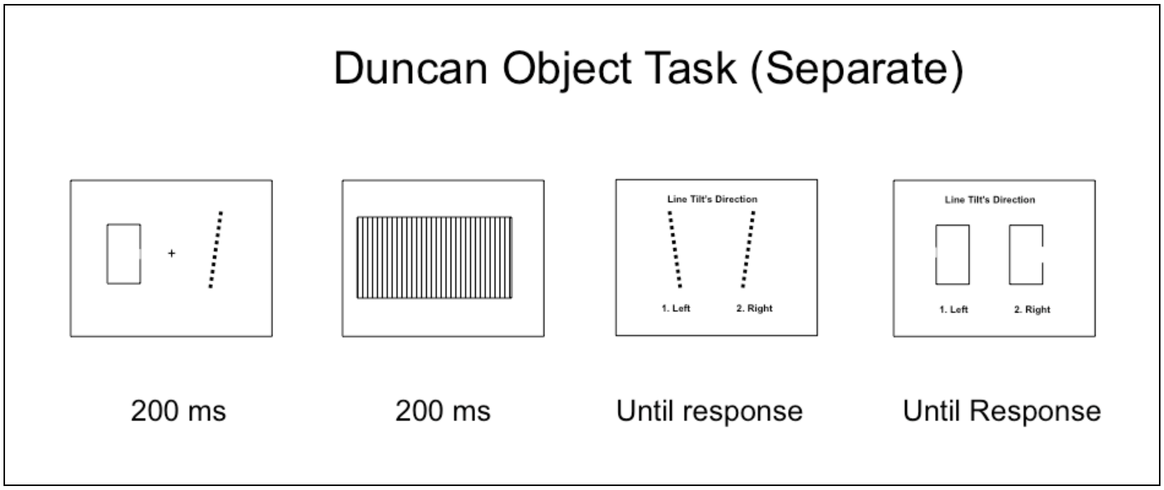

Figure 4. Sample of stimuli and procedure outline of the separate version of the Duncan object task. The example depicts a different-object condition where subjects were required to report the line tilt first, followed by the box gap.

Figure 4 illustrates the object task with separated stimuli. Two objects were presented at fixation, one to the left and one to the right. Subjects answered two questions about one stimulus (the same object) or one question about each stimulus (the different object condition). Based on previous findings (e.g., Awh et al., 2001), the Duncan object task with separated stimuli was assumed to engage object-based attention as well as spatial attention with both object-based attention and spatial attention more heavily engaged in the different object condition.

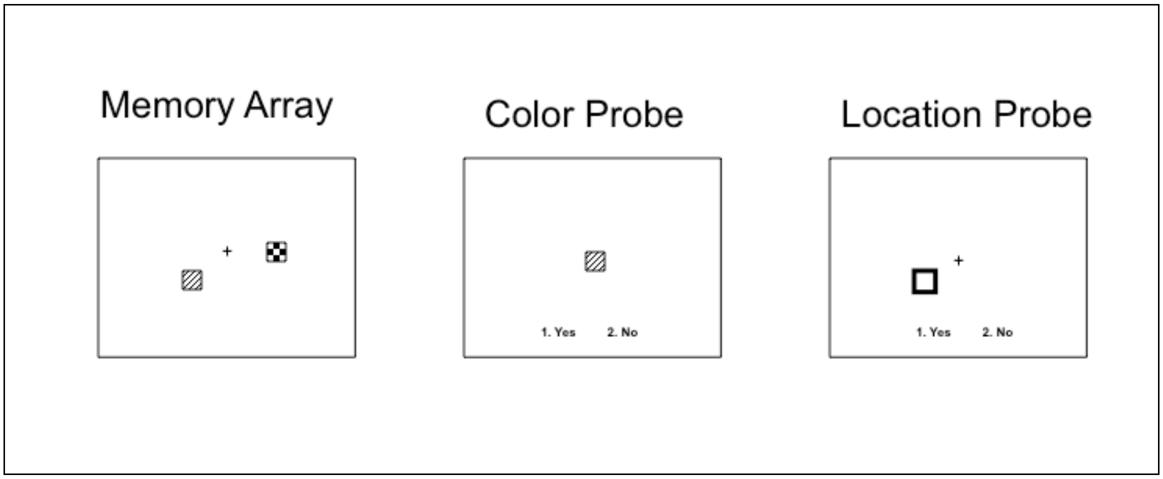

Figure 5. Sample of stimuli used in the memory task. The left panel denotes the memory array that was presented to subjects at the beginning of each trial. The center panel denotes a color probe, in which subjects have to indicate whether the color of the probe matched the color of any of the squares in the memory array. The right panel denotes a location probe, in which subjects have to indicate whether the location probe was in the same location of any of the squares in the memory array.

The memory tasks employed in Experiment 1 included a color memory task, a location memory task and a double memory task. An example of the memory array and memory probes used in the memory tasks is shown in Figure 5 (bottom). The color and location memory tasks were similar to the tasks employed in Tan (2008), in that subjects were asked to remember either the colors or the locations of objects in a memory array. For the color memory task, subjects were required to indicate whether a centrally presented probe was the same color as any of the objects in the memory array. For the location memory task, subjects indicated whether a black outline probe was at the same location as any of the objects in the memory array. Based on previous findings (e.g., Matsukura & Vecera, 2008; Tan, 2008), it was assumed that the color memory task engaged object STM, while the location memory task engaged spatial STM.

In the case of the double memory task, subjects were instructed to remember both the colors and the locations of objects in the memory array. The testing procedure was identical to that used for the color and the location memory tasks. Thus, subjects were never tested on the conjunctions of location and color, but only on either color or location information. Subjects were not tested on the conjunctions of the memory array because additional attentional resources would be required to bind both the location and color information into a coherent object (Wheeler & Treisman, 2002), which might interfere with the performance of the attention or memory task. While this might be an interesting research question in its own right, it would detract from the research question in the current study, which is whether object-based attention and object STM engaged similar processing resources. Hence, by testing either the location memory or the color information and not the conjunction of both, the double memory task was assumed to engage both object and spatial STM with minimal attentional requirements.

A dual-task paradigm was employed as the general procedure in Experiment 1, as shown in Figure 6 (bottom). Each group of subjects performed different combinations of tasks, which included an attention task and a VSTM task, in order to explore the interference effects of one task on the other. Each group of subjects performed three different conditions, namely the attention baseline condition, the VSTM baseline condition and the dual-task condition.

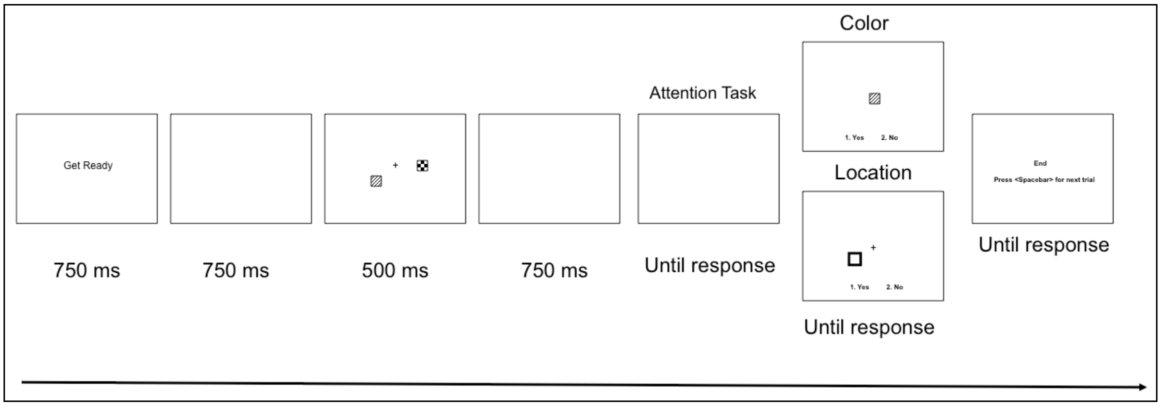

Figure 6. Sample of stimuli and procedure outline of a trial in the dual-task condition. Subjects began articulatory suppression when presented the “Get Ready!” frame. The memory array was presented before the attention task. Memory probes were presented after the attention task. Presentation sequence was similar in attention baseline, memory baseline and dual-task conditions.

In Experiment 1, the question addressed with the different attentional and memory tasks described above was whether the failure to find interference in the location memory condition in Tan (2008) and Matsukura and Vecera (2008) was due to the lack of a spatial component in their object task. Matsukura and Vecera (2008) and Tan (2008) found differences in the memory tasks rather than on the attention task, so the same was expected in Experiment 1. Thus, the question of interest was whether an interference effect would still be found in the color memory task when a spatial component is added to the Duncan object task by spatially separating the stimuli (Vecera & Farah, 1994). It was assumed that the Duncan object task with separated stimuli engaged both spatial and object-based attention. Comparing the interference on the memory task resulting from the different attention tasks should lead to a more comprehensive understanding of the interaction between the different types of visual attention and VSTM.

In the case of the visual search task and the Duncan object task with overlapping stimuli, the predicted pattern of interference on the color and location memory tasks are those already shown in previous studies. For the visual search task, accuracy on the location memory task should decrease with the increase of the number of search items (Matsukura and Vecera, 2008; Oh & Kim, 2004; Woodman & Luck, 2004), because spatial attention is engaged to a larger extent when searching for a target amongst more distractors. However, accuracy on the color memory task should not be affected by the number of search items (Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman et al., 2001). For the Duncan object task with overlapping objects, there should be a larger interference effect on the color memory task than the location memory task (Matsukura & Vecera, 2008; Tan, 2008). Furthermore, because an additional object-based attentional selection is required for the different objects condition, there should be a decrease in accuracy on the color memory task in the different objects condition compared to the same object condition, but no difference in the accuracy on the location memory task between the same and different objects condition (Tan, 2008).

In the case of the Duncan object task with separated stimuli, the prediction of the interference on color and location memory task accuracy in the dual-task condition is less straightforward. If, based on previous studies, it is assumed that spatial and object-based attention are dissociable cognitive components (Awh et al., 2001; Vecera & Farah, 1994), that spatial and object STM are also dissociable types of VSTM (Logie, 1995; Smith et al., 1995; Tresch et al., 1993), that spatial attention and spatial STM engage similar processing resources (Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman & Luck, 2004), and that object-based attention and object STM engage similar processing resources (Matsukura & Vecera, 2008; Tan, 2008), then there should be interference on both the color and location memory tasks. If the additional selection required for the different object condition engages both spatial and object-based attention to a larger extent, there should be lower accuracy for both the color and location memory tasks on the different objects condition compared to the same object condition. However, as suggested by Kramer et al., (1997), when a spatial component is introduced to the Duncan object task, spatial attention might drive the selection process and override object-based attention. If this were the case, interference would occur only on the location memory task and not on the color memory task. While such a finding would not necessarily contradict the findings and claims of Matsukura and Vecera (2008) and Tan (2008) that object-based attention and object STM engage similar processing resources, it would suggest a limited or boundary conditions under which this would occur.

One memory task condition not included in either Tan (2008) or Matsukura and Vecera (2008) is the double memory condition. This was included in the current study to examine the possible interference effect that the different attention task on the different memory tasks might have in a more sensitive within-subjects design. Also, the double memory condition was included to investigate whether the interference effect of the attention tasks on both object and spatial STM are distinct in the case when both are loaded. Previous studies have demonstrated a dissociation between object and spatial STM (e.g., Smith et al., 1995). Based on the literature, (e.g., Matsukura & Vecera, 2008; Oh & Kim, 2004), one should expect no interactions between the two different types of memory when they are both loaded in the context of a dual-task paradigm. However, this claim has not been systematically and empirically tested to the best of my knowledge. The double memory condition in the current study allowed a test of this claim. If the interference effect obtained for the color and location probes in the double memory condition is similar to that obtained from the color and location memory tasks respectively, this will provide more evidence for the claim that different sets of processing resources are indeed dissociable. However, if the pattern of interference is not similar for the double memory condition compared to the individual memory conditions, then this will suggest that the different processing resources just described may not be completely dissociable.

To summarize, four claims were tested in Experiment 1, including (a) spatial attention and spatial STM share similar processing resources, (b) object-based attention and object STM share similar processing resources, (c) these two sets of processing resources are dissociable, and (d) spatial features are not dominant over object features when both spatial and object STM or attention are engaged. The predicted results for each claim are summarized in Table 1.

Table 1: Predictions of Experiment 1

Claims	Task	Predictions
Spatial Attention and Spatial STM Engage Similar Resources	**Visual Search**	Location probe accuracy decreases as number of search items increases
	Duncan (Overlap)	Duncan (Overlap) object task does not engage spatial attention
	Duncan (Separate)	Location probe accuracy lower in the different object condition
Object-Based Attention and Object STM Engaged Similar Resources	**Visual Search**	Visual search task does not engage object-based attention
	Duncan (Overlap)	Color probe accuracy lower in the different object condition
	Duncan (Separate)	Location probe accuracy lower in the different object condition
Two Sets of Resources Dissociable	**Visual Search**	No difference in color probe accuracy as the number of search items increases
	Duncan (Overlap)	No difference in location probe accuracy for same vs. different object condition
	Duncan (Separate)	Both location and color probe accuracy lower in the different object condition
Spatial Features Not Dominant Over Object Features	**Visual Search**	Visual search task does not address this claim
	Duncan (Overlap)	Location probe accuracy not lower in different object condition for double memory task
	Duncan (Separate)	Color probe accuracy lower in the different object condition

Method

Subjects and Design

Subjects were 270 students with normal or corrected-to-normal vision who participated for course credit after giving informed consent. The data from an additional 28 subjects were discarded due to low accuracy rates in the attention task (< 70%). Three types of memory task (i.e., location, color and dual-memory) and three types of attention task (i.e., visual search, Duncan object task with overlapping and separated stimuli) were factorially combined. Thirty subjects were randomly assigned to each of the nine resulting task combinations (i.e., one attention task and one memory task). Within each task combination, there were three task conditions: memory task baseline, attention task baseline and dual-task. The order of the three task conditions was counterbalanced across subjects within each attention/memory task combination.

Tasks

For all tasks, the displays consisted of black figures on a white background unless otherwise noted. This is because previous studies also employed similar stimuli (e.g., Matsukura & Vecera, 2008; Vecera & Farah, 1994). The experiment was written using E-PRIME (www.psnet.com). The stimuli were presented on a 17-inch Dell Monitor. Subjects viewed the display freely from approximately 23.6 inches and wore sound deadening earmuffs throughout the experiment.

Memory task. Figure 5 (page 36) shows an example of the display frames and procedural outline of the memory task. The stimuli for the memory task were two colored squares each 0.25" x 0.25" (visual angle = 0.60º x 0.60º) in size. The colors and locations of the squares were selected randomly from eight possible colors (red, yellow, green, blue, magenta, brown, cyan and gray) and locations (eight points on an imaginary circle with a radius of 2.05", visual angle = 5.0º, from fixation). For the color memory task, subjects remembered the colors of the squares. At the end of the trial, one colored square (color probe, 0.25" x 0.25"; visual angle = 0.60º x 0.60º) was presented at fixation. The color of the probe was randomly chosen from the eight possible colors, with the restriction that it matched that of one of the two memory stimuli on half of the trials. Subjects made an unspeeded response to indicate whether the probe color was the same color as one of the two original squares. The procedure was similar in the location memory condition, with the exception that subjects remembered the spatial locations of the squares. At the end of the trial, one black square surrounding the area where a square might have occurred (location probe, 0.28" x 0.28"; visual angle = 0.68º x 0.68º) was presented. The location of the probe was selected randomly from the eight possible locations, with the restriction that its location matched that of one of the two memory stimuli on half of the trials. Subjects made an unspeeded response to indicate whether the probe was located at the same location as one of the two original squares. In the double memory condition, subjects were asked to remember both the color and the location of the two colored squares. On half of the trials, subjects were presented with a color probe and on the other half, subjects were presented with the location probe. For each type of probe, the value was randomly selected with the restriction that half matched one of the two memory stimuli. Thus, subjects needed to remember the separate features rather than the conjunction of features (i.e., a specific colored square at a specific location).

The memory task in the memory baseline condition consisted of 32 trials, and the memory task in the dual task condition consisted of 64 trials. The memory array was presented for 500 ms, followed by a blank frame of 750 ms prior to the onset of the attention task stimuli. Shortly (500 ms) after the offset of the response frame for the attention task, the memory probe was presented, and it remained on screen until subjects responded.

Object task (object-based attention task). Figure 3 (page 34) and Figure 4 (page 35) illustrate examples of the series of four displays constituting the object task with overlapping and separated stimuli respectively. The object task stimuli were similar to those used by Vecera and Farah (1994). The stimuli consisted of two objects, a box and a line. Each object had two dimensions. The box was either short or tall and had a gap on either the left or the right. The line was either dotted or dashed and tilted either to the left or the right. The width of the box was 0.28" (visual angle = 0.67º). The height of the tall and short box was 0.47" (visual angle = 1.14º) and 0.35" (visual angle = 0.86º) respectively. The box's gap was created by removing 0.08" (visual angle = 0.20º) from one side. The length of the line was 0.63" (visual angle = 1.53º) and it was tilted 8º rightward or leftward from the vertical position. The line was either dotted or dashed; dots and dashes contained the same number of pixels but in different pixel array configurations (Dots: 3 x 2; Dashes: 1 x 6). The box and line were at fixation, and were followed by a 2.18" (visual angle = 5.30º) x 1.56" (visual angle = 3.78º) pattern mask. In the spatial overlapping version, both the box and the line were presented at fixation, as illustrated in Figure 1. In the spatial separated version, the box and the line were each presented 0.79" (visual angle = 1.91º) from fixation, one to the left and one to the right. The box appeared randomly on the left side half of the time and on the right side the other half, and the same was true for the line. Other than the way the box and the line were presented, there was no difference between the overlapping and separated versions of the object task.

As typical in the literature, the object task was blocked by the dimensions to be monitored. In the same-object condition, subjects monitored either the box gap and box height, or the line texture and line tilt. In the different-object condition, the subjects monitored either box gap and line texture, or box gap and line tilt, or box height and line texture, or box height and line tilt. Because the number of dimension-pairs for different objects was twice that of the same object, each set of dimension-pairs from the same object blocks was used twice, thus equating the number of “same-object” and “different-object” trials. Non-reported dimensions did not vary within each block: the box height was short, the box gap was on the right, the line tilt was to the right and the line texture was dashed.

The object task consisted of 8 blocks. Subjects were instructed to monitor a pair of dimensions for each block; to be monitored dimension-pairs were randomly ordered across blocks. Subjects were also instructed to be as accurate as possible in their reports. There were 8 trials in each block, such that reported properties and spatial location of the box and line (when they were separated) were counterbalanced and randomly ordered in each block. After the presentation of the 500 ms blank frame following the memory task stimuli, the box and the line were presented for 200 ms followed by the pattern mask for 200 ms. The first dimension to report and the description of the response alternatives were then presented, and they remained on the screen until response. Subjects pressed “1” to indicate the first alternative (e.g., box gap: left) or “2” to indicate the second alternative (e.g., box gap: right).

The second dimension to report and the description of the response alternatives were then presented, again remaining on screen until the response was made. Again, subjects pressed "1" to indicate the first alternative (e.g., line tilt: left) or "2" to indicate the second alternative (e.g., line tilt: right). No feedback was given for the responses in the object task.

The order of reporting for each dimension-pair followed Vecera and Farah (1994) and were as such: box height followed by box gap, line texture followed by line tilt, box height followed by line texture, box height followed by line tilt, box gap followed by line texture, and box gap followed by line tilt. The choice of the report order was largely due to pragmatic considerations, because a full counterbalancing of the reporting order would require too many subjects. Awh et al. (2001) demonstrated that the spatial effect is attenuated when the reporting order is randomized.

Visual search task (spatial attention task). Figure 2 (page 33) illustrates an example of the stimuli used in the visual search task and also the procedural outline of the visual search task, which consisted of a single display. The visual search task was adopted from Matsukura and Vecera (2008). The search arrays consisted of 4 or 12 Landolt Cs, each measuring 0.19" x 0.19" (visual angle = 0.45° x 0.45°) with 0.03" line thickness (visual angle = 0.08°). Distractor stimuli had a 0.05" (visual angle = 0.12°) gap on the left or right side. The target had a similar gap on either the top or on the bottom. Targets were present on half of the trials. For a set size of 12, the stimuli were presented at 12 locations evenly spaced on an imaginary circle, with a radius of 1.56" (visual angle = 3.8°), which was centered at fixation. To maintain the same display density across set sizes, for a set size of 4, the stimuli were presented at 4 locations on a randomly chosen quarter of the imaginary circle.

