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Chapter 1

The Relationship between Attention and Working Memory

Daryl Fougnie
Vanderbilt University

Abstract

The ability to selectively process information (attention) and to retain information in an accessible state (working memory) are critical aspects of our cognitive capacities. While there has been much work devoted to understanding attention and working memory, the nature of the relationship between these constructs is not well understood. Indeed, while neither attention nor working memory represent a uniform set of processes, theories of their relationship tend to focus on only some aspects. This review of the literature examines the role of perceptual and central attention in the encoding, maintenance, and manipulation of information in working memory. While attention and working memory were found to interact closely during encoding and manipulation, the evidence suggests a limited role of attention in the maintenance of information. Additionally, only central attention was found to be necessary for manipulating information in working memory. This suggests that theories should consider the multifaceted nature of attention and working memory. The review concludes with a model describing how attention and working memory interact.

I. Introduction

The capacity to perform some complex tasks depends critically on the ability to retain task-relevant information in an accessible state over time (working memory) and to selectively process information in the environment (attention). As one example, consider driving a car in an unfamiliar city. In order to get to your destination, directions have to be retained and kept in working memory. In addition, one must be able to selectively attend to the relevant objects because there is more information in a scene than can be processed by our perceptual systems. In fact, the contents of working memory and attention often overlap. If the directions stored in WM instruct you to turn left after the yellow water tower, then attention may be guided towards objects that resemble a yellow water tower.

Although the contents of WM and attention are often the same, the exact relationship between these two constructs is not fully understood. Empirical work has largely focused on separate aspects of their relationship, asking questions such as: 1) is attending to something necessary to encode it into WM? 2) do the contents of WM automatically guide attention? 3) can an attention demanding task and a WM task be performed in parallel? 4) does our capacity for WM predict performance on attention tasks? By themselves, these questions can provide insight into our complex cognitive machinery, however, unless effort is expended to integrate the answers into a coherent framework, a general understanding of the connection between attention and WM will remain elusive.

Theoretical models of WM often describe a role for attention. However, across these models there is not much agreement on the role of attention. Some theorists argue that attention selects the information to be encoded into WM while others speak of attention in terms of post-perceptual processing limitations (Kintsch, Healy, Hegarty, Pennington, and Salthouse 1999; Miyake and Shah, 1999). While theoretical work on the relationship between attention and WM has generally assumed that both constructs denote a uniform set of processes, there is strong evidence implicating non-unitary attention and WM systems (Posner and Peterson, 1990; Smith and Jonides, 1999). Miyake and Shah (1999) have suggested that an understanding of the role of attention in WM might require a systematic mapping of the relationships between different aspects of WM and those of attention. Indeed, Awh and colleagues have suggested that the interaction of attention and WM depends on what stage of attention is engaged and what type of information is being maintained in WM (Awh, Vogel, and Oh, 2006). In this review of the existing literature, I will attempt a thorough review of the relationship amongst distinct processing stages in WM and distinct forms of attention. I begin by describing how the terms attention and WM are defined here.

Attention refers to the processing or selection of some information at the expense of other information (Pashler, 1998). It has been debated at which processing stage attentional selection occurs. There is evidence that attention can affect early perceptual processing (Cherry, 1953; Mangun and Hillyard, 1991) as well as evidence that attention affects only later processing stages (Osman and Moore, 1993). The strong support for both early and late selection has led to the proposal that there may be more than one form of attentional selection (Allport, 1993; Lavie, Hirst, de Fockert, and Viding, 2004, Luck and Vecera, 2002; Posner and Peterson, 1990). One detailed and influential taxonomy of attention has been developed by Posner and colleagues (Fan, McCandliss, Sommer, Raz, and Posner, 2002; Fan, McCandliss, Fossella, Flombaum, and Posner, 2005; Posner and Boies, 1971; Posner and Peterson, 1990). According to recent conceptions of this taxonomy, there are three attention networks that perform distinct roles: alerting, orienting, and executive attention. The alerting network controls the general state of responsiveness to sensory stimulation. The orienting network selects a subset of sensory information for privileged processing. Several mechanisms have been proposed to account for the beneficial effects of attentional orienting including neural boosting (Luck, Hillyard, Mouloua, and Hawkins, 1996; Mangun and Hillyard, 1991), distractor suppression (Reynolds, Pasternak, and Desimone, 2000; Slotnick, Schwarzbach, and Yantis, 2003), and noise reduction (Dosher and Lu, 2000). The executive attention network acts on post-sensory representations, and is needed when there is competition for access to a central, limited-capacity system. Paradigms that reveal the role of central attention include flanker tasks (Eriksen and Eriksen, 1974) and stroop tasks (Macleod, 1991; Stroop, 1935), and speeded dual-task performance.