Similar to the object task, the visual search task consisted of 8 blocks of 8 trials, 4 at each set size and randomly ordered. The target was present in 4 of the trials and absent in the other 4 trials and this was also randomly ordered. The quadrant in which the target appeared was counterbalanced across the 8 blocks of trials. After the 500 ms blank delay period following the offset of the memory stimuli, a 4 or 12 item search array appeared and remained until the subject responded. Subjects made a speeded response to the search array, indicating whether at target was present or absent. Subjects pressed “1” if the target was present and “2” if the target was absent.

In the visual search task, the assumption is that spatial attention will be more heavily engaged in the more difficult 12 items search array compared to the 4 items search array. In this case, differences between the 4 and 12-items condition will thus reflect the differences due to the engagement of spatial attention. If a memory task engaged similar processing resources as spatial attention, then task performance of either the visual search or the memory task should be more affected in the 12-items condition compared to the 4-items condition.

Procedure

To minimize verbal encoding (Besner, Davies, & Daniels, 1981), subjects repeatedly vocalized the letters ‘ABCD’ for each trial. For the responses relating to the object task and the memory task, subjects were instructed to be as accurate as possible and were not given any time limits. For the visual search task, subjects were instructed to be as fast and accurate as possible. The presentation sequence for the memory baseline task, the attention baseline task and the dual-task conditions were generally the same, such that subjects were presented with the same stimulus displays for all the three task conditions. However, during the baseline conditions, they were instructed to ignore the stimulus displays for the irrelevant task and to not respond to them. In the memory baseline task condition, they ignored the stimulus displays for the attention task. In the attention baseline condition, they ignored the stimulus displays for the memory task. A white 'X' was superimposed over the stimulus displays of the irrelevant task. The response frames for the irrelevant tasks were presented for 1000 ms. This included each of the two response frames in the object task, the search array in the visual search task and the memory probe frame in the memory task. Subjects were told to attend to and to respond to all the stimulus displays when they were in the dual-task condition.

The general presentation sequence for all task combinations is shown in Figure 6 (page 37). At the beginning of each trial, “Get Ready!” was presented at fixation for 750 ms, followed by a blank frame for 750 ms. Subjects were instructed to begin repeated vocalization of the letters ‘ABCD’ at this time. The two randomly chosen colored squares were then presented for 500 ms, followed by another blank frame for 750 ms. This was followed by the presentation of the stimuli for the attention task, followed by the response frame for the attention task, followed by the probe and the response frame for the memory task. “End” was then presented at fixation, prompting subjects to stop vocalizing. Subjects then initiated the next trial with the spacebar.

To familiarize the subjects with the stimulus displays sequences, they were required to complete practice trials prior to the experimental trials for each task. Subjects practiced 10 trials for the memory baseline condition, 16 trials for the attention baseline condition, and 16 trials for the dual-task condition. Subjects assigned to the object task conditions practiced 8 trials for each monitored dimension combination for the object task prior to starting the experimental trials and also 8 slower presentation trials before each block to become familiarized with the required response mapping for that block. In order to make the visual search task condition as similar as possible to the overlapping and separated object task conditions, the subjects practiced 48 trials of the visual search task (24 trials of 4 and 12 objects each) prior to starting the experiment and also 8 slower presentation trials before each block to familiarize them with the required response mapping, even though the response mapping for the visual search task was the same for all blocks.

Experiment 1: Results and Discussion

In Experiment 1, three different attention tasks were factorially crossed with three different memory tasks for nine separate groups of subjects. Within each attention and memory task combination, subjects performed three task conditions: the dual-task, the attention baseline and the memory baseline. As the interesting findings in Experiment 1 were found in the memory tasks rather than the attention task performance, the results and discussion is organized into three sections according to the different attention tasks. This organization highlights the interference effect of each attention task on the performance of the different memory tasks. For each section, I first describe and discuss the performance of the attention task for both the attention baseline and dual-task conditions in terms of accuracy and RT (visual search task) or accuracy (Duncan object task), and I then describe memory accuracy on the different memory tasks for both the memory baseline and dual-task conditions.

Task Combinations Including Visual Search

Attention Task: Visual Search

Based on the findings of Matsukura and Vecera (2008), one would not expect differences for accuracy or RT performance in the visual search task as a function of VSTM task. However, one would expect to find slower RT when subjects had to search for more items and faster RT and on trials in which the target was absent.

Accuracy. Mean accuracy for the visual search task is shown in Table 2 as a function of type of memory task (between-subjects) as well as attention task condition, set size, and target presence (within-subjects). Accuracy was generally high (i.e., > 0.90 in all conditions), showing that participants were doing the task as instructed. For each type of memory task, a 2 (Condition: baseline vs. dual task) x 2 (Set size: 4 vs. 12) x 2 (Target presence: present vs. absent) repeated-measures Analysis of Variance (ANOVA) was run on the mean accuracy rate in the visual search task. For each type of the memory task, the main effect of Target Presence was significant, in that subjects were more accurate for target absent trials than target present trials. The *F* ratios and *p* values for these main effects are summarized in Table 3. For the double memory task, the main effect of Set size also was significant, $F(1, 29) = 10.61$, $p < .001$. Mean accuracy was higher in the set size 4 (0.97) than the set size 12 condition (0.94), 95% C.I.(0.013,0.044), supporting the assumption that spatial attention is more heavily engaged in a 12-items search than a 4-items search. No other main or interaction effects were significant, $p > .10$.

Table 2. Mean Accuracy for the Visual Search Task as a Function of Set Size, Condition, and Target Presence

	Baseline				**Dual Task**			
	Set4		**Set12**		**Set4**		**Set12**	
	Present	**Absent**	**Present**	**Absent**	**Present**	**Absent**	**Present**	**Absent**
Color	0.95	0.96	0.92	0.96	0.95	0.98	0.93	0.98
Location	0.96	0.97	0.94	0.98	0.95	0.98	0.93	0.97
Double	0.95	0.98	0.91	0.96	0.97	0.98	0.92	0.96

Table 3. Summary of Significant Effects for Visual Search Task Accuracy Rate

Effect	**Memory Type**	**F ratio**	**p value**	**95% difference C.I.**	
				Lower	**Upper**
Target Presence (df = 1, 29)	Color	*12.08*	*.002*	0.013	0.05
	Location	9.98	*.004*	0.011	0.05
	Double	*14.76*	*.001*	0.012	0.052

RT. RT measures below 200 ms or above 3000 ms (0.9% of the data) and for incorrect trials were excluded from analysis. Mean RT for the visual search task is shown in Figure 7 as a function of type of memory task (between-subjects) as well as attention task condition, set size and target presence (within-subjects). For each type of memory task, a 2 (Condition: baseline vs. dual task) x 2 (Set size: 4 vs. 12) x 2 (Target presence: present vs. absent) repeated-measures ANOVA was run on the mean RT of the visual search task. For each of the memory tasks, the typical findings for the visual search task paradigm were found. This included: a main effect of Set size, in that RT was slower when there were more items in the search array; a main effect of Target presence, in that RT was slower when the target was absent; and a Set size x Target presence interaction effect, in that the difference in RT between the set size 12 and set size 4 trials was larger when the targets were present than when they were absent. The *F* ratios and *p* values for these main and interaction effects are summarized in Table 4. For the location memory task, the a main effect of Condition also was significant, $F(1, 29) = 8.31$, $p < .007$. RT was faster in the baseline (1548 ms) compared to the dual-task condition (1669 ms), 95% C.I. (35, 208). For the double memory condition, the Task x Set size interaction effect also was significant, $F(1, 29) = 4.60$, $p < .04$. The difference in RT between set size 12 and set size 4 trials was larger in the baseline (616 ms) compared to the dual-task condition (705 ms), 95% C.I.(2, 87). No other main and interaction effects were significant, $p > .17$.

Table 4. Summary of Significant Effects for Visual Search Task RT

Effect	**Memory Type**	**F ratio**	**p value**	**95% difference C.I.**[a]	
				Lower	**Upper**
Set Size (df = 1, 29)	**Color**	*185.64*	*.001*	550	744
	Location	212.97	*.001*	608	807
	Double	*203.78*	*.001*	566	755
Target Presence (df = 1, 29)	**Color**	*114.03*	*.001*	449	661
	Location	117.33	*.001*	433	635
	Double	*14.76*	*.001*	374	577
Set Size X Target Presence (df = 1, 29)	**Color**	*73.67*	*.001*	26	43
	Location	72.11	*.001*	29	47
	Double	*91.78*	*.001*	30	45

a: The 95% C.I. difference for the Set Size x Present Interaction is the difference between the search slope (i.e., (Set Size 12 – Set Size 4)/8) for absent and present trials

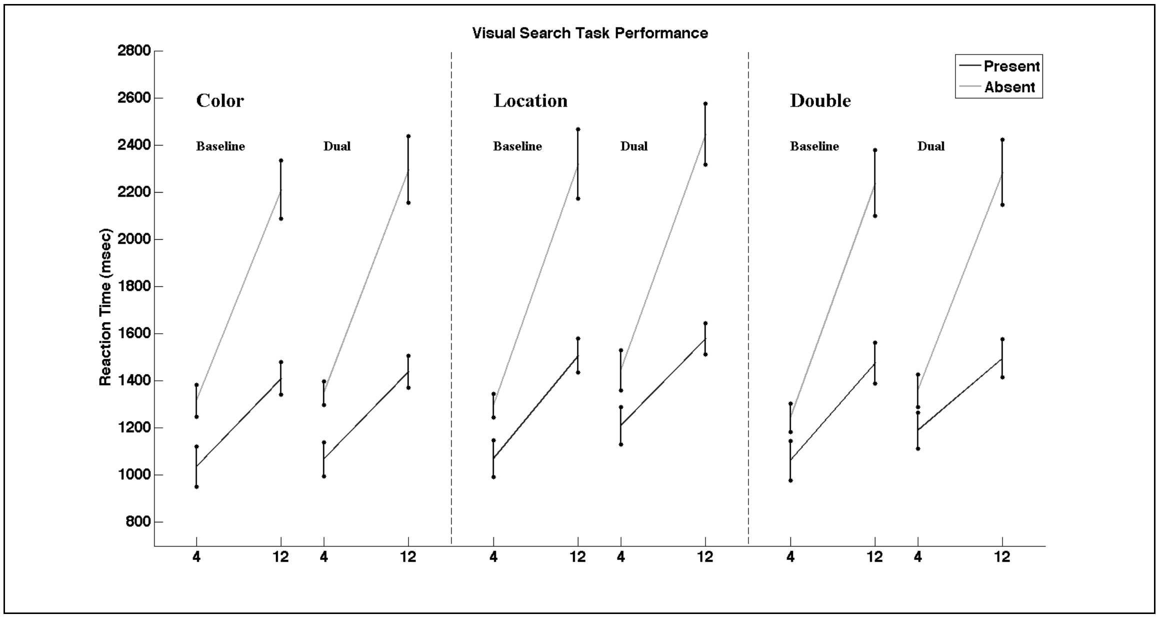

Figure 7. Mean RT in the visual search task in the attention baseline and dual-task conditions for the different types of memory task in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Overall, the RT results reflect typical findings in the visual search task. There were no indications of any speed-accuracy tradeoff. When subjects loaded VSTM, this did not affect the visual search task because the Condition variable (baseline vs. dual-task) generally did not interact significantly with other variables for any memory task. While RT was somewhat slowed when the location memory task was used (i.e., spatial STM was loaded), none of the interaction effects with Condition was significant. Also, although the Condition x Set size interaction effect was significant for those doing the double memory task, the search slope was lower for the dual-task than the baseline condition. Together, these results suggest that the visual search task in the current study is generally not affected when VSTM is loaded, which is similar to the findings of Matsukura and Vecera (2008). However, this finding is inconsistent with the findings of Oh and Kim (2004) and Woodman and Luck (2004), where they found that the search slope of the visual search task increased when spatial STM was loaded in the dual-task condition. The different findings may be due to differences in procedures between the visual search tasks that may have produced differences in reliance on spatial STM. In both Oh and Kim, as well as Woodman and Luck, the locations of the items were not constrained to being locations on a circle, as they were in the current experiment and in Matsukura and Vecera. This issue will not be pursued further because the selective interference effects of primary interest were found in memory task performance in the current experiment as well as in the other studies. Hence, the focus will be on performance in the memory tasks.

Memory Task

Mean accuracy on the memory task in each of the task conditions is presented in Figure 8 (bottom). A separate ANOVA examined performance on each memory task.

Color memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline, dual-task with 4 items search and dual-task with 12 items search). The one way ANOVA was significant, $F(2, 58) = 22.98$, $p < .001$. Paired sample t-tests showed that mean accuracy for the memory baseline condition (0.91) was higher for the dual-4 items condition (0.88), $t(29) = 4.53$, $p < .001$, 95% C.I.(0.029, 0.077) and the dual-12 items condition (0.88), $t(29) = 4.79$, $p < .001$, 95% C.I.(0.034, 0.085). However, there was no difference between the mean accuracy between the dual-4 items and dual-12 items conditions, *t(29)* = 0.429, *p* > .67, 95% C.I.(-0.024, 0.036).

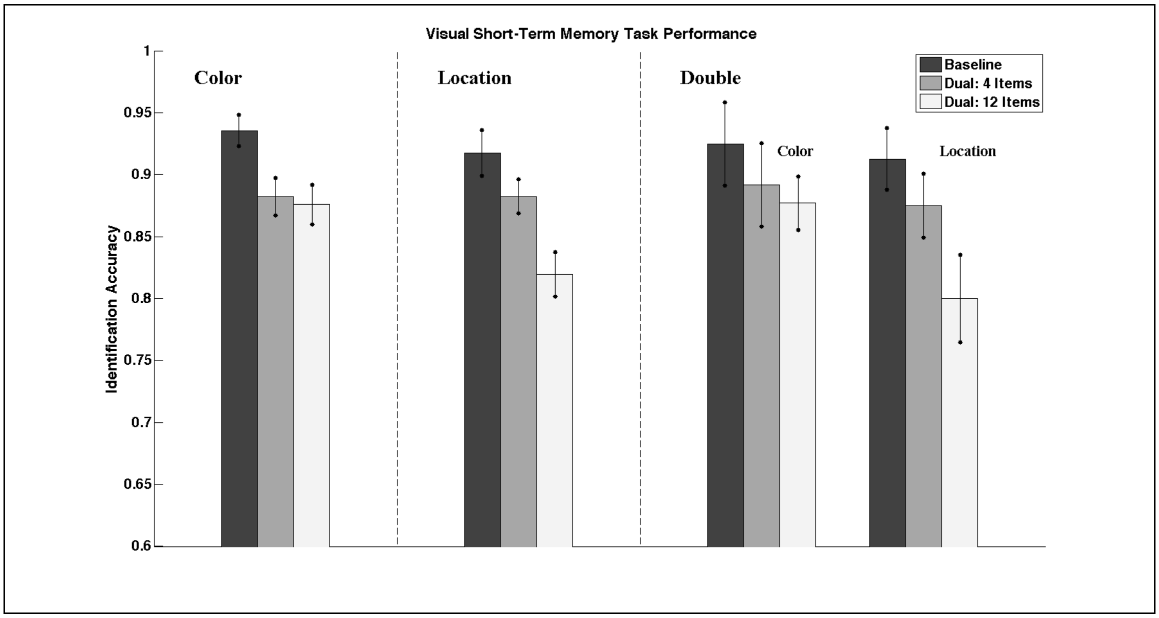

Figure 8. Mean accuracy in the memory task in the memory baseline, dual-task 4 items, and dual-task 12 items conditions for subjects performing the visual search task in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

While there was a general overall decrease in performance on the color memory task for the dual-4 items and dual-12 items conditions compared to the baseline condition, performance on the color memory task was not affected by the difficulty of the visual search task in the dual-task condition. This suggests that the visual search task and the color memory task engaged different processing resources. The results, therefore, support the assumption that the visual search task engages spatial attention and the color memory task engages object STM, and the pools of processing engaged by these cognitive components are to a certain extent dissociable from each other. The results with the color memory task and the interpretation that object STM does not engage the same resources as spatial attention are similar to those of Woodman and Luck (2001), Oh and Kim (2004) and Matsukura and Vecera (2008).

Location memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline, dual-task with 4 items search and dual-task with 12 items search). The one way ANOVA was significant, $F(2, 58) = 22.23$, $p < .001$. Paired sample t-tests showed that mean accuracy for the memory baseline condition (0.92) was higher than for the dual-4 items condition (0.88), $t(29) = 2.57$, $p < .016$, 95% C.I.(0.0072, 0.064) and the dual-12 items condition (0.82), $t(29) = 5.94$, $p < .001$, 95% C.I.(0.063, 0.133). The mean accuracy for the dual-4 items condition was higher than the for dual-12 items condition, $t(29) = 4.69$, $p < .001$, 95% C.I.(0.035, 0.090). There was a general overall decrease in performance of the location memory task for the dual-4 items and dual-12 items conditions compared to the baseline condition, but more importantly, performance on the location memory task was affected by the difficulty of the visual search task. Performance decreased when the number of search set items increased in the dual-task condition. Assuming that spatial attention is engaged to a larger extent when there are more search items in the display, and that performance on the location memory task reflects spatial STM, the fact that the location memory task performance decreased with the increase of search items in the dual-task condition suggests that the visual search task and the location memory task engaged similar processing resources, which are likely to be the processing resources engaged by spatial attention and spatial STM. The results with the location memory task and the interpretation that spatial STM engages the same resources as spatial attention are similar to those of Oh and Kim (2004), Woodman and Luck (2004) and Matsukura and Vecera (2008).

Double memory task. Subjects in the double memory task had to remember both color and the location information, but only one type of memory was probed on each trial. A 3 (Condition: baseline vs. dual-4 items vs. dual-12 items) x 2 (Probe type: color vs. location) repeated measures ANOVA was run on the mean accuracy rates. There was a main effect of Probe type, $F(1, 29) = 5.84$, $p < .022$, 95% C.I. (0.005, 0.065), in that mean accuracy for color probes (0.90) was better than for location probes (0.86). There also was a main effect of Condition, $F(1, 29) = 11.70$, $p < .001$. Pairwise comparisons showed that mean accuracy in the baseline condition (0.92) was marginally higher than in the dual-4 items condition (0.88), $t(29) = 1.938$, $p < .062$, 95% C.I.(-0.002, 0.073), and was higher in the dual-12 items condition (0.84), $t(29) = 5.07$, $p < .001$, 95% C.I.(0.048, 0.113). Mean accuracy in the dual-4 items condition also was higher than in the dual-12 items condition, $t(29) = 2.87$, $p < .008$, 95% C.I. (0.013, 0.077). The Probe type x Condition interaction effect was marginally significant, $F(2, 58) = 2.66$, $p < .078$. Paired sampled t-tests revealed no differences in mean accuracy for color and location probes in the baseline condition, $t(29) = 0.56$, $p > .57$, 95% C.I. (-0.033, 0.058), or the dual-4 items condition, $t(29) = 0.73$, $p > .47$, 95% C.I.(-0.030, 0.063). However, mean accuracy for location probes was lower than for the color probes in the dual-12 items condition, $t(29) = 3.13$, $p < .004$, 95% C.I.(0.027, 0.13). The interaction shows that when spatial attention is engaged in the dual-task condition, there is selective interference for location probes only in the dual-12 items condition. Overall, the findings with the double memory task mirror the findings with the color and location memory tasks. When spatial attention is heavily engaged (i.e., in the 12-items visual search), it interferes with spatial STM. This further strengthens the claim that spatial attention and spatial STM engage similar processing resources, and that these shared processing resources are dissociable from the resources engaged by object STM.