The separate contributions of the three attention networks can be illustrated by a comparison within a single hypothetical task. Suppose a participant is asked to name the color of a word presented on a computer display. Immediately preceding word presentation, a brief flash cues the target location, a non-target location, or all possible locations. The alerting network is responsible for the shift in arousal that occurs when a cue indicates an upcoming target. The orienting network is responsible for the improved performance when the cue indicates the target location. The ability to select among activated representations is mediated by executive attention. For example, suppose on some trials that the word spelled by the text conflicts with the color of the text. Participants will be slower to respond because both the color and word representations are activated (Stroop, 1935).

Several theorists have made claims of a non-unitary attention system by distinguishing between perceptual and central attention (Johnston, McCann, Remington, 1995; Luck and Vecera, 2002; Pashler 1989, 1991, 1993; Vogel, Woodman, and Luck, 2005). Here, these two terms respectively map on to orienting and executive attention. Perceptual attention or orienting refers to the selection of a subset of sensory information. Central or executive attention share in depicting a central, amodal processing capacity shared broadly in post-perceptual cognition.

WM is often defined as the mental workspace where important information is kept in a highly active state, available for a variety of other cognitive processes (Baddeley and Hitch, 1974). It includes the processes that encode, store, and manipulate this information. WM is distinguishable from two other forms of memory storage, iconic memory and long-term memory (LTM). Iconic memory is a short-lived sensory trace of unlimited capacity lasting around 300ms (Averbach and Coriell, 1961; Sperling, 1960). In contrast, WM is a capacity-limited store that is less transient and more durable than iconic memory (Phillips, 1974). While WM is a temporary store lasting on the order of seconds, information that is stored in LTM may last a lifetime. Many theorists view WM as the subset of knowledge in LTM that is currently activated (Cowan, 1995; Oberauer, 2002; but see Baddeley and Logie, 1999).

Working memory, like attention, is a complex and multifaceted construct. It has been suggested that there are independent stores for verbal, spatial, and visual information (Baddeley and Logie, 1999). Strong evidence has also accrued that the processes involved in the storage of items in WM are separable from the processes that manipulate or update the contents of WM (Cornoldi, Rigoni, Venneri, and Vecchi, 2000; D'Esposito, Postle, Ballard, and Lease, 1999; D'Esposito, Postle, and Rypma, 2000; Kane and Engle, 2002; Postle, Berger, and D'Esposito, 1999; Postle, et al., 2006; Smith and Jonides, 1999). In addition, encoding and storage processes in WM seem to be distinct (Marois, Todd, and Chun, in preparation; Woodman and Vogel, 2005).

The above mentioned definitions explicitly acknowledge the non-unitary nature of WM and attention. The relationship between attention and WM may depend on the type of attention and WM processes involved. In this review, I will discuss how two major types of selective attention, perceptual and central, relate to distinct process in WM: encoding, storage, and manipulation. This review will not discuss the relationship between alerting and WM. I view alerting as an important topic of inquiry but one that is distinct from selective attention. This omission is also necessitated by the lack of knowledge relating WM and alerting. Since orienting in visual space is better understood than other forms of perceptual attention, the discussion of orienting will only focus on the visual domain. Reflecting this focus, the term visuospatial attention (selection in visual space) will be used throughout instead of perceptual attention.

While theories on the relationship between WM and attention (Cowan, 1995; Duncan, 1996; Rensink, 2002), suggest a close connection, even isomorphism, between the two constructs, the available evidence suggests important distinctions. I will propose that attention is only minimally involved in WM maintenance, but it is important for the encoding and manipulation of information in WM. This is not to suggest that the current literature presents a clear picture of the relationship between WM and attention. Instead, this review will suggest that there are still many unanswered fundamental questions. Whenever possible, future lines of research will be suggested to answer outstanding questions.