Task Combinations Including Duncan Object Task (Overlap)

Attention Task: Duncan Object Task (Overlap)

Based on previous findings (Matsukura & Vecera, 2008; Tan, 2008), one would expect no differences in performance in the Duncan object task with overlapping stimuli as a function of VSTM task. However, one would expect to find higher accuracy rates when subjects reported both properties from the same object (e.g., Duncan, 1984). Accuracy rates were collapsed over the first and second report because no or only very small and non-predicted differences were found between first and second report accuracy in a preliminary analysis. The accuracy rate and statistical analysis including first and second report are reported in Appendix A.

Mean accuracy on the Duncan object task with overlapping stimuli is shown in Figure 9 as a function of type of memory task (between-subjects) as well as attention task condition and whether the reported properties were from the same or different objects (within-subjects). A separate 2 (Condition: baseline vs. dual-task) x 2 (Properties: same object vs. different objects) repeated measures analysis was run on mean accuracy rate for each memory task. There was a main effect of Condition for each type of memory task, in that subjects were more accurate in the baseline condition. There also was a main effect of

Properties, in that subjects were more accurate when they reported properties from the same object. This result is consistent with the findings of previous studies (Duncan, 1984; Vecera & Farah, 1994). The *F* ratios and *p* values for these main effects are summarized in Table 5. No other main and interaction effects were significant, $p > .41$. Just as with the visual search task condition, there were no selective interference effects as a result of holding different types of information in STM. Hence, the focus will be on the memory task performance.

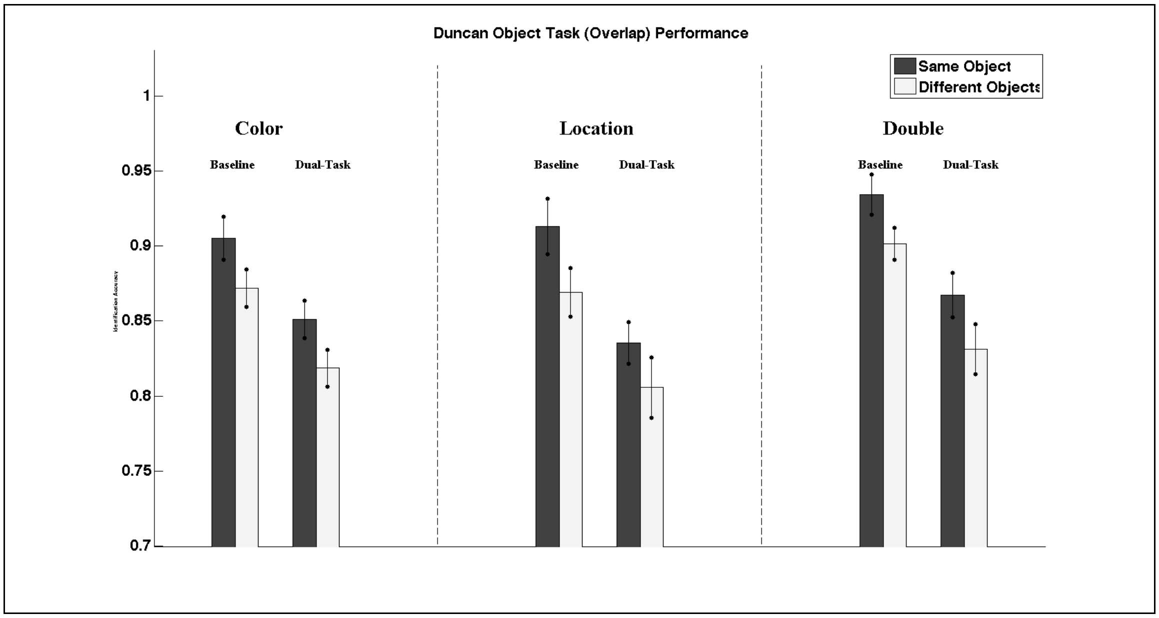

Figure 9. Mean accuracy in the Duncan object task with overlapping stimuli in the attention baseline and dual-task conditions for the different memory tasks as a function of whether the reported properties are from the same or different objects in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Table 5. Summary of Significant Effects for Accuracy on the Duncan Object Task (Overlap)

Effect	**Memory Type**	**F ratio**	**p value**	**95% difference C.I.**	
				Lower	**Upper**
Task (df = 1, 29)	**Color**	34.09	*.001*	0.035	0.072
	Location	29.92	*.001*	0.043	0.098
	Dual	43.50	*.001*	0.047	0.09
Object (df = 1, 29)	**Color**	29.47	*.001*	0.02	0.045
	Location	22.24	*.001*	0.021	0.053
	Dual	25.40	*.001*	0.02	0.048

Memory Task

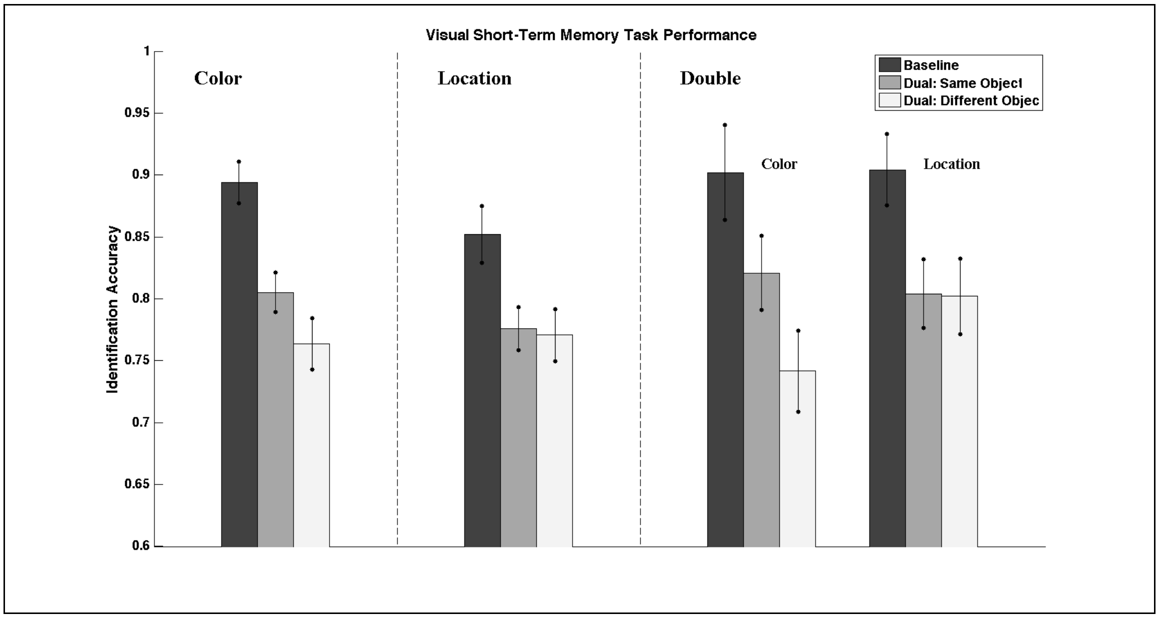

Figure 10. Mean accuracy in the memory task in the memory baseline, dual-task same object and dual-task different objects conditions for subjects performing the Duncan object task with overlapping stimuli in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Mean accuracy on the memory task in each of the task conditions is presented in Figure 10. A separate ANOVA examined performance on each memory task.

Color memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline, dual-task trials with properties from the same object and dual-task trials with properties from different objects). The one way ANOVA was significant, $F(2, 58) = 35.33$, $p < .001$. Paired sample t-test showed that mean accuracy in the memory baseline condition (0.894) was higher than in the dual-same object condition (0.81), $t(29) = 6.82$, $p < .001$, 95% C.I.(0.062, 0.115), and the dual-different objects condition (0.76), $t(29) = 7.51$, $p < .001$, 95% C.I.(0.095, 0.166). Mean accuracy in the dual-same object condition was higher than in the dual-different objects condition, $t(29) = 2.48$, $p < .019$, 95% C.I. (0.0074, 0.076). Compared to the memory baseline condition, there is a general overall decrease in performance on the color memory task for the dual-same object and dual-different objects conditions compared to the baseline condition. In addition, performance of the color memory task was affected by whether the properties in the Duncan object task with overlapping stimuli are from the same or different objects. Accuracy decreased in the dual-different object condition compared to the dual-same object condition. Assuming that the Duncan object task with overlapping stimuli engages object-based attention and that the color memory task engages object STM, this finding suggests that the pools of resources engaged by these two cognitive components are similar. The finding in the color memory task is similar to the findings of Tan (2008) and consistent with that of Matsukura and Vecera (2008).

Location memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline trials, dual task trials with properties from the same object and dual-task trials with properties from different objects). The one way ANOVA was significant, $F(2, 58) = 12.61$, $p < .001$. Paired sample t-test showed that mean accuracy in the memory baseline condition (0.85) was higher than in the dual-same object condition (0.78), $t(29) = 4.31$, $p < .001$, 95% C.I. (0.039, 0.112), and the dual-different objects condition (0.77), $t(29) = 3.94$, $p < .001$, 95% C.I. (0.039, 0.123). Mean accuracy in the dual-same object and dual-different objects conditions were not different, $t(29) = 0.33$, $p > .74$. While there was a general overall decrease in performance on the location memory task for the dual-task conditions compared to the baseline condition, performance on the location memory task was not affected by whether the two properties came from the same or different objects in the dual-task conditions. This pattern suggests that the Duncan object task with overlapping stimuli and the location memory task engaged different processing resources. Assuming that the Duncan object task with overlapping stimuli engages object-based attention and that the location memory task engages spatial STM, this finding suggests that the pools of resources engaged by these two cognitive components are to a certain extent dissociable from each other. Just as with the color memory task, the findings in the location memory task are similar to the findings of Tan (2008) and consistent with those of Matsukura and Vecera (2008).

Double memory task. A 3 (Condition: baseline vs. dual-same object vs. dual-different objects) x 2 (Probe type: color vs. location) repeated measures ANOVA was run on the mean accuracy rates. There was a main effect of Condition, $F(1, 29) = 29.58$, $p < .001$. A weighted contrast analysis showed that the mean accuracy in the baseline condition (0.90) was higher than in the dual-same object condition (0.81), $t(29) = 5.11$, $p < .001$, 95% C.I. (0.054, 0.127), and the dual-different objects condition (0.77), $t(29) = 6.75$, $p < .001$, 95% C.I.(0.092, 0.171). Mean accuracy in the dual-same object condition also was higher than in the dual-different objects condition, $t(29) = 2.72$, $p < .011$, 95% C.I. (0.010, 0.071). There was no difference between the accuracy on the color and location memory probes, $F(1, 29) = 0.76$, $p > .39$. The Condition x Probe type interaction effect was significant, $F(2, 58) = 3.39$, $p < 0.041$. Pair sampled t-tests revealed no differences in the mean accuracy of the color and location memory performance in the baseline condition, $t(29) = 0.079$, $p > .93$, 95% C.I. (-0.056, 0.051), or the dual-same object condition, $t(29) = 0.71$, $p > .48$, 95% C.I. (-0.031, 0.065). However, mean accuracy for the color probes was lower than for location probes in the dual-different object condition, $t(29) = 2.39$, $p < .024$, 95% C.I. (0.0086, 0.112), showing that when object-based attention was engaged in the dual-task condition, selective interference on color memory occurred only for the dual-different objects condition. A weighted contrast comparison also demonstrated that mean accuracy for the location probes in the dual-different objects condition was not different for either color or location probes in the dual-same object condition, $t(29) = 0.51$, $p > .61$, 95% C.I. (-0.052, 0.031). Overall, the findings in the double memory task mirror the findings in the color and location memory tasks. The findings show that when object-based attention is engaged, it interferes with object STM. This further strengthens the claim that object-based attention and object STM engage similar processing resources, and these shared processing resources appear to be dissociable from the resources engaged by spatial STM.

Task Combinations Including the Duncan Object Task (Separate)

Attention Tasks: Duncan Object Task (Separate)

Based on the results just described with the Duncan object task with overlapping stimuli, one would not expect differences in the performance of the Duncan object task with separated stimuli as a function of VSTM task (i.e., memory task). However, one would expect to find higher accuracy when subjects reported properties from the same object. The accuracy rates were collapsed over first and second report because no or only very small and non-predicted differences were found in accuracy in a preliminary analysis. The accuracy rate and statistical analysis including the first and second report performance is reported in Appendix A.

Mean accuracy performance on the Duncan object task with overlapping stimuli is shown in Figure 11 as a function of type of memory task (between-subjects) as well was attention task condition and whether the reported properties were from the same or different objects (within-subjects). A separate 2 (Condition: baseline vs. dual-task) x 2 (Properties: same object vs. different objects) repeated measures analysis was run on mean accuracy rate for each memory task. Just as with the overlapping stimuli, there was a main effect of Condition for each type of memory task, in that subjects were more accurate in the baseline condition. There also was a main effect of Properties, in that subjects were more accurate when they reported properties from the same object. The latter is consistent with the findings of previous studies (Vecera & Farah, 1994) in which accuracy of report was lower when the properties appeared in different objects. The *F* ratios and *p* values for these main effects are summarized in Table 6. No other main and interaction effects were significant, $p > .54$. Just as with the visual search task and the Duncan overlapping objects task, there were no selective interference effects as a result of holding different types of information in STM. Hence, the focus of the discussions will be on the memory task performance.

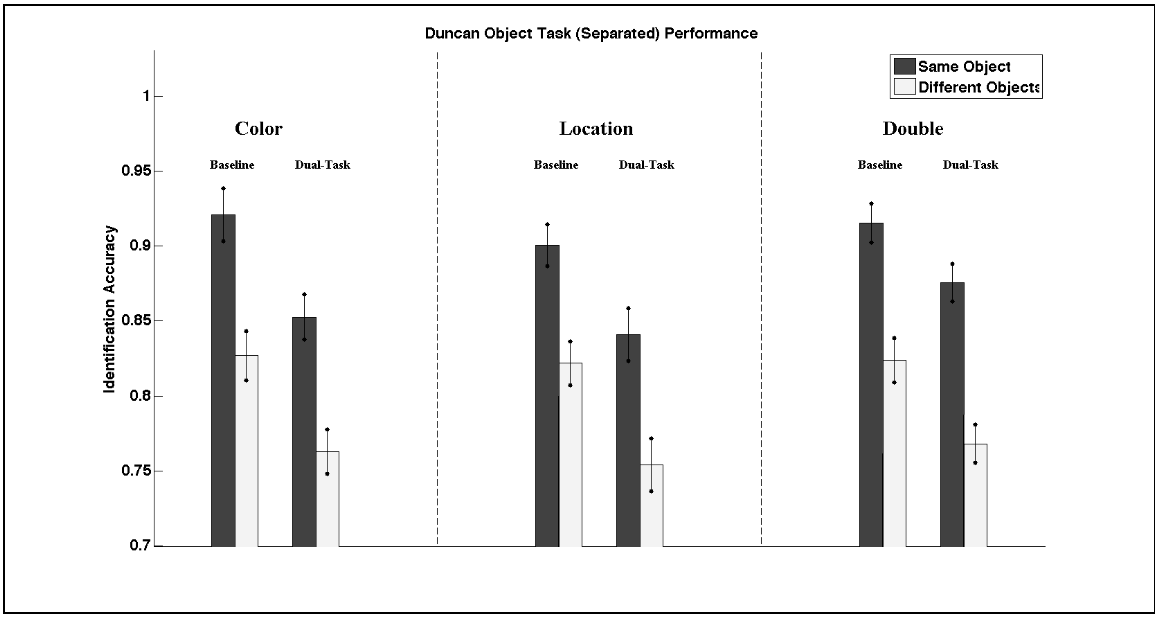

Figure 11. Mean accuracy in the Duncan object task with separated stimuli in the attention baseline and dual-task conditions for the different memory tasks as a function of whether the reported properties are from the same or different objects in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Table 6. Summary of Significant Effects for Accuracy on the Duncan Object Task (Separated)

Effect	Memory Type	F ratio	p value	95% difference C.I.	
				Lower	Upper
Condition (df = 1, 29)	Color	58.87	*.001*	0.049	0.084
	Location	33.55	*.001*	0.041	0.086
	Dual	45.17	*.001*	0.033	0.062
Properties (df = 1, 29)	Color	67.45	*.001*	0.069	0.114
	Location	68.40	*.001*	0.062	0.103
	Dual	195.35	*.001*	0.085	0.114

Memory Task

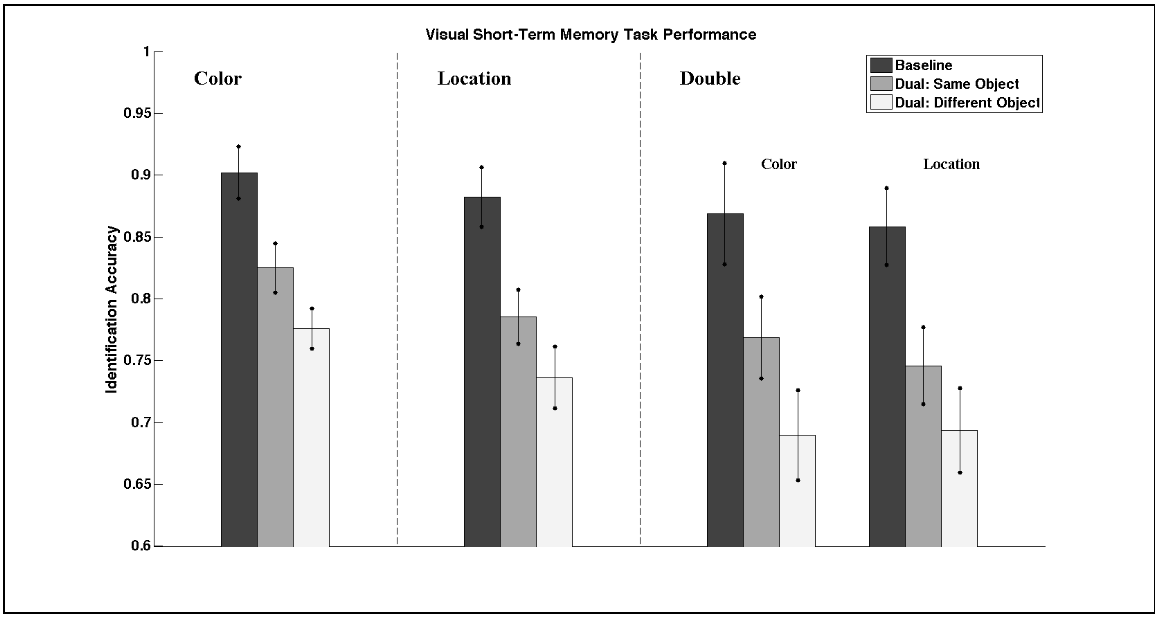

Figure 12. Mean accuracy in the memory task in the memory baseline, dual-task same object and dual-task different objects conditions for subjects performing the Duncan object task with separated stimuli in Experiment 1. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Mean accuracy on the memory task in each of the task conditions is presented in Figure 12. A separate ANOVA examined performance on each memory task.

Color memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline, dual-task trials with properties from the same object and dual-task trials with properties from different objects). The one way ANOVA was significant, $F(2, 58) = 28.04$, $p < .001$. Paired sample t-test showed that mean accuracy in the memory baseline condition (0.90) was higher than in the dual-same object condition (0.83), $t(29) = 4.01$, $p < .001$, 95% C.I.(0.038, 0.116), and the dual-different objects condition (0.78), $t(29) = 7.70$, $p < .001$, 95% C.I.(0.093, 0.16). Mean accuracy in the dual-same object condition was higher than in the dual-different objects condition, $t(29) = 3.26$, $p < .003$, 95% C.I. (0.018, 0.080). Compared to the memory baseline condition, there was a general overall decrease in performance in the dual-task conditions. In addition, color memory accuracy was affected by whether the reported properties in the Duncan object task with separated stimuli came from the same or different objects. Accuracy decreased in the dual-different object condition compared to the dual-same object condition. Assuming that an additional attentional selection is required when subjects need to report properties from different objects and hence object-based attention is engaged to a larger extent, the lower performance in dual-different objects condition compared to the dual-same object condition suggests that the Duncan object task with separated stimuli and the color memory task engages similar processing resources, which are likely to be processing resources engaged by object-based attention and object STM.