Just as Aristotle once sought to carve nature at the joints, the method employed here is to carve attention and WM into their basic components to allow a more methodological comparison. For this reason a separate section is devoted to each WM process. Within each section, the interaction between attention and WM processes is discussed separately for central and visuospatial attention. Sections III and IV will focus on the relationship of attention with encoding and storage respectively. Section V will explore the interaction between manipulation/updating the contents of WM and attention. The final section will attempt a synthesis of the previous sections along with a model of attention's role in WM. Before proceeding however, section II will first review the evidence that central and visuospatial attention are distinct forms of attention.

II. Visuospatial and Central Attention

Attention can affect both initial feed-forward processing in early sensory cortex and the later processing stages (in higher-cognitive areas). For instance, electroencephalogram (EEG) studies have demonstrated that knowledge about the location (hemifield) that visual stimuli will appear can affect positive and negative deflections of EEG signals at around 100 ms post-stimulus onset (Mangun and Hillyard, 1991), revealing the effect of 'perceptual attention' at an early sensory processing stage (Boddy, 1972). Attention can also affect EEG signals associated with later central processing stages, such as those involved in the selection and initiation of responses (Osman and Moore, 1993).

Indeed, it has been demonstrated that the processing stage that is modulated by attention depends on the demands imposed by a task (Vogel, et al., 2005). Tasks with large perceptual demands may show attentional modulation of early sensory processing. In contrast, tasks with minimal attentional demands may involve selection of attended information only at late stages of processing. However, while this may demonstrate that attentional selection is sensitive to the nature of task demands, it is not strong evidence for two separate attention systems since both systems may be controlled by the same source. Indeed, neuroimaging studies reveal that a common parietofrontal network is involved in orienting in space, time, or to internal representations (Coull and Nobre, 1998; Nobre, Coull, Vandeberghe, et al., 2004) and that perceptual discriminations activate brain regions that are also involved in response selection (Jiang and Kanwisher, 2003). Strong evidence for distinct visuospatial and central attention networks must demonstrate that a single source is not involved in controlling both forms of attention.

One method of demonstrating distinct attentional networks is to show that visuospatial attention and central attention can simultaneously act on distinct stimuli. Evidence for this comes from a variant of the psychological refractory period (PRP) paradigm that demonstrated that shifts of visuospatial attention could select stimuli in a secondary visual discrimination task during task one central processing (Giesbrecht, Dixon, and Kingstone, 2001; Pashler 1989; 1991). A PRP paradigm involves the presentation of two tasks in close temporal proximity. If central processing for the two tasks overlap, than the response for the second task will be slowed. Increasing the overlap in central processing typically results in an increased PRP effect. One common manipulation is to vary the temporal distance between task one and task two stimulus onset, otherwise known as stimulus onset asynchrony (SOA). PRP effects grow larger as SOA is decreased. In the variant developed by Pashler (1989; 1991), the SOA was varied between a speeded reaction time task (task 1) and a visual identification task (task 2). Responses to the identification task were not speeded, but a mask would appear shortly after task two array presentation to disrupt processing. If visuospatial attention shifts require central processing, then shorter SOAs should result in worse performance because visuospatial attention may not have shifted to the target before mask presentation. Instead, Pashler found that the SOA manipulation had very little effect on accuracy for the visual task under most conditions. Pashler concluded that visual attention is immune to the central bottleneck and represents a distinct form of attention (Pashler, 1989; 1991; 1994).

Important distinctions between visuospatial and central attention are also suggested by PRP experiments that use a locus of slack logic. Based on the premise of successive processing stages (Sternberg, 1969), locus of slack logic allows the experimenter to assess whether a specific processing stage occurs before, during, or after central processing. The procedure involves manipulating task two difficulty and observing the effect on task two RT at short and long SOAs. If the manipulation alters a processing stage that occurs before central attention then the effect of difficulty will be underadditive, i.e. the manipulation will affect performance less at shorter SOAs. This occurs because the additional processing required by the difficulty manipulation can be performed during task one central processing—it is absorbed in the slack. Additivity occurs when the effect of difficulty is independent of SOA and overadditivity occurs when the more difficult task results in worse performance at short SOAs. Additivity implies that the processing stage affected by the difficulty manipulation occurs after central processing. Overadditivity implies that the difficulty manipulation increased the demands on central attention.

Evidence from these procedures reveal that visuospatial and central attention operate at different temporal processing stages. Johnston and colleagues (Johnston, McCann, and Remington, 1995) found a task manipulation (increasing stimulus similarity) that affected a stage after visuospatial attention but before central attention. In one experiment, stimulus similarity was manipulated in a spatial cuing task (Posner, 1980). Increasing stimulus similarity made the task more difficult, but this effect did not interact with cue validity, suggesting that the effect of this manipulation occurred at a stage of processing after visuospatial attention. In a subsequent experiment, manipulating stimulus similarity revealed underadditive effects with SOA in a PRP task suggesting that increased stimulus similarity taxes processing stages prior to the engagement of central processing. These studies demonstrate that visuospatial and central attention operate at separate temporal stages, a conclusion that dovetails with the supposition that the two types of attention can be allocated to distinct events.

In contrast, Jolicoeur and colleagues have argued that central processing interferes with visuospatial attention based on work demonstrating that target detection reduces the N2pc (Dell'Acqua, Sessa, Jolicoeur, and Robitaille, 2006; Jolicoeur, Sessa, Dell'Acqua, and Robitaille, 2005). The N2pc is lateralized electrophysiological response characterized by greater negativity occurring 200ms post-stimulus for attended stimuli, and is therefore useful as an indicator of visuospatial attention (Woodman and Luck, 2003). To measure whether the N2pc was reduced after target detection, Jolicoeur and colleagues utilized the attentional blink (AB). The AB procedure involves detecting targets embedded within a rapid serial visual presentation (RSVP) stream. Even when items are presented at a rate of ten per second, participants are very good at detecting a target and encoding it for later report. However, when two targets have to be reported, there is a large detriment in the detection of the second target (T2) if it occurs within 200-500 ms of the first target (T1)—a deficit known as an AB (Raymond, Shapiro, Arnell, 1992). Theories of the AB often suggest that failures of T2 consolidation occur because central processing is engaged by T1 (Chun and Potter, 1995; Jolicoeur and Dell'Acqua, 1998). Jolicoeur et al. (2005) used a modified AB procedure in which T1 was presented at fixation but T2 was lateralized either to the left or the right of the display. When T1 had to be reported and was in close temporal proximity to T2, detection of T2 was low. This impaired detection corresponded with a reduced N2pc magnitude, which led Jolicoeur and colleagues to suggest that visuospatial attention and central processing are not independent attentional resources.

One may question whether the observed N2pc suppression truly reflects effects on visuospatial attention because the use of the N2pc as a gauge of visuospatial attention makes the assumption that detection of T2 will not affect the N2pc. A recent EEG study using an AB task with all stimuli at fixation found that the activity for detected T2s diverged (increased negative deflection) at 276 ms from the activity for undetected targets (Sergent, Baillet, and Dehaene, 2005), suggesting that the detection of T2 alone can modulate evoked potentials within the time window used by Jolicoeur et al. to quantify the N2pc (200-300ms). Additionally, other research argues that visuospatial attention can shift during the AB (Peterson and Juola, 2000).

To summarize, I suggest that most of the evidence supports the idea that visuospatial attention and central attention are distinct forms of attention. The only evidence for a strong link between the two forms of attentional selection comes from experiments that measure the strength of the N2PC during the AB (Dell'Acqua, et al., 2006; Jolicoeur, et al., 2005). However, those studies are difficult to interpret because it remains unclear whether EEG signals occurring 200-300ms post-stimulus are unaffected by target detection in the AB. Future research is required to establish the role of the N2pc in the AB, and to clarify whether attention can shift during target consolidation. In the following sections, I will discuss the role that visuospatial and central attention perform in WM encoding, storage, and manipulation.

III. WM Encoding

1. Visuospatial Attention

The issues relevant to a review on attention and WM depend largely on the existing theoretical positions advanced in the literature. For example, many researchers believe that an item must first be attended before it can be encoded into WM (e.g. Mack and Rock, 1998). A review of visuospatial attention and WM would be incomplete unless it discussed the evidence for this belief. Some questions cut across sections, such as the presence or absence of dual-task interference between attention and WM. While the topics may shift across sections, the underlying theme is unchanging. All evidence bearing on the independence or codependence of attention and WM will be discussed. This section will focus on three questions: 1) can visuospatial attention shift while information is being encoded into WM, 2) is selective encoding of a visual array mediated by visuospatial attention, and 3) is visuospatial attention necessary and sufficient for encoding into WM.