Location memory task. A one-way repeated measures ANOVA was run on the mean accuracy rates as a function of condition (memory baseline, dual-task trials with properties from the same object and dual-task trials with properties from different objects). The one way ANOVA was significant, $F(2, 58) = 25.36$, $p < .001$. Paired sample t-test showed that mean accuracy in the memory baseline condition (0.88) was higher than in the dual-same object condition (0.79), $t(29) = 4.88$, $p < .001$, and the dual-different objects condition (0.74), $t(29) = 6.57$, $p < .001$. Mean accuracy in the dual-same object and dual-different objects conditions were not different, $t(29) = 2.40$, $p < .023$. Compared to the memory baseline condition, there is a general overall decrease in performance on the location memory task for the dual-same object and dual-different objects conditions. As with the color memory task, accuracy in the location memory task was affected by whether the reported properties in the Duncan object task with separated stimuli were from the same or different objects. Performance decreased in the dual-different object condition compared to the dual-same condition. Because the stimuli were separated in space, there was an additional spatial selection when subjects needed to report properties from different objects. Assuming that this additional spatial selection engaged spatial attention to a greater extent, the lower performance on the dual-different objects condition suggests that the Duncan object task with separated stimuli and the location memory task engaged similar processing resources, which are likely to be processing resources engaged by spatial attention and spatial STM. Together with the findings in the color memory condition, the findings in the location memory condition suggest that there is both an object-based and a spatial attentional selection component for the Duncan object task with separated stimuli. This is consistent with findings in previous studies claiming independent spatial and object-based effects can be observed using a task similar to the Duncan object task with separated stimuli (e.g., Awh et al., 2001).

Double memory task. A 3 (Condition: baseline vs. dual-same object vs. dual-different objects) x 2 (Probe type: color vs. location) repeated measures ANOVA was run on the mean accuracy rates. There was a main effect of Condition, $F(2, 58)$ 36.78, $p < .001$. A weighted contrast analysis showed that the mean accuracy in the memory baseline condition (0.86) was higher than the dual-same object condition (0.76), $t(29) = 5.11$, $p < .001$, 95% C.I. (0.060, 0.152), and the dual-different objects condition (0.69), $t(29) = 7.72$, $p < .001$, 95% C.I.(0.126, 0.217). Mean accuracy in the dual-same object condition also was higher than the dual-different objects condition, $t(29) = 4.35$, $p < .001$, 95% C.I. (0.035, 0.097). There was no difference in accuracy on the color and location probes, $F(1, 29) = 0.34$, $p > .56$. The Condition x Probe type interaction effect also was not significant, $F(2, 58) = 0.29$, $p < .748$, suggesting similar dual-task decrements for the two type of probes. Overall, the findings with the double memory task mirrored those found with the color and location memory task, in that the Duncan object task with separated stimuli interfered with both color and location memory. Assuming that reporting properties from different objects required both an additional spatial and object-based attentional selection, and that both spatial and object-based attention are engaged to a larger extent when this happens, the findings further strengthen the claims that object-based attention engages similar processing resources with object STM, that spatial attention engages similar processing resources with spatial STM, and that both pools of processing resources are distinct and dissociable from each other.

The findings in the Duncan object task with separated stimuli also provided evidence for two further claims in the literature. One is that spatial and object-based attention can operate within the same selection task (Awh et al., 2001). The other is that spatial attention does not override object-based selection when a spatial component was introduced to the selection task (Kramer et al., 1997). If object-based selection is overridden by spatial attention when the stimuli were separated, then one would expect less interference in the color memory task compared to the location memory task. However, this was not the case.

It must be noted that the findings for the memory tasks in the Duncan object task with separated stimuli condition can also be accounted for with a processing difficulty account. If one assumes that it is more difficult for subjects to report properties from different objects than from the same object, it would not be surprising that lower memory performance was found when subjects performed dual-task different objects trials compared to dual-task same object trials. While this claim might carry substantial weight if one only considered the findings from the Duncan object task with separated stimuli in isolation, this claim loses some of its weight when one considers the findings from the visual search task and the Duncan object task with overlapping stimuli. If one assumes that it was more difficult to search among 12 items compared to 4 items in the visual search task, and it was more difficult to report properties from different objects than from the same object in the Duncan object task with overlapping stimuli, then one would expect to find lower performance in the color memory task in the dual-12 items condition compared to the dual-4 items condition, and also lower performance in the location memory task in the dual-different object condition compared to the dual-same object condition. While one could claim that it is possible that the Duncan object task with separated stimuli is more difficult than the other two tasks, and hence the interference in memory task performance manifested as a result, this explanation is quite post-hoc and is not parsimonious. Thus, taking the findings of all the conditions in Experiment 1 into account, they strongly support the claims that object-based attention and object STM engaged similar processing resources, spatial attention and spatial STM engaged similar processing resources, and both sets of processing resources are dissociable from each other.

CHAPTER 3: EXPERIMENT 2

Experiment 1 was designed to investigate the relationship between VSTM and attention with three different attention task: the visual search task reflecting spatial attention, the Duncan (1984) object-based attention task with no spatial component and a modification of the Duncan object-based attention task with a spatial component (Vecera & Farah, 1994), in which the objects were separated in space. The design allowed comparison to results of previous findings (e.g., Matsukura & Vecera, 2008; Oh & Kim, 2004; Tan, 2008; Woodman & Luck, 2004). Taken together, the findings in Experiment 1 suggest that attention and STM engage similar processing resources for both the spatial and object-based components. As mentioned in the introduction, the relationship between spatial attention and spatial STM is relatively well established (e.g., Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman et al., 2001; Woodman & Luck, 2004). However, the relationship between object-based attention and object STM is less well established due to limited empirical support, in that only the Duncan (1984) object task with overlapping stimuli has been used to establish the relationship (Matsukura & Vecera, 2008; Tan, 2008). Hence, the reported relationship between object-based attention and object STM might be a task artifact of the Duncan object task. Experiment 2 was designed to further examine the relationship between object-based attention and object STM with a different object attention task.

Although the Duncan (1984) object task is well established in demonstrating the effects of object-based attention and is often employed in the literature, there is a potential problem with using it in the context of investigating the interaction effects between VSTM and attention as was done in Experiment 1. The stimuli presented in the Duncan object task are usually brief, presented between 100 ms and 200 ms, and they are masked. The brief presentation is because the object task emphasizes accuracy and hence the stimuli need to be masked to prevent ceiling performance. However, it is quite possible that the brief presentation of the masked stimuli requires subjects to engage some form of object STM capacity in order to do the task. That is, the Duncan object task, which was employed as an object-based attention task, may also involve object STM.

The visual search task requires spatially scanning the screen for targets and this is more likely to interfere with the spatial STM component rather than the object STM component. Previous research failed to obtain an interference effect on the visual search task (i.e., on spatial attention) when object VSTM was loaded (Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman et al., 2001). One possibility is that loading object STM interferes with object-based attention (Tan, 2008) or vice-versa (Matsukura & Vecera, 2008) only under the condition in which the object-based attention task heavily engages object STM capacity, as may be true for the Duncan object task. Although Matsukura and Vecera's finding that the interference effect on spatial STM is larger for a visual search task than for the Duncan object task rules out a strict general processing capacity account, it could be the case that an object-based attention task interferes with object STM only when the attention task itself taxes object STM capacity. It may be that the double dissociation observed by Matsukura and Vecera occurs only under these limiting conditions.

Experiment 2 was designed to further explore the relationship between object-based attention and object STM without the limitations just described. This was achieved by adopting the Egly et al. (1994) task, which combines a spatial cueing methodology with an object-based selection task. An example of a typical trial in the Egly et al. object task is shown in Figure 13.

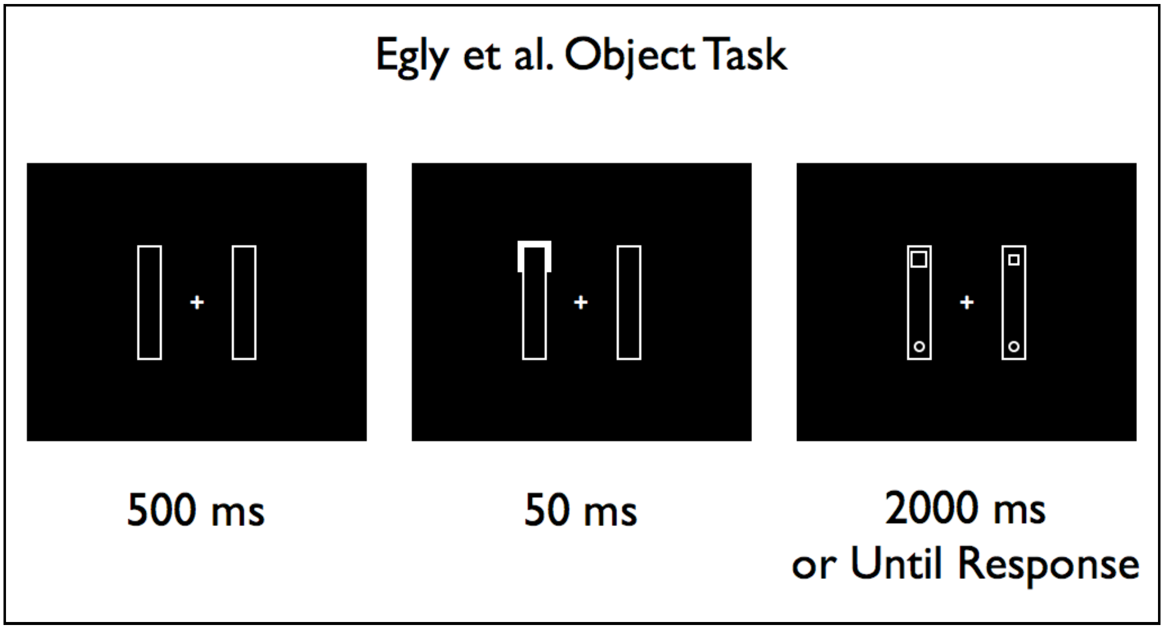

Figure 13. Sample of stimuli and timing for displays in the Egly et al. object task. The example depicts an valid cue condition with a larger square as the target.

The Egly et al. task employs two rectangle outlines arranged either vertically or horizontally on the sides of an imaginary square. One end of one rectangle is cued prior to the presentation of three distractors and a target. Subjects respond to the target (a larger circle/square), which can appear in the cued location or a non-cued location. Invalid cue targets, which appear at a non-cued location, can appear either in the same cued object (i.e., the other end of the cued rectangle) or in another object (i.e., the equidistant end of the uncued rectangle). There are two general findings using this task. First, RT to valid cue targets is fastest, indicating both spatial and object-based attention selection effects. This is referred to as the validitiy effect. Second, RT to the invalid cue targets in the different object is slower than to the invalid cue targets in the same object, indicating an object-based attentional selection effect. This is referred to as the object effect. Because both the validity and the object effect in the Egly et al. task reflect both spatial and object-based attention, it is an appropriate task to employ in order to investigate the interaction between object attention and VSTM. Furthermore, the displays employed in the Egly et al. task are similar to those employed in a typical visual search task, in that most of the stimuli (with the exception of the spatial cue) remain on the screen until a response is made. Hence, unlike the Duncan object task, there is minimal demand on object STM capacity in the Egly et al. task. Examination of the differences in the magnitude of the object effect and of the validity effect for within versus between objects under conditions in which different types of VSTM are loaded will allow a direct comparison of the effect of VSTM on object attention.

Experiment 2 employed a dual-task paradigm similar to that employed in Experiment 1, in which groups of subjects were exposed to different memory tasks. The same three memory tasks were varied across subjects (color memory, location memory and double memory), but all subjects performed the Egly et al. (1994) object task. As just noted, the Egly et al. object task engages both spatial and object-based attention and there are fewer demands on object STM than in the Duncan object task. If a similar pattern of results were still found in Experiment 2, it would further extend the claims made by Matsukura and Vecera (2008) and by Tan (2008).

The employment of the Egly et al. (1994) object task in Experiment 2 also addressed the criticisms for possible confounding variables in Matsukura and Vecera (2008) and Experiment 1 of the present study. Although a double dissociation was established in these study, the double dissociations were established using different attention tasks. Hence, one can argue that the differences in the interference effects could be due to the procedural characteristics of different tasks rather than to the fact that the different tasks engaged the different cognitive components. Baddeley (2007) pointed out that when employing the dual-task paradigm to explore possible interference effects on VSTM, one general difficulty is to ensure that the tasks employed are at least somewhat comparable. By using the same attention task within the context of the dual-task paradigm in Experiment 2, the problems of the confounding variables would be addressed. If a similar pattern of results were found, this would provide further evidence to the above claims.

Before one could make a prediction on the outcome of the experiment, it is necessary to understand how spatial attention and object-based attention might be manifested in the Egly et al. object task. In the Egly et al. object task, subjects are always cued to a corner of one of the rectangles. Assuming the framework of attentional shift postulated by Posner and Petersen (1990; see also Brown & Denney, 2007), attention would be engaged on the spatial location of the cue. If the target also appears in the same location, subjects would be faster to react to it. However, if the target does not appear in the same location as the cue (i.e., invalid cue condition), attention needs to disengage from the location of the cue and shift towards the location of the target. In both the invalid-same object and invalid-different object cue conditions, it is assumed that a spatial shift is required for attention to shift towards and engage onto target location. Because both the target location is equidistant from the cue in both the invalid cue conditions, spatial attention should engage approximately the same amount of processing resources in both cue conditions. However, the situation is different in the case of object-based attention. In the case when the shift is within the same object, attention does not need to disengage from the object, but when the shift is towards a different object, attention needs to disengage from the cued object and to engage onto the other object. Thus, if one were to define the delay in engagement onto invalid cue targets as the ‘attentional shifting cost due to an invalid cue’, the attentional shifting cost for the invalid-same object cue condition would be the result of only an additional spatial attentional shift, while the shifting cost for the invalid-different object cue condition would be the result of both a spatial and an object-based attentional shift.

If one assumes that spatial attention and spatial STM engage similar processing resources, then engaging spatial STM should interfere with the spatial shift. Similarly, if one assumes that object-based attention and object STM engage similar processing resources, then engaging object STM should interfere with the object-based shift. Hence, one would predict different patterns of attentional shifting cost in the dual-task condition compared to the baseline condition across the memory type conditions. For the color memory condition, in which object STM is thought to be engaged, one would predict that the attentional shifting cost in the dual-task condition would be larger than the baseline in the invalid-different cue trials because an object-based attentional shift only occurs for the invalid-different cue trials. For the location memory condition, in which spatial STM is thought to be engaged, one would predict that the attentional shifting cost in the dual-task condition would be larger than the baseline in both the invalid-same and invalid-different cue trials because spatial attentional shift occurs in both conditions. For the double memory condition, in which both spatial and object STM are thought to be engaged, one would predict that the attentional shifting cost in the dual-task condition would be larger than the baseline in both the invalid-same and invalid-different cue trials because a spatial attentional shift occurs in both conditions. Furthermore, because there is an additional object-based shift required in the invalid-different cue trials, one would predict that the attentional shifting cost in the invalid-different cue trials of the double memory condition would be larger than that of the color memory condition and the location memory condition. Obtaining these above predicted results would greatly strengthen the claims that spatial attention and spatial STM engage similar processing resources, that object-based attention and object STM engage similar processing resources, and that both sets of processing resources are dissociable to a great extent.

To summarize, the purpose of Experiment 2 was to test whether the claims (a) that spatial attention and spatial STM share similar processing resources, (b) that object-based attention and object STM share similar processing resources, and (c) that both sets of processing resources are dissociable would hold true when a different attention task that does not heavily engage object-based STM was used in the dual-task paradigm. The predicted results of Experiment 2 are summarized in Table 7.

Table 7. Predictions of Experiment 2

Claims	Task	Predictions
Spatial Attention and Spatial STM Engage Similar Resources	**Color Memory**	Spatial STM not engaged.
	Location Memory	Increased attention shifting cost in dual-task condition for both same and different object condition
	Double Memory	Increased attention shifting cost in dual-task condition for both same and different object condition
Object-Based Attention and Object STM Engage Similar Resources	**Color Memory**	Increased attention shifting cost in dual-task condition for different object condition
	Location Memory	Object STM not engaged
	Double Memory	Increased attention shifting cost in dual-task condition for different object condition
Two Sets of Resources Dissociable	**Color Memory**	Does not address the claim.
	Location Memory	Does not address the claim.
	Double Memory	Increased attention shifting cost in dual-task condition larger than that of color or location memory task

Method

Subjects and Design

Subjects were 144 students with normal or corrected-to-normal vision who participated for course credit after giving informed consent. The data from 16 additional subjects were discarded due to low accuracy rates (< 70%) in the Egly et al. (1994) object task. Similar to Experiment 1, three types of memory task (i.e., location, color and dual-memory) were employed. However, only the Egly et al. object task was employed as the attention task. Forty-eight subjects were randomly assigned to each of the memory tasks. Within each memory task condition, there were three task conditions: memory baseline, attention baseline and dual-task. The order of the three task conditions was counterbalanced across subjects within each memory task.

Tasks

For all tasks, unless otherwise noted, the displays consisted of white figures on a black background. This was because previous studies also employed similar stimuli (e.g., Egly et al., 1994; Hecht & Vecera, 2007). The experiment was written and presented using EPRIME (www.psnet.com). The stimuli were presented on a 17-inch Dell Monitor. Subjects viewed the display freely from approximately 23.6" and wore sound deadening earmuffs throughout the experiment.

Memory task. The memory tasks were similar to Experiment 1, with the following exceptions. First, the memory array was increased from two to four. This was because an earlier study by Lee and Vecera (2005) with a similar procedure employed four items. Thus, subjects were shown four squares instead of two squares during the memory array frame. Second, the color of the location probe was changed from black to white. As in Experiment 1, subjects were instructed to remember the color, location or both color and location information about the items in the memory array so that they could correctly respond to the memory probe presented at the end of the trial.

Attention task (Egly et al. object task). Figure 13 (page 71) illustrates an example of the displays comprising the stimuli used for the Egly et al. (1994) object task and the procedural outline of the task. The initial display consisted of a fixation cross and two rectangles. The fixation cross was 0.16" x 0.16" (visual angle = 0.40º x 0.40º). The two outline rectangles were 0.41" (visual angle = 1.0º) wide by 2.46" (visual angle = 6.0º) long. The rectangles were aligned either horizontally or vertically, and the ends of each rectangle were equidistant from one another and fell 4.2º from fixation.

Subjects were spatially cued to a location on one of the rectangles by brightening the edges at that end of a rectangle with a 0.04" (visual angle = 0.10º) thick white line. The cue appeared for 50 ms immediately prior to onset of the target display and could appear at any of the four ends of the rectangles. The target and three distractors, which were all white outline circles or squares, were then presented one at each of the four ends of the rectangles. Two circles and two squares appeared on each trial. The target stimulus was a larger shape 0.37" in diameter (visual angle = 0.90º). The distractors were all smaller shapes, 0.21" in diameter (visual angle = 0.5º).

On any trial, the target could appear in three possible locations: the cued location (i.e., valid trials), the uncued end of the cued rectangle (i.e., invalid same-object trials), or the uncued rectangle (i.e., invalid different-object trials). When the target appeared in the uncued rectangle, it always appeared in the end that was closest to the cue, rather than the end that was diagonally across from the cued location. As a result, both invalid target locations were equidistant from the cued location. Valid trials occurred on 60% of all trials, and each of the invalid conditions appeared on 20% of the trials.

After the 500 ms blank delay period following the offset of the memory stimuli, a fixation cross was presented for 500 ms, followed by the two rectangles. After the rectangles were presented for 500 ms, the spatial cue appeared for 50 ms. Immediately after the offset of the cue, one target and three distractors were presented for 2000 ms, or until subjects made a response. Subjects pressed the "1" key if the target was a large circle and the "2" key if the target was a large square. If subjects failed to make a response for a trial, it was logged as an incorrect response. Subjects received visual feedback in the form of a red cross for 250 ms whenever a wrong response was made. A blank frame of 250 ms was then presented when a correct response was made. Subjects performed a total of 160 trials in the attention baseline and 160 trials in the dual-task conditions. Each subject also performed 24 unanalyzed practice trials before the start of the experimental trials.

Procedure

The general procedure for Experiment 2 was similar to that of Experiment 1 in that there was articulatory suppression (Besner et al., 1981) throughout the experimental trials, and the order of the task conditions (attention baseline, memory baseline and dual-task) was counterbalanced over subjects. Subjects were given 12 practice trials in each of the task conditions in order to familiarize them with the presentation sequence of the task and the display frames to which they should respond depending on task condition. As in Experiment 1, a white X was superimposed on displays that should be ignored during the baseline conditions. Instructions stressed both speed and accuracy for all tasks.