The pioneering work of Sperling (1960) and Averbach and Coriell (1961), using the partial report procedure, demonstrated that it was possible to selectively encode a portion of a visual display as long as the cue indicating the relevant items was presented while an iconic representation of the to-be-encoded stimuli persisted. Top-down control over the contents of WM is considered by some to be a paradigmatic example of attentional selection. However, the partial report procedure demonstrates the possibility of selective encoding but does not specify what is doing the selecting. It is often assumed that selective encoding in partial report is mediated by visuospatial attention (e.g. Pashler, 1991), but the evidence for this is rarely reviewed. Comparisons of various experiments suggest that partial report cues are only effective if they segregate targets via distinct perceptual features. Features that lead to successful target guidance within the partial report procedure include: location, color, shape, size, or brightness (Averbach and Coriell, 1961; Banks and Barber, 1977; Sperling, 1960; Turvey and Kravetz, 1970; von Wright, 1968, 1970), but do not include selection by alphanumeric category (Sperling, 1960; von Wright, 1970). Similarly, filtering studies (i.e. tasks that involve attending to some information and ignoring other information) find that selective attention is easier when target identity is defined by basic physical attributes than by content (Treisman, 1964).

A recent paper (Vogel et al., 2005), argues that visuospatial attention is *only* involved in the partial report procedure if the cue appears before the target display. If the cue occurs after or simultaneously with the target display, visuospatial attention may not have time to switch before perceptual processing has terminated. The authors cited EEG evidence indicating that, while both pre-cue and simultaneous cue conditions yield improved accuracy for validly cued trials, only the pre-cue condition revealed an effect of validity on the N400 waveform (a negative electrophysiological response that is sensitive to semantic mismatch; Kutas and Hillyard, 1980). On the assumption that the N400 is an indicator of the perceptual quality of a stimulus (the N400 is reduced by adding noise to a stimulus; Vogel, Luck, and Shapiro, 1998), these results reveal an influence of visuospatial attention only in the pre-cue condition. However, this may not generalize beyond the specific methodology employed, especially since target stimuli were only presented for 100ms before masked. Instead, this finding may reflect the rather unsurprising conclusion that visuospatial attention cannot effect perceptual processing after perceptual processing has terminated. The dissociation of validity effects between accuracy and the N400 in the post-cue condition suggests a potential role of post-perceptual selection in partial report.

Another study suggests that non-predictive, salient cues improve partial report performance for the cued item (Schmidt, Vogel, Woodman, and Luck, 2002). This effect was also replicated for sudden-onset items, i.e. stimuli that were perceived as new objects. Analogously, non-predictive cues and sudden-onsets are known to capture visuospatial attention (Hopfinger and Mangun, 1998; Müller and Rabbitt, 1989). The report benefit for cued or onset items seems likely to be due to the capture of visuospatial attention. This apparent conflict with the Vogel et al. (2005) study (sudden onsets are akin to simultaneous probes) could be tested by determining whether sudden onsets modulate the N400 in a partial report procedure.

The initiation of eye movements (saccades) may also affect encoding in the partial report procedure (Irwin and Gordon, 1998). Irwin and Gordon instructed participants to attend to one side of a partial report display. Once the letters disappeared, participants had to make a saccade to either the left or the right side of the display. Of interest is whether participants could attend to one side of the display while making a saccade to the other side of the display. Letters proximate to the saccade end point showed a performance benefit as high as the benefit for items on the attended side. The results show that visuospatial attention was modified by saccade direction. This is consistent with work showing that saccades are preceded by visuospatial attention (Hoffman and Subramaniam, 1995; McConkie and Rayner, 1976; Peterson, Kramer, and Irwin, 2004). Irwin and Gordon argued that, prior to letter offset, visuospatial attention shifted to the planned saccade endpoint and thus improved the detection of nearby letters.

The existing literature substantiates the hypothesis that selective encoding within the partial probe procedure is influenced by visuospatial attention. This is consistent with work on change detection (explicit search for change) and inattentional blindness (implicit detection of change), which suggest that attention acts as a gateway for WM encoding. Experiments using these paradigms reveal that drastic changes to scenes often go undetected if the motion signal accompanying a change is disrupted (Rensink, O'Regan, and Clark, 1997). This blindness to important details has led many to conclude that we do not store a coherent and detailed visual representation of the world (Noë, Pessoa, and Thompson, 2000; O'Regan, 1992; Rensink, 2002; Simons and Levin, 1997). We have the impression that we perceive a veridical visual world because, under normal viewing conditions, attention is drawn to the location of a change by a low-level motion signal (Rensink, 2002). Our poor ability to detect changes in the absence of attention has lead to the suggestion that attention is necessary, but not sufficient, for detection/encoding (Mack and Rock, 1998; Rensink, 2002; Simons, 2000; Wolfe, 1999).