Experiment 2: Results and Discussion

In Experiment 2, there were three different memory task groups performing the same attention task (i.e., Egly et al. object task). Unlike Experiment 1, the interesting results were found in the attention task rather than in the memory task. Specifically, the attentional shifting costs varied as a function of VSTM loading. Hence, the focus of the results and discussion is on the effect of the different memory tasks on attention shifting within or between objects in the Egly et al. object task. Performance on the Egly et al. object task in terms of accuracy and RT in both the attention baseline and dual-task conditions will first be presented. The attention shifting cost for each memory task condition in both the attention baseline and dual-task conditions will then be examined in order to investigate the effects of loading different types of VSTM on attention shifting. Finally, performance on the memory task in both the memory baseline and dual-task conditions for the different memory conditions will be examined.

Egly et al. Object Task

Overall Performance

Accuracy. Mean accuracy in the Egly et al. object task is shown in Table 8 as a function of type of memory task (between subjects) and condition and type of target (within-subjects). Separate 2 (Condition: baseline vs. dual-task) x 3 (Cue type: valid vs. invalid-same vs. invalid-different) repeated measures ANOVAs were run for each memory task group. Both accuracy rates and RT in the Egly object task were examined. For each memory task, the main effect of Cue type was significant, in that subjects were more accurate in the valid trials than the invalid-same and invalid-different trials, but there were no differences between the invalid-same and invalid-different trials. The F ratios and p values for these main effects are summarized in Table 9 (bottom). Also, the main effect of Condition was significant for both the location memory task, $F(1, 47) = 4.36$, $p < .042$, and the double memory task, $F(1, 47) = 5.44$, $p < .024$. No other main or interaction effects were significant, $p > .30$.

Table 8. Mean Accuracy as a Function of Memory Task and Condition in the Egly et al. Object Task

	Baseline			**Dual Task**		
	Valid	**Invalid-Same**	**Invalid-Different**	**Valid**	**Invalid-Same**	**Invalid-Different**
Color	0.93	0.89	0.89	0.92	0.90	0.89
Location	0.89	0.86	0.86	0.91	0.88	0.89
Double	0.90	0.87	0.88	0.93	0.90	0.89

Table 9. Summary of Significant Cueing Main Effect on Accuracy in the Egly et al. Object Task

Effect	Memory Type	F ratio	p value	95% difference C.I.					
				Valid vs. Invalid Same		Valid vs. Invalid Different		Invalid Same vs. Invalid Different	
				Lower	Upper	Lower	Upper	Lower	Upper
Cue (df = 2, 94)	Color	*13.13*	*.001*	0.011	0.037	0.019	0.049	-0.023	0.002
	Location	7.97	*.001*	0.014	0.047	0.01	0.04	-0.012	0.023
	Dual	*9.14*	*.001*	0.013	0.046	0.013	0.045	-0.014	0.016

RT. Mean RT in the Egly et al. object task is shown in Figure 14 as a function of type of memory task (between subjects) and condition and type of target (within subjects). RTs below 200 ms or above 2000 ms (< 2% of the data) and RTs for incorrect trials were excluded from analysis.

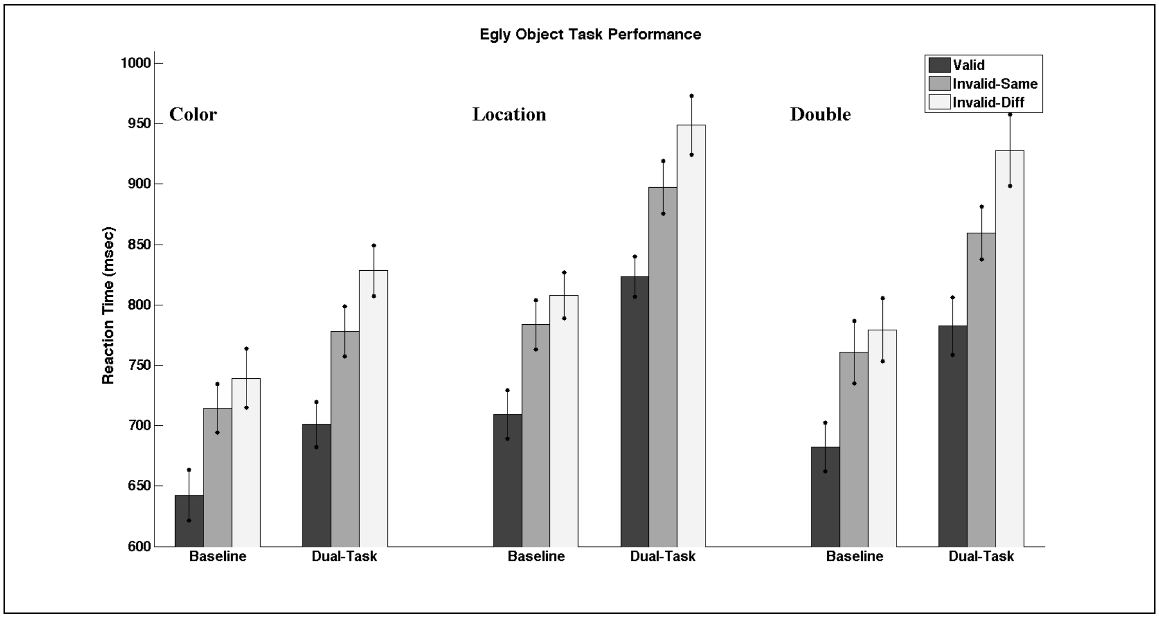

Figure 14. Mean RT in the Egly et al. object task as a function of condition and cue validity for the different memory task conditions in Experiment 2. Left Panel: Color memory; Center Panel: Location memory; Right Panel: Double memory. Error bars denote 95% within-subjects confidence interval.

For each memory task, the main effect of Condition was significant, in that subjects were slower in the in the dual-task condition compared to the baseline condition. The main effect of Cue type also was significant. Paired t-tests showed that RT in the valid trials was faster than both the invalid-same and invalid-different trials, and RT in the invalid-same trials was faster than the invalid-different trials. This is a typical finding for the Egly object task (e.g., Egly et al., 1994; Lavie & Driver, 1996; Shomstein & Behrmann, 2008). The Condition x Cue type interaction effect also was significant, in that when the difference in RT between the dual-task condition and the baseline condition was considered, there was no difference between the valid and invalid-same trials, but the difference in RT for the invalid-different trials was larger than for the other two types of trials. The *F* ratios and *p* values for these main and interaction effects are summarized in Table 10.

Table 10. Summary of Significant Effects for RT in the Egly et al. Object Task

Effect	Memory Type	F ratio	p value	95% difference C.I. (Baseline vs. Dual-Task)					
				Lower	Upper				
Task (df = 1, 47)	Color	*15.36*	*.001*	34.28	106.59				
	Location	47.45	*.001*	86.95	158.68				
	Dual	*27.75*	*.001*	71.59	160.04				
Cue (df = 2, 94)				Valid vs. Invalid Same		Valid vs. Invalid Different		Invalid Same vs. Invalid Different	
				Lower	Upper	Lower	Upper	Lower	Upper
	Color	*102.7*	*.001*	58.85	90.06	93.33	130.98	24.58	50.82
	Location	130.31	*.001*	59.03	89.66	97.31	126.87	25.38	50.11
	Dual	*101.57*	*.001*	60.28	95.08	101.36	141.16	29.32	57.84
Task x Cue (df = 2, 94)				Valid vs. Invalid Same		Valid vs. Invalid Different		Invalid Same vs. Invalid Different	
				Lower	Upper	Lower	Upper	Lower	Upper
	Color	*3.55*	*.033*	-15.50	10.31	3.78	26.71	0.12	25.18
	Location	3.06	*.052*	-12.28	12.27	-0.24	27.20	1.53	25.44
	Dual	*10.44*	*.001*	-11.72	10.77	11.12	37.41	11.84	37.64

Attentional Shifting Cost

To further examine the Condition x Cue type interaction effect, the attentional shifting cost due to each type of invalid cue was calculated for each subject. The attentional shifting cost was calculated by subtracting the mean RT for the valid cue trials from the respective mean RT of the invalid cue trials. Thus, there was an attention-shifting cost for invalid-same trials and an attention shifting cost for invalid-different trials. Attention shifting cost was calculated for each condition (baseline and dual-task). Mean attentional shifting costs under each memory task are shown in Figure 15.

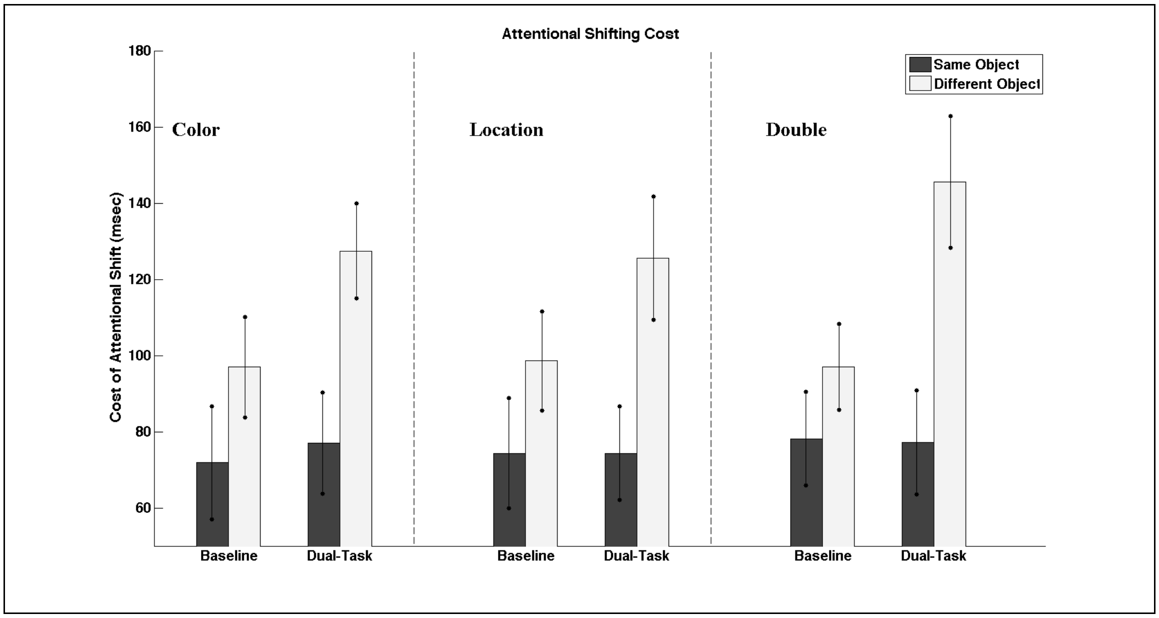

Figure 15. Mean attentional shifting cost for the invalid trials in the Egly et al. object task as a function of condition and memory task in Experiment 2. Left Panel: Color memory; Center Panel: Location memory; Right Panel: Double memory. Error bars denote 95% within-subjects confidence interval.

As previously described, if the memory task engaged the same processing resources required for the attentional shift, it would interfere with the attentional shift in the dual-task condition relative to the baseline condition. Interference with the shift would increase the cost associated with the attention shift. A spatial shift should occur on all invalid cue trials, but an object-based attention shift should only occur on the invalid-different trials.

Color memory task. A 2 (Condition: baseline vs. dual-task) x 2 (Target location: same object vs. different object) repeated measures ANOVA was used to analyze the attentional shifting cost. The attentional shifting cost was marginally larger in the dual-task condition (102 ms) than the baseline condition (84 ms), $F(1, 47) = 2.94$, $p < .093$, 95% C.I. (-3.1, 38.8), and larger when the target appeared in the different object (112 ms) compared to when it appeared in the same object (74 ms), $F(1, 47) = 33.42$, $p < .001$, 95% C.I. (24.5, 50.8). The Condition x Target location interaction effect was significant, $F(1, 47) = 4.12$, $p < .048$. Pairwise comparisons showed that the attentional shifting cost for the same object condition was similar in both the baseline (71 ms) and dual-task conditions (77 ms), $t(47) = 0.405$, $p > .68$, 95% C.I. (-31.0, 20.6). However, the attentional shifting cost for the different object condition was larger in the dual-task condition (127 ms) compared to the baseline condition (96 ms), $t(47) = 2.68$, $p < .01$, 95% C.I. (7.6, 53.4). This finding is consistent with the predicted results. Attentional shifting cost was larger in the dual-task condition only when the target appeared in a different object. Assuming that the color memory task engaged object STM and that object STM and object-based attention engaged similar processing resources, there should be an interference effect in the dual-task condition only when an additional object-based attentional shift is required, which only occurs for the different object condition

Location memory task. A 2 (Condition: baseline vs. dual-task) x 2 (Object: same object vs. different object) repeated measures ANOVA was used to analyze the attentional shifting cost. The attentional shifting cost was larger when the target appeared in the different object (112 ms) compared to when it appeared in the same object (74 ms), $F(1, 47) = 37.68$, $p < .001$, 95% C.I. (25.38, 50.11). The Condition x Target location interaction effect was significant, $F(1, 47) = 5.15$, $p < .028$. Pairwise comparisons showed that the attentional shifting cost for the same object condition was similar in both the baseline (74 ms) and dual-task conditions (74 ms), $t(47) = 0.001$, $p > .99$, 95% C.I. (-24.54, 24.55). However, the attentional shifting cost for the different object condition was larger in the dual-task condition (126 ms) compared to the baseline condition (97 ms), $t(47) = 1.977$, $p < .054$, 95% C.I. (-0.5, 54.4). This finding is inconsistent with the predicted results. Attentional shifting cost was larger in the dual-task condition only for the different object condition but not for the same object condition. Assuming that the location memory task engaged spatial STM and that spatial STM and spatial attention engaged similar processing resources, there should have been an interference effect in the dual-task condition when an additional spatial attentional shift was required, which occurred for both the same and different object conditions.

Double memory task. A 2 (Condition: baseline vs. dual-task) x 2 (Target location: same object vs. different object) repeated measures ANOVA was used to analyze the attentional shifting cost. The attentional shifting cost was larger in the dual-task condition (111 ms) compared to the baseline condition (88 ms), $F(1, 47) = 5.30$, $p < .026$, 95% C.I. (3.0, 44.6), and when the target appeared in the different object (121 ms) was larger than when it appeared in the same object (78 ms), $F(1, 47) = 37.80$, $p < .001$, 95% C.I. (29.3, 57.8). The Condition x Target location interaction effect was significant, *F(1, 47)* = 14.90, *p* < .001. Pairwise comparisons showed that the attentional shifting cost for the same object condition was similar in both the baseline (78 ms) and dual-task conditions (77 ms), *t(47)* = 0.085, *p* > .933, 95% C.I. (-21.5, 23.4). However, the attentional shifting cost for the different object condition was larger in the dual-task condition (146 ms) compared to the baseline condition (97 ms), *t(47)* = 3.71, *p* < .001, 95% C.I. (3.71, 22.25).

The numerical value of the attentional shifting cost in the different object condition of the double memory condition (146 ms) was larger than in the color memory condition (127 ms) and the location memory condition (126 ms), but the difference was not reliable. Because a difference was expected, a 3 (Memory type: color vs. location vs. double) x 2 (Condition: baseline vs. dual task) x 2 (Target location: same object vs. different object) mixed ANOVA with Memory type as a between-subject variable was run on the attentional shifting cost. The mixed ANOVA failed to find a significant three-way interaction effect, *F(2, 141)* = 1.19, *p* > .30. This suggested that the difference in attentional shifting cost between the baseline and the dual-task condition in the different object condition did not differ significantly across Memory type, despite the fact that the attentional shifting cost was numerically larger. There are two possible interpretations for this numerically larger but statistically non-significant difference in attentional shifting cost. The first possibility is that there is a lack of power. In the present study, 48 subjects were run in each condition. Although this is a large number for the Egly et al. object task (usually around 20 subjects are run in studies using the Egly et al. object task), a power analysis of the difference in the attentional shifting cost between the dual-task and baseline conditions using the sample standard deviation (88) as an estimate of the population standard deviation revealed that 598 subjects would be required for each condition to get a significantly larger attentional shifting cost in the double memory condition of the magnitude observed. Attentional shifting cost is a difference score and there was high variability in the score both within each memory task and across memory tasks and therefore a large number of subjects would be required to detect a real difference. One could address this issue with a within-subjects experimental design, which might be more sensitive to a real difference.

The second possibility is that the numerically larger attentional shifting cost might be due to statistical noise. In order to investigate this possibility, the difference in attentional shifting cost between the dual-task and baseline condition for each subject was computed. In this case, a negative difference would imply that loading STM did not interfere with the attentional shifts, while a positive difference would imply that loading STM interfered with the attentional shifts. The histogram distribution of this difference was then plotted as a function of target location (i.e., same object versus different objects) and the memory task (i.e., color, location and double memory task). These histograms are presented in Figure 16. Examining the histogram distributions allows one to get a better idea of whether the larger attentional shifting cost in the double memory condition might be due to statistical noise. An obvious indication would be the existence of outliers, which could increase the variance and/or mean attentional shifting cost in the different memory conditions. Depending on which memory task condition the outliers appeared, this could either mask any possible real differences between the conditions, or increase the level of statistical noise in the data.

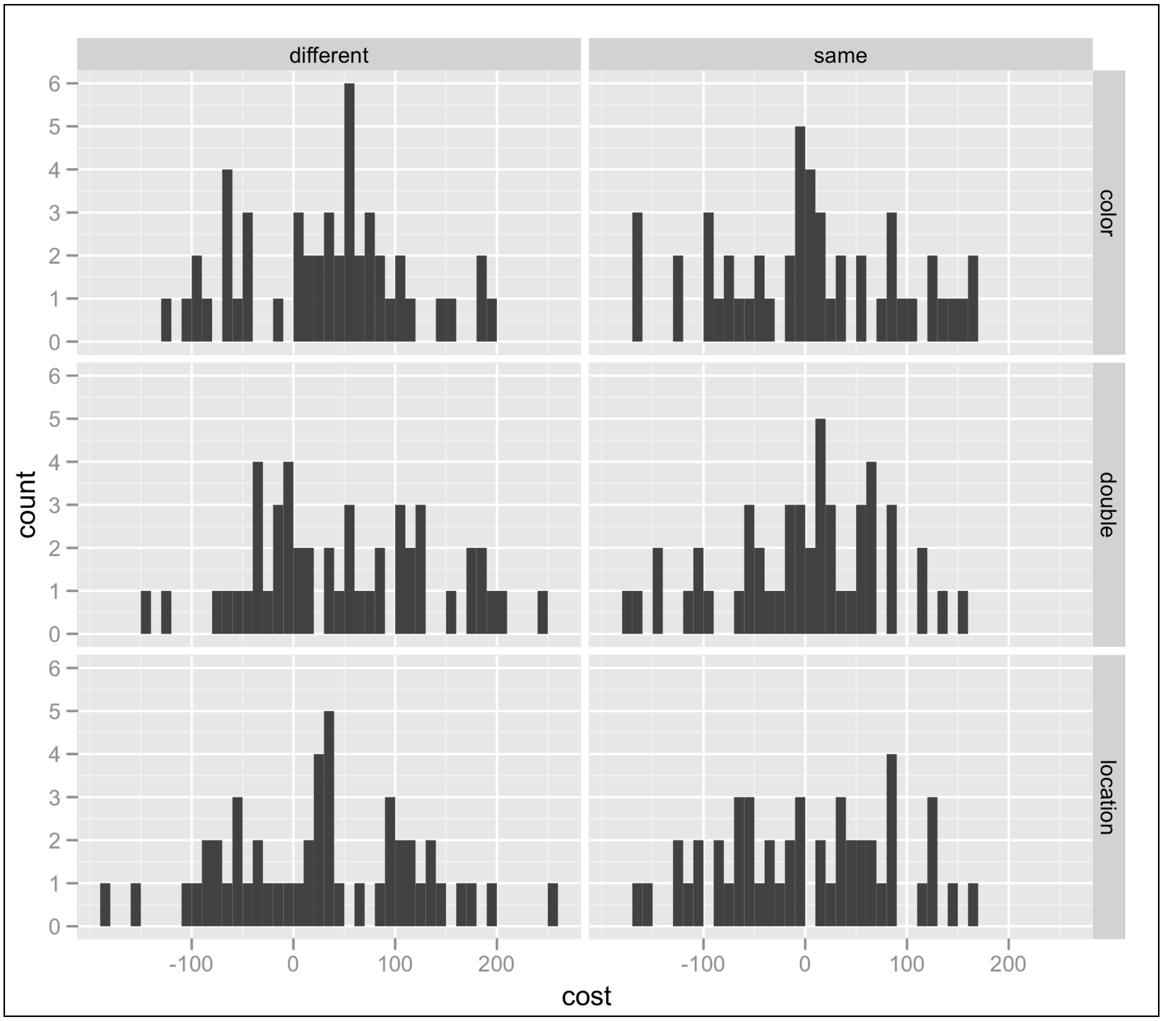

Figure 16. Histogram plots of difference in attentional shifting cost between the dual-task and baseline conditions as a function of target location and memory task. The panels on the left column denote histograms in the different object condition and the panels on the right column denote histograms in the same object condition. The panels in the first row denote histograms in the color memory condition. The panels in the second row denote histograms in the double memory condition. The panels in the third row denotes histogram in the location memory condition.

From the histograms, it can be seen that the distributions for the different object condition is shifted more to the right compared to same object condition. This is consistent with the finding that the attentional shifting cost in the different object condition was larger than in the same object condition. However, the histogram distributions for the different object condition in the double memory task did not show any indication of positive outliers. This suggests the numerically larger attentional shifting cost in the double memory condition was not due to the influence of outlier points. A further examination of the histogram distributions in the different object condition revealed no obvious difference between them, in that the shape of the distributions for the three memory conditions look highly similar. This could be due to the high variability in the data. While the examination of the histogram distributions ruled out the hypothesis that the numerically larger attentional shifting cost in the double memory condition was due to outlier points, it still does not allow one to unequivocally reject either interpretation. In other words, the numerically larger but statistically non-significant attentional shifting cost in the double memory condition could either be due to a lack of power, or due to statistical noise.

The lack of power interpretation would make the finding in the double memory condition partly consistent with the predicted results, while the statistical noise interpretation would make the finding in the double memory condition inconsistent with the predicted result. The null finding does not unequivocally support either interpretation. The two interpretations lead to different conclusions about whether the processing resources engaged by spatial attention and spatial STM are dissociable from those engaged by object-based attention and object STM. This issue will be explored further in the General Discussion section under the heading ‘Dissociable Sets of Processing Resources?’, where the implications of adopting either interpretation are discussed and a further study is proposed to differentiate between the interpretations.

Similar to the findings with the location memory task, attentional shifting cost was larger in the dual-task condition only for the different object condition. Assuming that the location memory task engaged spatial STM and that spatial STM and spatial attention engaged similar processing resources, there should be an interference effect in the dual-task condition when an additional spatial attentional shift is required, which occurred for both the same and different object conditions. The pattern of results suggests that attentional selection for spatial locations within the same object might be facilitated (e.g., Müller and Kleinschimdt, 2003) and is inconsistent with the predicted findings. This issue will be further explored in the General Discussion section under the heading 'Modulation of Spatial Attention Within an Object'.

One might argue that a processing difficulty account could explain the findings in Experiment 2. The numerically larger attentional shifting cost in the different object condition of the double memory task might be due to the fact that it was more difficult for subjects to maintain both color and location information compared to maintaining either the color or location information (see Figure 15, page 85). This explanation is unlikely because if it were true, one also would expect a larger attention shifting cost for the same object condition in the double memory task. Of course, one could argue that spatial attentional selection within the same object is facilitated and hence a processing difficulty argument need not apply. However, this account is post-hoc and less parsimonious than the offered explanation. Furthermore, mean accuracy in the Egly et al. object task did not differ in the invalid same and invalid different trials for any memory tasks and when the overall mean RTs were examined (see Figure 14, page 83), subjects were slower in the location memory task. Hence, if the processing difficulty account were correct, one would expect a larger attentional shifting cost, either numerically or significantly, to manifest in the location memory task condition rather than the double memory task. This was clearly not the case. Based on these results, the processing difficulty account is rejected.

Memory Task Performance

Mean accuracy performance for each memory task is shown in Figure 17 as a function of condition.

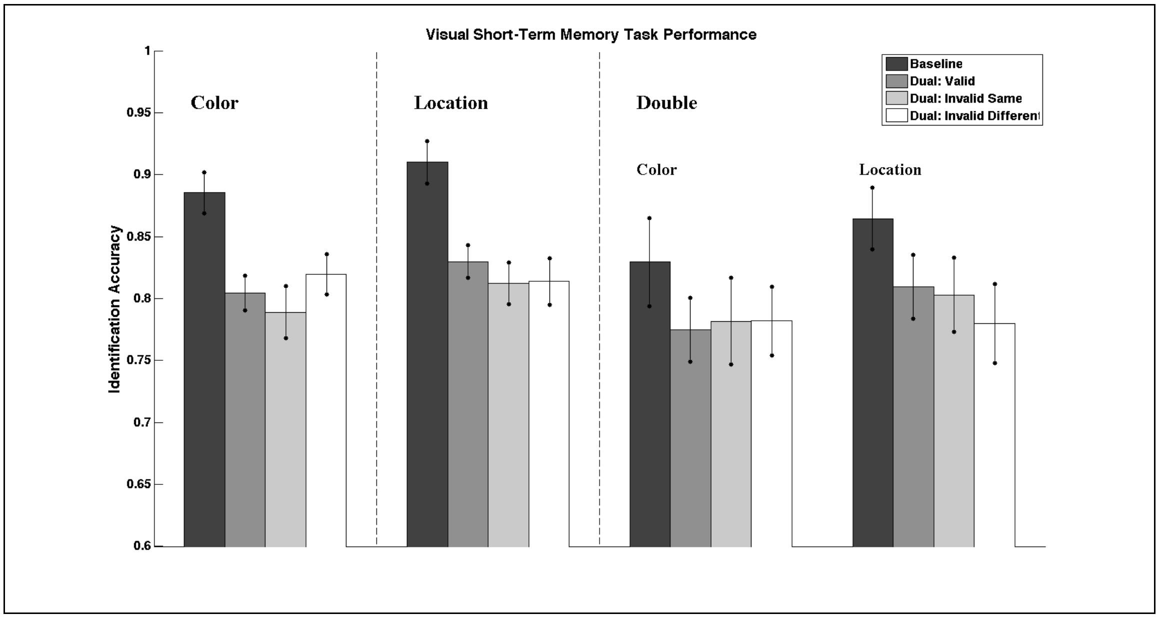

Figure 17. Mean accuracy in the memory task in the memory baseline, dual-task valid, dual-task invalid-same and dual-task invalid-different conditions in Experiment 2. Left Panel: Color memory task; Center Panel: Location memory task; Right Panel: Double memory task. Error bars denote 95% within-subjects confidence interval.

Color memory task. A one-way repeated measures ANVOA was run on mean accuracy as a function of condition (baseline, dual-valid, dual-invalid-same and dual-invalid-different). The one way ANOVA was significant, $F(3, 141) = 17.92$, $p < .001$. Paired sample comparisons showed higher mean accuracy for the baseline condition than the three dual-task conditions, which did not differ. The test statistics for these comparisons are summarized in Table 11 (top).

Table 11. Summary of Paired Comparisons for Accuracy in Memory Tasks

	Paired Sample Comparisons			95% Difference C.I.	
		t value	p value	Lower	Upper
Color	Baseline vs. Valid	6.90	*.001*	0.057	0.105
	Baseline vs. Invalid-Same	5.72	*.001*	0.062	0.13
	Baseline vs. Invalid-Different	5.21	*.001*	0.04	0.091
	Valid vs. Invalid-Same	1.07	*.29*	-0.014	0.044
	Valid vs. Invalid-Different	1.21	*.23*	-0.04	0.01
	Invalid-Same vs. Different	1.91	*.062*	-0.063	0.0016
Location	Baseline vs. Valid	7.29	*.001*	0.058	0.102
	Baseline vs. Invalid-Same	6.82	*.001*	0.069	0.126
	Baseline vs. Invalid-Different	5.96	*.001*	0.064	0.129
	Valid vs. Invalid-Same	1.34	*.18*	-0.009	0.043
	Valid vs. Invalid-Different	1.20	*.23*	-0.011	0.043
	Invalid-Same vs. Different	0.09	*.92*	-0.03	0.027
Double	Baseline vs. Valid	3.81	*.001*	0.026	0.084
	Baseline vs. Invalid-Same	3.29	*.002*	0.021	0.088
	Baseline vs. Invalid-Different	4.27	*.001*	0.035	0.097
	Valid vs. Invalid-Same	0.001	*.99*	-0.026	0.026
	Valid vs. Invalid-Different	0.949	*.34*	-0.013	0.035
	Invalid-Same vs. Different	0.805	*.42*	-0.017	0.039

Location memory task. A one-way repeated measures ANVOA was run on mean accuracy as a function of condition (baseline, dual valid, dual invalid-same and dual invalid-different). The one way ANOVA was significant, $F(3, 141) = 22.67$, $p < .001$. Similar to the color memory task, paired sample comparisons showed higher mean accuracy for the baseline condition than the three dual-task conditions, which did not differ. The test statistics for these comparisons are summarized in Table 11 (middle).

Double memory task. A 2 (Probe type: color vs. location) x 4 (Condition: baseline vs. dual valid vs. dual invalid-same vs. dual invalid different) repeated measures ANOVA was used to analyze subjects' mean accuracy rates. There was a main effect of Condition, $F(3, 141) = 8.58$, $p < .001$. Weighted contrast analysis showed higher mean accuracy for the baseline condition than the other three dual-task conditions, but the differences between the three dual-task conditions were not significant, replicating the findings in the color and location memory tasks. The test statistics for the weighted contrast analysis are summarized in Table 11 (bottom). The main effect of Probe type was not significant, $F(1, 47) = 1.51$, $p > .22$. The Condition x Probe type interaction effect also was not significant, $F(3, 141) = 0.796$, $p > .49$.

Generally, for all the memory tasks, the mean accuracy in the baseline condition was higher than in the dual-task conditions and there were no differences among the different dual-task conditions. In other words, unlike the visual search task and the Duncan object tasks in Experiment 1, there was no selective interference on the different dual-task conditions by the Egly et al. object task. There was no selective interference on the location memory probes when spatial attention was more heavily engaged and there was no selective interference on the object memory probes when object attention was more heavily engaged. Differences in requirements for the different tasks, such as the number of responses and the method of stimuli presentation, might be responsible for the different outcomes. This will be discussed in the General Discussion under the heading 'Locus of Interference'.

Overall, the findings in Experiment 2 were not entirely consistent with the findings in Experiment 1. First, neither object STM or spatial STM were taxed by the attention task, meaning that the selective interference did not show up on the memory accuracy performance in the dual-task condition. Second, when the Egly et al. object task was used, in which a spatial shift was required on some trials and both a spatial shift and an object-based shift were required on other trials, the pattern of interference did not entirely agree with the claims that were supported in Experiment 1. As Experiment 2 was specifically designed to address methodological issues concerning Experiment 1, these findings suggest that the findings in Experiment 1 must be treated with caution.

CHAPTER 4: GENERAL DISCUSSION

The present study examined several claims regarding the relationship between spatial and object-based attention and spatial and object STM by employing different combinations of attention and memory tasks within the context of a dual-task paradigm. In Experiment 1, three types of attention tasks were employed, namely (a) the visual search task, which is thought to engage spatial attention, (b) the Duncan object task with overlapping stimuli, which is thought to engage object-based attention, and (c) the Duncan object task with separated stimuli, which is thought to engage both spatial and object-based attention. Three different memory tasks also were employed, namely (a) the color memory task, which is thought to engage object STM, (b) the location memory task, which is thought to engage spatial STM, and (c) the double memory task, which is thought to engage both spatial and object STM. In Experiment 2, the same memory tasks were used, and the Egly et al. (1994) object task was employed as the attentional task. In this task, no shift of attention is thought to be required on valid trials, a spatial shift is thought to be required on invalid same-object trials, and both a spatial and an object-based shift are thought to be required on invalid different-object trials.

The claims examined in the present study included: (a) spatial attention and spatial STM engage similar processing resources, (b) object-based attention and object STM engage similar processing resources, and (c) these two sets of processing resources are dissociable from each other. While the claim that spatial attention and spatial STM engage similar processing resources that are dissociable from those engaged by object STM is generally accepted and supported by several studies (Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman et al., 2001; Woodman & Luck, 2004), the claim that object-based attention and object STM engage similar processing resources that are dissociable from those engaged by spatial STM is less supported (Matsukura & Vecera, 2008; Tan, 2008). Thus, the present study focused primarily on the claim that object-based attention and object STM engage similar processing resources dissociable from those engaged by spatial attention and spatial STM.

The two studies supporting the claim that object-based attention and object STM share similar processing resources (i.e., Matsukura & Vecera, 2008; Tan, 2008) used the Duncan (1984) object task to engage object-based attention. There are at least two concerns with employing the Duncan object task as a means to engage object-based attention in a dual-task paradigm. First, the Duncan object task does not have a spatial component, so one is not able to examine whether object STM is affected by engaging object-based attention when the task includes a spatial component (e.g., Awh et al., 2001; Vecera & Farah, 1994). Second, the Duncan object task places heavy demands on object STM because stimulus presentation is brief and masked. In other words, the Duncan object task might interfere with a memory task that engages object STM not because the Duncan object task engages object-based attention, but because it engages object STM. These concerns limit the validity of the conclusions from the studies that claimed object-based attention and object STM engage similar processing resources. The first concern was addressed in both Experiments 1 and 2 in the present study by including a spatial component in the tasks thought to engage object-based attention. The second concern was addressed in Experiment 2, where the stimuli were not masked and hence placed little demands on object STM.

The present study also was designed to address a methodological problem related to the claim that the processing resources thought to engage spatial attention and spatial STM are dissociable from the processing resources thought to engage object-based attention and object STM. The study that provided support for this claim was Matsukura and Vecera (2008). They demonstrated a double dissociation between the two sets of processing resources with a combination of attention and memory tasks in a dual-task paradigm. However, while the memory tasks varied only in content and not procedure (i.e., location and color memory tasks), the attention tasks were fundamentally different. The task thought to engage spatial attention (i.e., visual search task) required a single speeded response and did not require that the information be stored in VSTM and the task thought to engage object-based attention (i.e., Duncan object task) required two unspeeded responses to briefly presented, masked, stimuli that needed to be maintained in VSTM. This raises the possibility that the double dissociation may have been due to some of the procedural differences. The present study addressed this problem by using a single attention task in Experiment 2 (i.e., the Egly et al. object task) in which both a spatial and an object-based effect could be examined.

The results of Experiment 1, in which accuracy in the different memory tasks was selectively impaired by the different attention tasks, generally support the claims examined in the present study. The visual search task interfered with the location memory task, in that accuracy on the location memory task decreased when the number of items in the visual search display increased from 4 to 12 (i.e., it decreased when spatial attention was more engaged). This result supports the claim that spatial attention and spatial STM engage similar processing resources. The color memory task did not vary as a function of the number of items in the visual search task. This result supports the claim that the processing resources shared by spatial attention and spatial STM were dissociable from those engaged by object STM. The Duncan (1984) object task with overlapping stimuli interfered with the color memory task, in that accuracy on the color memory task was lower in the different object than the same object condition (i.e., it decreased when object-based attention was more engaged). This result supports the claim that object-based attention and object STM engage similar processing resources. Accuracy on the location memory task did not vary as a function of same or different object in the Duncan object task with overlapping stimuli. This result supports the claim that the processing resources shared by object-based attention and object STM were dissociable from those engaged by spatial STM. The Duncan object task with separated stimuli interfered with both the color and location memory tasks, in that both the color and memory accuracy decreased as both object-based and spatial attention were engage. Furthermore, the same pattern of results was replicated in the double memory task for all three attention tasks, providing further support for the model shown in Figure 1 (page 28).

The results in Experiment 2 were less straightforward. Although RT in the Egly et al. (1994) object task was slowed by the different memory tasks (i.e., there was a general dual-task decrement), the pattern of results was not fully in line with the predictions based on the claims examined in the present study. If the model shown in Figure 1 (page 28) were true, then loading of object STM should interfere with an object-based attentional shift, leading to an increased attentional shifting cost in the dual-task different condition when the target was in a different object from the cue. Similarly, the loading of spatial STM should interfere with a spatial attentional shift, leading to increased attentional shifting cost in both the dual-task same and different conditions (because each requires a spatial shift). Furthermore, if the two sets of processing resources are dissociable from each other, then when both object and spatial STM were engaged in the double memory task, the increase in attentional shifting cost for the different object condition would be larger than when either just spatial STM or just object STM was engaged.

In contrast to the predictions, the results of Experiment 2 showed that loading STM had no effect on attentional shifting cost when the target appeared in the same object as the cue. That is, the dual-task shifting cost did not differ from the baseline shifting cost with the color memory task, the location memory task and the double memory task. Loading object STM, spatial STM or both object and spatial STM had no impact on shifting spatial attention within an object. While no increase in attentional shifting cost in the dual-task condition was expected when object STM was engaged, because no object-based attentional shift was required when shifting within an object, an increase in attentional shifting cost was expected when spatial STM was engaged (i.e., with the location and double memory tasks). The results showed that spatial attentional shifts within an object were independent of VSTM loading under the conditions examined. Assuming that the resources engaged by object STM and spatial STM are dissociable and that engaging object STM does not interfere with spatial attentional shifts, the findings in the same object condition in Experiment 2 suggest that when a spatial attentional shift occurs within the context of an object, it does not tap into the same processing resources required by either object STM or spatial STM. In other words, shifting locations within an object appears to be fundamentally different from shifting locations between objects.

When the target appeared in the different object from the cue (thus requiring both a spatial and an object-based attentional shift), the results were consistent with the predictions for the color and location memory tasks, in that there was an increase in attentional shifting cost to a different object when either object or spatial STM was loaded. These findings support the claims that object-based attention and object STM engage similar processing resources and that spatial attention and spatial STM engage similar processing resources.

The evidence supporting the claim that both sets of processing resources were dissociable was equivocal. The prediction was that if both sets of processing resources were dissociable, then when both object STM and spatial STM were loaded in the double memory task, the attentional shifting cost would be larger than in the color memory task, in which only object STM was loaded, or the location memory task, in which only spatial STM was loaded. While the cost of attentional shifting with the double memory task was numerically larger than with either the color or the location memory task, the difference was not statistically significant. Two possible interpretations were offered for the numerically larger but non-significant attentional shifting cost in the double memory task. The first interpretation was that because of the high level of variance associated with subjects' performance in the Egly et al. object (1994) task, there was a lack of power to detect a real difference. However, it was noted that 48 subjects were run with each memory task, and that this is a large sample size for most experiments of this type. The second interpretation was that the numerically larger attentional shifting cost with the double memory task was not statistically significant because it was not a real difference.

The two interpretations of the results for the double memory task in Experiment 2 lead to conclusions that are at odds with each other. If the first interpretation were correct, one would conclude that both sets of processing resources were dissociable and independent from each other. In contrast, if the second interpretation were correct, one would conclude that the two sets of processing resources are not completely dissociable from each other. In the next section, I shall discuss the implications of each possible conclusion and propose a study that would be able to distinguish between them.

Dissociable Sets of Processing Resources?

The main purpose of Experiment 2 was to provide further empirical support for the claim that object-based attention and object STM engage similar processing resources. To a certain extent, this claim was supported by the findings with the color memory task. However, Experiment 2 was also designed to investigate whether there was support for the claim that the set of processing resources engaged by object-based attention and object STM are independent and dissociable from the set of processing resources engaged by spatial attention and spatial STM. As mentioned in the previous section, the results in Experiment 2 were equivocal towards this claim, mainly due to the difficulty in interpreting whether the cost of shifting attention to a different object while doing the double memory task was larger than while doing either the color memory task or the location memory task.

Interpreting the numerically larger attentional shifting cost in the different object condition as a real difference means that there was interference with both the object-based and spatial attentional shifts from jointly loading spatial and object STM. Thus, the findings in Experiment 2 would be consistent with those in Experiment 1. The findings would support the relationship between visual attention and VSTM that is illustrated in Figure 1 (page 28).

That is, there are two sets of processing resources that are independent and dissociable from each other.

The alternative interpretation, that there was no difference in the attentional shifting cost across the three memory tasks means that loading object STM, spatial STM or both object and spatial STM produced the same level of interference on the attentional shift in the different object condition. While the model in Figure 1 (page 28) does not make a claim about whether the attentional shifting cost would be different between the color memory task and the location memory task, it does predict that the attentional shifting cost would be larger with the double memory task. There are two ways to reconcile the model illustrated in Figure 1 (page 28) and the failure to find a larger attentional shifting cost with the double memory task. Assuming both object-based and spatial attention are independent from each other, it is possible that in the double memory task, both the color and location information were recoded into a single memory code rather than being maintained as two separate memory codes. For example, the memory code could be of an integrated object (e.g., Vogel & Luck, 1997; Vogel et al., 2001), in which case the number of items held in VSTM would be constant across the three memory tasks. However, it must be noted that attentional resources are required to bind the color and location information into an integrated object (Wheeler & Treisman, 2002). Given that attentional resources were limited in the dual-task condition, it is questionable whether such a strategy would be pursued. Furthermore, the independence and dissociation of object and spatial STM when employed in a dual-task paradigm has been demonstrated in numerous studies in the literature (e.g., Klauer & Zhao, 2004; Logie, 1986; Logie et al., 1990; Logie & Marchetti, 1991; Tresch et al., 1993; see Logie, 1995 for a review). These findings cast doubt on the possibility that both color and location information were recoded into a single memory code.

Another way to reconcile the findings with the model is to assume that object and spatial STM remain independent from each other while the cognitive components associated with spatial and object-based attention interact with each other. In this scenario, the fact that spatial attentional shifts within an object were buffered from the loading of spatial STM is an indication that these spatial attentional shifts were somehow modulated by the presence of the object. There is evidence in the literature that attentional selection of spatial locations within an object is facilitated compared to selection of locations outside an object (e.g., Brown & Denney, 2007; Müller and Kleinschimdt, 2003). Also, previous studies have provided evidence for the interaction of spatial and object-based attention within a single task paradigm, by demonstrating that attending to an object alters the spatial gradient of the space surrounding the object (Kravitz & Behrmann, 2008), that object-based attention only operates within spatially attended regions (Lavie & Driver, 1996), or that attention automatically spreads across the spatial regions of an object even though attention was only directed to a region of the object (Davis, Driver, Pavani & Shepherd, 2000). These findings suggest that object-based and spatial attentional selection within any single task paradigm are not dissociable and independent from each other. This would account for why the attentional shifting cost in the different object condition when both object and spatial STM were loaded did not increase, because the prediction that a larger attentional shifting cost would be observed was built on the assumption that the object-based and spatial attentional shifts were independent from each other.

If the second interpretation of the results of Experiment 2 were correct, it also would have implications for interpreting the results of Experiment 1. One of the purposes for conducting Experiment 2 was because the Duncan (1984) object task employed in Experiment 1 heavily engaged object STM. Even though interference effects were found in both the color and location memory tasks when subjects concurrently performed the Duncan object task with separated stimuli, this could be due to the fact that object STM was heavily engaged by the Duncan object task, and not because both object-based and spatial attentional selection were independently engaged. In other words, if one were to interpret the results of Experiment 2 as not supporting the claim of independence and dissociation between the two sets of processing resources, it would suggest that the findings in previous studies supporting such a claim (Matsukura & Vecera, 2008; Tan, 2008) might be the result of a task artifact.

The two different interpretations of the numerically larger but not statistically different attentional shifting cost in the dual-task condition for the double memory task lead to different and contrasting conclusions. The assumption that a real difference was not detected because of lack of statistical power leads to the conclusion that the two sets of processing resources are independent and dissociable from each other. In contrast, the assumption that no real difference exist leads to the conclusion that the two sets of processing resources are not independent and dissociable from each other. In order to tease apart the two possible interpretations and conclusions, I propose a future study using a similar method as Experiment 2 while varying the spatial distance between the two objects in the Egly et al. (1994) object task.

In this proposed study, there would be a 'far' and 'near' condition in which the spatial distance between the target and cue in the Egly et al. object task is varied. In other words, the length of the rectangle objects in the task would be varied. When this was the case, the cost of the spatial attentional shifts also would vary with the distance between the target and the cue in the different object condition (e.g., Downing and Pinker, 1995). However, because the number of objects still remains the same, the cost of object-based attentional shifts in the different object condition should remain the same in both the near and far conditions. On the assumption that the two sets of processing resources are independent and dissociable, the prediction is that when object STM is loaded, there should be no differences in the attentional shifting cost in the dual-task different object condition between the near and far conditions. Furthermore, when spatial STM is loaded, the attentional shifting cost in the dual-task different object condition should increase with the spatial distance between the target and the cue. When both spatial and object STM are loaded, there should be an attentional shifting cost in the dual-task different object condition that should be larger than when either only spatial STM or only object STM was loaded. The attentional shifting cost also should increase with the spatial distance between the target and the cue, and this increase should be comparable to the increase observed when only spatial STM was loaded.

In contrast, on the assumption that spatial and object-based attention interact with each other in the context of the Egly et al. (1994) object task, the increase in attentional shifting cost in the dual-task different object condition should be similar when either object STM or spatial STM is loaded. Furthermore, there should be no increase in the attentional shifting cost when both object and spatial STM are loaded in the double memory task. The results from this proposed future experiment will provide evidence regarding which of the two possible interpretations and conclusions of the results of Experiment 2 in the present study is better.

Modulation of Spatial Attention Within an Object

The results in Experiment 2 suggest that the presence of an object facilitates spatial attentional shifts within it. Either spatial attention minimally engaged processing resources when shifting within an object and hence is not affected by spatial STM engaging the similar processing resources, or spatial shifts within an object are buffered from the interfering effects of spatial STM because spatial attentional shifts within an object might be different from those examined in the typical spatial attention study (Posner & Petersen, 1990).

In some studies investigating object-based attention, subjects have to report properties located in a single object or multiple objects without being cued to any of the objects (e.g., Duncan, 1984; Kramer & Watson, 1997, 1999; Lavie & Driver, 1996; Matsukura & Vecera, 2006). The general finding in these studies is that subjects usually reported the properties better when they were located in the same object. While the spatial location of the properties were not controlled in some earlier studies (e.g., Duncan, 1984; Vecera & Farah, 1994), they were controlled in later studies such that the spatial distance between the properties was similar when they were located in the same or different objects (e.g., Davis, Drive, Pavani & Sheppard, 2000; Kramer & Watson, 1997, 1999; Matsukura & Vecera, 2006). If it is assumed that accessing the spatial locations of the properties is a prerequisite for reporting them, then the findings of these studies imply, but do not directly demonstrate, that accessing spatial locations within the same object was different from accessing spatial locations in different objects. In these cases, the claim that accessing or processing spatial locations is facilitated in the same object was inferred rather than directly demonstrated.

Although it was not the main purpose of the study, Kim and Cave (1995) provided some direct evidence suggesting that spatial locations are processed differently when they are located within objects. However, an ‘object’ in Kim and Cave was not a stimulus defined by a common boundary or contour (as in the Egly et al. task), rather it was a set of stimuli sharing common features such as shape or color. Kim and Cave asked subjects to search for a target in a search array that had items with different shapes and colors. On 25% of the trials, the search array was followed by a dot probe (small black dot) appearing in a position formerly occupied by a target or a distractor. RT to the dot probe increased as a function of the distance of the dot probe from the target, demonstrating the effects of spatial attention. However, subjects were faster and more accurate when the dot probe appeared in the position of a distractor that shared either the same color or shape as the target than when it appeared in the position of a distractor that shared neither feature with the target. These findings were replicated in Kim and Cave (2001) using different types of stimuli. These findings showed that spatial locations within items in a search array defined by the same features as the search target received preferential processing over locations that were outside these items.

Müller and Kleinschimdt (2003) provided neurological evidence for the claim that spatial locations within an object are processed differently. Subjects were required to perform a modified version of the Egly et al. (1994) object task using a central cue, in which the ends of the fixation cross (i.e., an ‘X’) lit up to indicate the direction in which the target might appear. Using fMRI, activity in the subjects’ early visual cortex was measured while they were performing the task. After central cueing, in which attention was directed to a specific corner of one of the objects, activity in early visual areas was enhanced not only at corresponding retinotopic representations, but also at representations of other locations covered by the object. While activity was greater for representations of cued locations than uncued locations on the cued object, higher activation was found in the uncued locations in the same object than equidistant locations on the other object when the cue was invalid. Müller and Kleinschimdt interpreted their findings as showing an interaction of object-based spatial selection with an object-independent spatial mechanism in directing attention. Within the context of the present study, the findings of Müller and Kleinschimdt suggest that spatial locations within a cued object were different than spatial locations in the uncued object. Hence, this might account for why even though spatial STM might be engaged in the location memory and double memory tasks, a spatial attentional shifting cost failed to manifest when the cue and target appeared in different spatial locations of the same object in the dual-task condition.

Recently, Kravitz and Behrmann (2008) also demonstrated that a cued object could affect the gradient of spatial attention surrounding it. After an object was cued, a target would appear in the region surrounding the object. Subjects were faster to respond to targets closer to the center of mass of the object than targets further away, even though all targets were equidistant from the cue. Furthermore, RT to targets in the surround of a fixed, attended object was shown to be a linear function of distance from the center of mass of the object, and changes to the shape of the object and its center of mass altered RT. The findings of this study provided further evidence that the presence of an object affects the processing and attending of spatial locations.

In the context of the current study, the studies just described suggest that it might not be appropriate to consider the attentional selection of spatial locations within an object as similar to the attentional selection of spatial locations that are not within the same object. In other words, the spatial attentional shifts within the same object for the Egly et al. object task in Experiment 2 might not be comparable to the typical spatial attentional shift (e.g., Posner et al., 1980; Posner & Petersen, 1990). In fact, one could make the argument that the findings of Müller and Kleinschimdt (2003) show that little or no attentional selection is required for spatial locations within an object once the object had already been attended (selected). This would account for the results in Experiment 2, in which no attentional shifting cost was found for the dual-task condition when the target and cue were in the same object. If one only considered the attentional shifting costs for the dual-task condition when the target and cue were in different objects, this would fit with the model in Figure 1 (page 28). In other words, the fact that no attentional shifting cost was found for the dual-task condition when the target and cue were in the same object and when spatial or both spatial and object STM were loaded does not necessarily rule out the claim that the set of processing resources required for spatial attention and spatial STM and the set required for object-based attention and object STM are dissociable from each other.

The discussion thus far has been that selection of locations within an object does not require the same spatial attention resources as selection of location between objects. If the claim is generalized to locations within or outside of the current selected object, then a further prediction is that loading spatial STM should interfere with shifting attention to any spatial locations outside an attended or cued object, even if the location is not in itself in another object. To investigate this claim, I propose a future study using a similar dual-task paradigm as in Experiment 2, but with the attention task adopted from Brown and Denney (2007). In order to investigate the process of attentional shifting underlying object-based and spatial attention, Brown and Denney modified the Egly et al. (1994) object task such that there was only one object in the visual display. By cueing spatial locations inside and outside of the object and presenting the target in an uncued location, four different types of attentional shifts could be identified, namely (a) location to location shifts within the object, (b) location to location shifts not within the object, (c) shifting from a location within the object to a location outside the object, and (d) shifting from a location outside the object to a location within the object. In my proposed study, either object or spatial STM would be loaded while subjects performed the modified Egly et al. object task with only a single object. The result would show whether an attentional spatial shift within an object and one that is not within an object are affected differently by loading spatial or object STM. Specifically, examining the increase in attentional shifting cost when either object or spatial STM is loaded for conditions (a) and (c) would allow an answer to the question about whether the failure to find an increase in the attentional shiftng cost for the same object condition in Experiment 2 was due to the fact that spatial attentional shifts within an object are different from a shift to a location outside an object.

Locus of Interference

The locus of interference in the dual-task condition was different in the two experiments. Although there was a general overall decrement in performance in both the attention and memory tasks in the dual-task condition for both experiments, the selective interference of VSTM and attention components engaging similar processing resources was manifest in different tasks over the two experiments. In Experiment 1, attention tasks engaging similar processing resources impaired performance in the memory tasks. In

Experiment 2, attention task performance was impaired when VSTM engaging similar processing resources was loaded.

While the factors that determine the locus of interference in the dual-task condition are likely multi-faceted, one likely factor is whether the attention task was speeded. Using both a modified speeded version of the Duncan object task and an unspeeded version of the original Duncan (1984) object task, Tan (2008) observed no effect on the Duncan object task with an unspeeded response of loading spatial versus object STM, but there was a difference when the response was speeded. The reverse was found in the performance of the memory tasks. Accuracy varied as a function of VSTM type when the Duncan object task was unspeeded, but no differences were found when it was speeded. Matsukura and Vecera (2008) also demonstrated no difference in performance in the unspeeded Duncan object task when different VSTM types were loaded. These findings suggest that the nature of response in the Duncan object task (i.e., speeded or unspeeded) is an important factor in determining the locus of interference in the dual-task condition.

There are several possible explanations for the influence of response speed on the locus of interference in the dual-task condition. In the speeded version of the Duncan (1984) object task, subjects are told to respond as quickly and as accurately as possible to the stimuli, which places an implicit emphasis on speed and may increase the likelihood of interference on the task when processing resources are limited. In contrast, subjects make two responses without any time constraints for the unspeeded version of the Duncan object task. Hence, there is less emphasis on speed and it is less likely for the task to show interference even though processing resources are limited. Furthermore, because subjects in the unspeeded Duncan object task are required to make two responses, information must be held in VSTM for a longer time, allowing decay, and there may be response interference from two responses rather than one. Thus, the decay or interference of information in VSTM is likely to be more severe in the unspeeded Duncan object task, especially if similar resources are engaged.

While the speeded nature of the Duncan object task provides a possible explanation for the locus of interference in the dual-task condition, this explanation is unlikely to be the sole explanation. This is because the results from the visual search tasks are incongruent with an account in which speeded responses lead to interference on the attention task rather than the VSTM task. In the visual search task employed in the current and also previous studies (Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman & Luck, 2004), subjects are required to make a single speeded response. If the speeded nature of the task were the only factor influencing the locus of interference, then in the dual-task condition, selective impairment of performance due to engaging similar processing resources should occur in the visual search task and not the memory task. However, the data in the current study showed the opposite pattern. While there was sometimes an increase in the overall RT in the dual-task condition when spatial STM was loaded (i.e., with the location memory task), search slopes did not increase in the dual-task condition. Because loading spatial STM did not increase the difficulty of target search, the speeded nature of the response cannot be the sole explanation for the differences between Experiments 1 and 2 in locus of interference in the dual-task paradigm.

The findings from previous studies using the visual search task have been mixed, suggesting that the locus of interference is unlikely to be explained by a single factor and is likely to be caused by a combination of several factors. While Oh and Kim (2004) and

Woodman and Luck (2004) both found an interference effect of loading spatial STM on both the attention and memory tasks, in that search slopes were increased and memory performance was decreased, Matsukura and Vecera (2008) and the present study found an interference effect in the memory task but not the attention task. In other words, search slopes did not increase when spatial STM was loaded, but location memory performance was impaired as a function of spatial attention engagement. One factor that could be contributing to the inconsistencies in the visual search task is the presentation of the stimuli. In the studies that found an interference effect (Oh & Kim, 2004; Woodman & Luck, 2004), the presentation of the search items was less constrained than in the present study and Matsukura and Vecera (2008), in which no interference effect was found. In the former studies, search items were randomly arranged in three of four quadrants on the screen, while in the latter studies, search items were arranged in a circular pattern similar to the face of a clock. When the arrangement of the search items is constrained, subjects might be able to develop search strategies and this might lessen the possible interference effects on the visual search task. In contrast, when the arrangement of search items is less constrained, subjects may need to engage more spatial attention in order to find the target. Hence, this might increase the possibility of interference on the visual search task when spatial STM is loaded at the same time.

As the focus of the present study was not on the locus of interference in the dual-task paradigm, it must be noted that these claims must are simply educated conjectures rather than empirically supported assertions. While the general conclusions of the present study are not affected by the difference in the locus of interference between the two experiments, the factors affecting the locus of interference in the dual-task paradigm remain a theoretically interesting area for further research. A systematic investigation into this topic might provide a better understanding of the cognitive processes involved when two or more cognitive components compete for the same set of processing resources. Although the present study was not designed to investigate this question, the finding that the locus of interference might be affected by characteristics associated with the task provides a possible platform from which further research could be launched.

Visual Short-Term Memory or Working Memory?

The memory tasks employed in both Experiments 1 and 2 involved the simple maintenance of visual information without any form of manipulation. According to Mohr and Linden (2005), the maintenance of visual information is distinct from the manipulation of visual information, in that the former does not require engaging resources associated with the central executive (Baddeley, 1986, 1996). Because attention tasks are assumed to engage central executive resources, one should not expect to find any interference in the memory or attention tasks in the present study according to the claims of Mohr and Linden. However, this was not the case as interference effects were observed for both the memory tasks (Experiment 1) and the attention tasks (Experiment 2). The findings in the present study, together with similar findings in previous studies (e.g., Matsukura & Vecera, 2008; Oh & Kim, 2004; Woodman & Luck, 2004), are inconsistent with the claims of Mohr and Linden.

Mohr and Linden (2005) based their claims on the finding that when subjects were asked to perform a random number generation task concurrently with either a visual maintenance task or a visual manipulation task, the random number generation task interfered with the latter but not with the former. The random number generation task was assumed to engage central executive resources, the visual maintenance task was assumed to engage VSTM, and the visual manipulation task was assumed to engage WM. In the random number generation task, subjects were required to generate numbers randomly by vocalizing the numbers. Hence, it was not a visual task by nature and required little or no visual resources. This could account for why an interference effect occurred in the present study and not in Mohr and Linden (2005).

However, the claim that no interference effect was found in Mohr and Linden (2005) because of the non-visual nature of the random number generation task raises more questions than answers. In the WM model proposed by Baddeley (1986; 1996) and adopted in both the present study and Mohr and Linden, it is assumed that the central executive is not involved in information maintenance, but rather it is involved in processes such as executive control, selection of task relevant information and the activation of long-term memory. The slave systems (i.e., visuo-spatial sketchpad, phonological loop) are responsible for the maintenance of information. Hence, the fact that the attention task interfered with the memory task in Experiment 1 and that the reverse occurred in Experiment 2, suggests that the simple maintenance of visual information requires central executive resources. This is at odds with the WM model proposed by Baddeley.

One possibility for this apparent inconsistency is that most of the tasks used to investigate the central executive or the visuo-spatial sketchpad (see Baddeley, 1986; Logie, 1995, for reviews), including the random number generation task used by Mohr and Linden (2005), are not tasks that emphasize attentional selection of task relevant information (Baddeley, 1996). Instead, most of the tasks employed to investigate the central executive involve attentional control, in which subjects are required to switch between several tasks, or the online manipulation of visual information, in which subjects are required to transform or recode the information in STM (Baddeley, 1996). It may be that attentional selection and the maintenance of visual information in STM engage similar processing resources in the central executive and that these are different from the resources required for attentional control or the online manipulation of visual information. Thus, the claim that the maintenance of visual information in VSTM does not engage central executive processing resources (Mohr and Linden, 2005) might be inaccurate.

Two possibilities can account for both the findings of Mohr and Linden (2005) and the present study. The first possibility is that the central executive resources engaged by maintaining visual information in VSTM could be specific for visual stimuli. Hence, the random number generation task, a non-visual task, is unlikely to compete for the same set of central executive resources and would not lead to interference. However, it must be noted that this account implies that the central executive is sensitive to stimulus modality, which is at odds with Baddeley's (1986) model of WM. The second possibility is that maintaining visual information in VSTM engages minimal central executive resources rather than no central executive resources. If an attention task emphasizing selection required more central executive resources than the random number generation task, which emphasizes control, then the difference is accounted for. The non-interference in Mohr and Linden and the interference in the present study are due to the amount of central executive resources required by the attention task, suggesting that the engagement of central executive resources is not an all-or-none process.

Although the present study was not specifically designed to investigate the central executive in the Baddeley (1986, 1996) WM model, the findings in the present study raise several interesting questions about the interaction of the central executive with the visuo-spatial sketchpad. One conclusion that could be drawn from the present study is that the separation between the central executive and the slave systems might not be as distinct and as clear as Baddeley has claimed.

Conclusions

The present study investigated the relationship between the different types of visual attention and VSTM. Limited empirical support was provided for the claims that: (a) spatial attention and spatial STM engage similar processing resources, (b) object-based attention and object STM engage similar processing resources, and (c) these two sets of processing resources are dissociable from each other. While the results from Experiment 1 provided support for the above claims, the results from Experiment 2 suggested that the results in Experiment 1 that provided support for the above claims might be due to a task artifact in that the object attention task in Experiment 1 may have required object STM. However, as a portion of results in Experiment 2 was ambiguous and open to at least two different interpretations, two further experiments for future research were proposed.

Although the results in Experiment 2 did not allow a clear interpretation, the mixed nature of the findings highlights the fact that the relationship between visual attention and visual STM is complex. Highlighting of the complexity is an important contribution. The extant claim in the literature that object-based attention and object STM engage similar processing resources was established with limited empirical support (Matsukura & Vecera, 2008; Tan, 2008). Although this claim was further substantiated in Experiment 1 by the pattern of differences across the memory tasks produced by the Duncan object task with separated stimuli (e.g., Vecera & Farah, 1994) and by differences in the Egly et al. (1994) object task produced by the color memory task in Experiment 2, the results from the location and double memory task conditions in Experiment 2 suggest that the claim that the set of processing resources engaged by object-based attention and object STM is dissociable from the set of processing resources engaged by spatial attention and spatial STM may not be accurate. Although the nature of the overlap may not be clear, identification that there may be overlap contributes further to the understanding of the interaction between visual attention and VSTM.

Based on the findings in the present study and also previous studies (see the earlier sections entitled 'Dissociable Sets of Processing Resources?' and 'Modulation of Spatial Attention Within an Object'), one could reject the model shown in Figure 1 (page 28) depicting the relationship between visual attention and VSTM. A more plausible model, given the current results, depicting the relationship between visual attention and VSTM is shown in Figure 18. In this model, the two sets of processing resources are dissociable when the different types of VSTM (i.e., object STM and spatial STM) are engaged. However, when both object-based attention and spatial attention are engaged, the model shows that they engage similar processing resources, at least under certain circumstances (e.g., in the Egly et al. object task). However, it must be noted that this model is highly speculative and more research is required to further test this model.

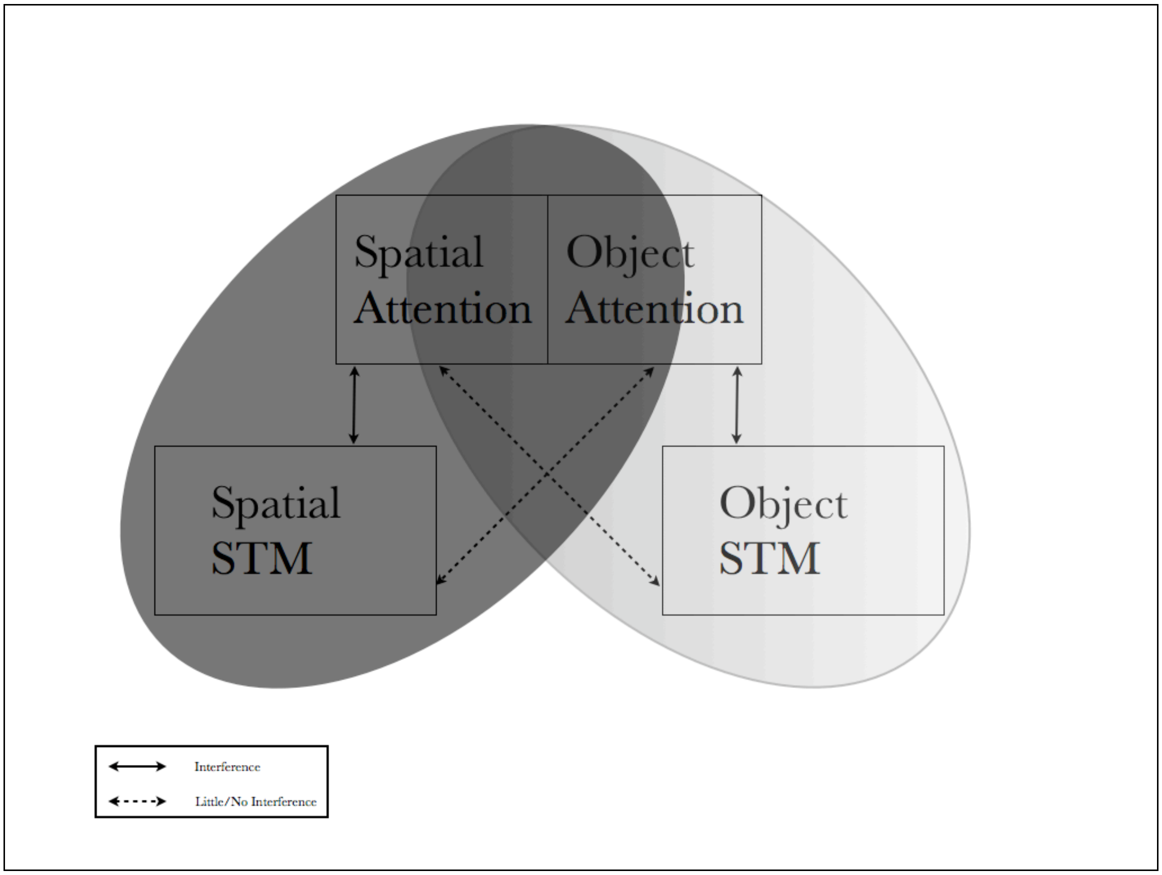

Figure 18. Revised proposed relationship between visual attention and VSTM based on the findings in the present study. It is proposed that while spatial STM and object STM are dissociable from each other, there is probably some overlap in the processing resources engaged by spatial attention and object-based attention.

The present study raises several other interesting questions. For example, the results of the present study suggest that the locus of interference in a dual-task paradigm is due to factors such as the speeded nature of the task and how stimuli are presented. This might be an area for further research because it could be informative about circumstances under which different cognitive components compete for similar processing resources. This knowledge would be particularly useful in an applied setting where the operator needs to select task relevant information over task irrelevant information for further processing while maintaining visual information at the same time.

Another theoretical question raised by the present study is whether VSTM engages the central executive. The findings in the present study, together with those of Matsukura and Vecera (2008), Oh and Kim (2004) and Woodman and Luck (2004), suggest that maintaining visual information in VSTM requires central executive resources. The findings also suggest that the separation between the central executive and the visuo-spatial sketchpad in the Baddeley (1986) WM model might not be as distinct and clear as previously claimed, although further research would be required to establish this claim.

In conclusion, the findings in the present study provide a further understanding of the workings of both visual attention and VSTM. While issues to be resolved still remain, such as investigating the difference in the interference effect of spatial STM on spatial attentional shifts within an object and spatial attentional shifts not within an object, the findings in the present study contribute significantly to the literature on visual attention and VSTM.

APPENDIX A: COMPLETE REPORT OF STATISTICAL TESTS

Table A. Statistical Tests of Visual Search Task (Mean Accuracy)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 29)*	0.453	0.5
	Set Size	*(1, 29)*	2.22	0.14
	Target	*(1, 29)*	12.08	0.002
	Task x Set Size	*(1, 29)*	0.326	0.57
	Task x Target	*(1, 29)*	0.925	0.34
	Set Size x Target	*(1, 29)*	2.75	0.1
	Task x Set Size x Target	*(1, 29)*	1.04	0.31
Location	Task	*(1, 29)*	0.138	0.71
	Set Size	*(1, 29)*	0.892	0.35
	Target	*(1, 29)*	9.98	0.004
	Task x Set Size	*(1, 29)*	0.105	0.74
	Task x Target	*(1, 29)*	0.708	0.4
	Set Size x Target	*(1, 29)*	1.89	0.18
	Task x Set Size x Target	*(1, 29)*	1.75	0.19
Double	Task	*(1, 29)*	0.38	0.54
	Set Size	*(1, 29)*	14.76	0.001
	Target	*(1, 29)*	10.61	0.003
	Task x Set Size	*(1, 29)*	0.416	0.52
	Task x Target	*(1, 29)*	0.528	0.47
	Set Size x Target	*(1, 29)*	2.27	0.14
	Task x Set Size x Target	*(1, 29)*	0.042	0.83

Table B. Statistical Tests of Visual Search Task (RT)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 29)*	1.46	0.23
	Set Size	*(1, 29)*	185.64	0.001
	Target	*(1, 29)*	114.03	0.001
	Task x Set Size	*(1, 29)*	0.378	0.54
	Task x Target	*(1, 29)*	0.74	0.39
	Set Size x Target	*(1, 29)*	73.67	0.001
	Task x Set Size x Target	*(1, 29)*	0.622	0.43
Location	Task	*(1, 29)*	8.31	0.007
	Set Size	*(1, 29)*	212.97	0.001
	Target	*(1, 29)*	117.33	0.001
	Task x Set Size	*(1, 29)*	1.02	0.321
	Task x Target	*(1, 29)*	0.602	0.44
	Set Size x Target	*(1, 29)*	72.11	0.001
	Task x Set Size x Target	*(1, 29)*	0.517	0.47
Double	Task	*(1, 29)*	1.95	0.17
	Set Size	*(1, 29)*	203.78	0.001
	Target	*(1, 29)*	91.78	0.001
	Task x Set Size	*(1, 29)*	4.6	0.04
	Task x Target	*(1, 29)*	0.049	0.82
	Set Size x Target	*(1, 29)*	106.36	0.001
	Task x Set Size x Target	*(1, 29)*	0.261	0.61

Table C. Statistical Tests of Duncan Object Task, Overlap (Mean Accuracy)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 29)*	34.09	0.001
	Object	*(1, 29)*	29.47	0.001
	Report	*(1, 29)*	0.402	0.53
	Task x Object	*(1, 29)*	0.005	0.94
	Task x Report	*(1, 29)*	0.166	0.68
	Object x Report	*(1, 29)*	3.56	0.07
	Task x Object x Report	*(1, 29)*	0.135	0.71
Location	Task	*(1, 29)*	27.92	0.001
	Object	*(1, 29)*	22.24	0.001
	Report	*(1, 29)*	0.45	0.51
	Task x Object	*(1, 29)*	0.671	0.41
	Task x Report	*(1, 29)*	0.944	0.33
	Object x Report	*(1, 29)*	0.632	0.43
	Task x Object x Report	*(1, 29)*	0.536	0.47
Double	Task	*(1, 29)*	43.5	0.001
	Object	*(1, 29)*	25.4	0.001
	Report	*(1, 29)*	0.581	0.45
	Task x Object	*(1, 29)*	0.05	0.82
	Task x Report	*(1, 29)*	0.083	0.77
	Object x Report	*(1, 29)*	0.645	0.42
	Task x Object x Report	*(1, 29)*	0.161	0.69

Table D. Statistical Tests of Duncan Object Task, Separate (Mean Accuracy)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 29)*	58.87	0.001
	Object	*(1, 29)*	67.44	0.001
	Report	*(1, 29)*	0.038	0.84
	Task x Object	*(1, 29)*	0.066	0.79
	Task x Report	*(1, 29)*	1.002	0.32
	Object x Report	*(1, 29)*	4.53	0.04
	Task x Object x Report	*(1, 29)*	0.003	0.95
Location	Task	*(1, 29)*	33.55	0.001
	Object	*(1, 29)*	68.39	0.001
	Report	*(1, 29)*	0.228	0.63
	Task x Object	*(1, 29)*	0.375	0.54
	Task x Report	*(1, 29)*	0.043	0.83
	Object x Report	*(1, 29)*	0.006	0.93
	Task x Object x Report	*(1, 29)*	0.606	0.44
Double	Task	*(1, 29)*	45.17	0.001
	Object	*(1, 29)*	195.35	0.001
	Report	*(1, 29)*	1.12	0.29
	Task x Object	*(1, 29)*	0.795	0.38
	Task x Report	*(1, 29)*	6.56	0.016
	Object x Report	*(1, 29)*	9.41	0.005
	Task x Object x Report	*(1, 29)*	4.03	0.054

Table E. Statistical Tests of Egly et al. Object Task (Mean Accuracy)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 47)*	0.062	0.8
	Cue	*(2. 94)*	13.13	0.001
	Task x Cue	*(2. 94)*	1.21	0.3
Location	Task	*(1, 47)*	4.36	0.042
	Cue	*(2. 94)*	7.97	0.001
	Task x Cue	*(2. 94)*	0.25	0.77
Double	Task	*(1, 47)*	5.44	0.024
	Cue	*(2. 94)*	9.14	0.001
	Task x Cue	*(2. 94)*	0.97	0.38

Table F. Statistical Tests of Egly et al. Object Task (RT)

Memory Type	Effect	df	F ratio	p value
Color	Task	*(1, 47)*	15.36	0.001
	Cue	*(2. 94)*	102.7	0.001
	Task x Cue	*(2. 94)*	3.55	0.033
Location	Task	*(1, 47)*	47.45	0.001
	Cue	*(2. 94)*	130.31	0.001
	Task x Cue	*(2. 94)*	3.06	0.052
Double	Task	*(1, 47)*	27.75	0.001
	Cue	*(2. 94)*	101.57	0.001
	Task x Cue	*(2. 94)*	10.44	0.001

APPENDIX B: COMPLETE REPORT OF TASK PERFORMANCE IN EXPERIMENTS 1 AND 2

Table A. Mean Accuracy in Visual Search Task[a]

	Baseline			
	Set 4		Set 12	
	Present	Absent	Present	Absent
Color	0.95 (0.06)	0.96 (0.07)	0.92 (0.09)	0.06 (0.09)
Location	0.96 (0.06)	0.97 (0.07)	0.94 (0.12)	0.98 (0.05)
Double	0.95 (0.07)	0.98 (0.05)	0.91 (0.10)	0.96 (0.05)

	Dual Task			
	Set 4		Set 12	
	Present	Absent	Present	Absent
Color	0.95 (0.08)	0.98 (0.05)	0.93 (0.09)	0.98 (0.04)
Location	0.95 (0.09)	0.98 (0.03)	0.93 (0.12)	0.97 (0.05)
Double	0.97 (0.06)	0.98 (0.03)	0.92 (0.10)	0.96 (0.09)

a. standard deviation denoted in parenthesis

Table B. Mean RT in Visual Search Task[a]

	Baseline			
	Set 4		Set 12	
	Present	Absent	Present	Absent
Color	1036 (323)	1315 (372)	1410 (330)	2211 (574)
Location	1070 (230)	1295 (296)	1507 (323)	2319 (595)
Double	1061 (226)	1243 (247)	1476 (359)	2238 (595)

	Dual Task			
	Set 4		Set 12	
	Present	Absent	Present	Absent
Color	1068 (262)	1349 (328)	1439 (290)	2297 (585)
Location	1211 (287)	1443 (381)	1578 (302)	2445 (540)
Double	1189 (216)	1359 (268)	1495 (372)	2285 (568)

a. standard deviation denoted in parenthesis

Table C. Mean Accuracy in Memory Task in the Visual Search Task Combinations[a]

	Color	Location	Double	
			Color	Location
Baseline	0.94 (0.06)	0.92 (0.06)	0.93 (0.10)	0.91 (0.09)
Dual: Set 4	0.88 (0.09)	0.88 (0.08)	0.89 (0.11)	0.88 (0.09)
Dual: Set 12	0.88 (0.09)	0.82 (0.11)	0.88 (0.08)	0.80 (0.13)

a. standard deviation denoted in parenthesis

Table D. Mean Accuracy For Duncan Object Task (Overlap)[a]

	Baseline	
	Same Object	Different Object
Color	0.91 (0.07)	0.87 (0.09)
Location	0.91 (0.09)	0.87 (0.11)
Double	0.93 (0.09)	0.90 (0.09)

	Dual Task	
	Same Object	Different Object
Color	0.85 (0.11)	0.82 (0.11)
Location	0.84 (0.11)	0.81 (0.13)
Double	0.87 (0.10)	0.83 (0.11)

a. standard deviation denoted in parenthesis

Table E. Mean Accuracy in Memory Task in the Duncan Object Task (Overlap) Combinations[a]

	Color	Location
Baseline	0.89 (0.07)	0.85 (0.11)
Dual: Same	0.81 (0.08)	0.78 (0.09)
Dual: Different	0.76 (0.11)	0.77 (0.10)

	Double	
	Color	Location
Baseline	0.90 (0.14)	0.90 (0.09)
Dual: Same	0.82 (0.11)	0.80 (0.09)
Dual: Different	0.74 (0.12)	0.80 (0.10)

a. standard deviation denoted in parenthesis

Table F. Mean Accuracy For Duncan Object Task (Separate)[a]

	Baseline		Dual Task	
	Same Object	Different Object	Same Object	Different Object
Color	0.92 (0.09)	0.83 (0.10)	0.85 (0.10)	0.76 (0.11)
Location	0.90 (0.09)	0.82 (0.08)	0.84 (0.11)	0.75 (0.11)
Double	0.92 (0.09)	0.82 (0.11)	0.88 (0.11)	0.77 (0.11)

a. standard deviation denoted in parenthesis

Table G. Mean Accuracy in Memory Task in the Duncan Object Task (Separate) Combinations[a]

	Color	Location
Baseline	0.90 (0.09)	0.88 (0.11)
Dual: Same	0.83 (0.11)	0.79 (0.08)
Dual: Different	0.78 (0.11)	0.74 (0.11)

	Double	
	Color	Location
Baseline	0.87 (0.12)	0.86 (0.14)
Dual: Same	0.77 (0.13)	0.75 (0.13)
Dual: Different	0.69 (0.13)	0.69 (0.16)

a. standard deviation denoted in parenthesis

Table H. Mean Accuracy of Egly Object Task[a]

	Baseline			Dual Task		
	Valid	Invalid (Same)	Invalid (Diff)	Valid	Invalid (Same)	Invalid (Diff)
Color	0.93 (0.08)	0.89 (0.09)	0.89 (0.09)	0.92 (0.06)	0.90 (0.09)	0.89 (0.09)
Location	0.89 (0.09)	0.86 (0.11)	0.86 (0.11)	0.91 (0.07)	0.88 (0.11)	0.89 (0.08)
Double	0.90 (0.06)	0.87 (0.09)	0.88 (0.08)	0.93 (0.05)	0.90 (0.08)	0.89 (0.06)

a. standard deviation denoted in parenthesis

Table I. Mean RT of Egly Object Task[a]

	Baseline			Dual Task		
	Valid	Invalid (Same)	Invalid (Diff)	Valid	Invalid (Same)	Invalid (Diff)
Color	642 (162)	714 (153)	739 (170)	901 (144)	778 (146)	828 (162)
Location	709 (139)	784 (143)	808 (145)	823 (163)	897 (186)	949 (197)
Double	682 (138)	761 (142)	779 (148)	782 (164)	860 (155)	928 (199)

a. standard deviation denoted in parenthesis

Table J. Mean Attention Shifting Cost of Egly Object Task[a]

	Baseline		Dual Task	
	Same Obj	Different Obj	Same Obj	Different Obj
Color	72 (79)	97 (87)	77 (58)	127 (62)
Location	74 (60)	99 (55)	74 (75)	126 (81)
Double	78 (73)	97 (78)	77 (69)	145 (86)

a. standard deviation denoted in parenthesis

Table K. Mean Accuracy of Memory Task in the Egly Object Task Combinations[a]

	Color	Location	Double	
			Color	Location
Baseline	0.89 (0.08)	0.91 (0.08)	0.83 (0.13)	0.86 (0.13)
Dual: Valid	0.80 (0.09)	0.83 (0.09)	0.78 (0.12)	0.81 (0.15)
Dual: Invalid Same	0.79 (0.13)	0.81 (0.13)	0.78 (0.14)	0.80 (0.16)
Dual Invalid Diff	0.82 (0.10)	0.81 (0.12)	0.78 (0.12)	0.78 (0.17)

a. standard deviation denoted in parenthesis

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