The necessity of attention for WM encoding is suggested by work showing that attention influences the likelihood of detection in change detection tasks (Irwin and Zelinsky, 2002; Hollingworth, 2004; Rensink et al., 1997; Scholl, 2000; Wolfe, Reinecke, and Brawn, 2006). Scholl (2000) manipulated the salience or onset of an item within an array, thereby drawing visuospatial attention to the item's location. Even though changes were equally likely to occur for any object, changes were more frequently detected for salient or late-onset items.

Attention has been manipulated in a variety of other ways: comparing performance between locations of central or marginal interest, instructing participants to attend to a dot as it moves around a display, having participants respond to the identity of cued items, or having participants make saccades to locations in a display. The basic finding is that changes to attended items are detected more frequently than unattended items. The attentional benefit seems to remain for the last 2-4 items attended, perhaps indicating that attending to an item means that it is encoded into a limited capacity store. However, these results don't imply that attention is *necessary* for encoding into WM. The benefit of attended over unattended items may simply be a product of the processing benefit afforded to attended items. In fact, some evidence does suggest that encoding can occur outside the focus of attention. Unattended items in a change detection task may still show above chance performance (e.g. Irwin and Zelinsky, 2002). The same is true in inattentional blindness studies where attention is diverted by another task. Some participants may fail to detect the appearance of an unexpected stimulus, but often half of them succeed (Mack and Rock, 1998). These examples do not provide strong evidence for encoding outside of attention. Distracting tasks in inattentional blindness studies may not be sufficiently demanding to prevent attentional capture by unexpected items. In addition, having participants attend to various regions in a change detection display may allow attention to slip to unattended regions on occasion (see Lachter, Forster, and Ruthruff, 2004, for similar explanations to account for late attentional selection). Future work will be needed to determine whether the occasional ability to detect changes in unattended stimuli represents true encoding without attention.

The main evidence that attention is not sufficient for the detection of change comes from inattentional blindness paradigms where the main object of interest undergoes change (Levin and Simons, 1997, 2000; Simons and Levin, 1998). For example, participants may not notice the only actor in a motion picture change into a different person across a cut (Levin and Simons, 1997). Another method of ensuring that items in a display have been attended is to have participants report the lowest digit not present in a visual search array. Very few participants detect changes to array items even under these conditions (Becker and Pashler, 2002). These results seem to imply that attending to an object is not sufficient for WM encoding. However, some authors argue that change blindness may not be principally due to a failure of storage, but rather a failure to compare the pre and post-change representation (Angelone, Levin, and Simons, 2003; Mitroff, Simons, and Levin, 2004; Scott-Brown, Baker, and Orbach, 2000; Simons, Chabris, Schnur, and Levin, 2002). Another demonstration of the insufficiency of attention for detection is the failure of participants to reliably notice task-irrelevant items presented near the focus of visuospatial attention (Koivisto, Hyönä, and Revonsuo, 2004; Most, Simons, Scholl, and Chabris, 2000; Newby and Rock, 1998).

Detection of task-irrelevant items is less susceptible to the issue of comparison failures and therefore provides converging evidence that visuospatial attention is not sufficient for encoding. In conclusion, there is evidence that attention is not sufficient for encoding, but the evidence is inconclusive as to whether attention is necessary for encoding.

Evidence bearing on whether visuospatial attention can shift during WM encoding was discussed in the previous section. To recap, while there is some evidence that consolidating items in WM impairs the N2pc (an EEG marker of visuospatial attention), it could not be ruled out that this N2pc suppression was due to a failure of post-perceptual selection (Dell'Acqua, et al., 2006; Jolicoeur, et al., 2005). Another study using the AB paradigm found evidence for rapid shifts of attention during encoding (Peterson and Juola, 2000). Clearly, more work is needed on this topic.

2. Central Attention

The encoding of information into WM is considered by some to be a central attention task (e.g. Jolicoeur and Dell'Acqua, 1998). If WM consolidation requires central attention, then dual-task combinations of encoding and central attention should result in substantial interference. There is evidence both for and against this.

Pashler (1993) found that participants' ability to encode a spatial array was not affected by overlap with a speeded tone judgment. In his task, a speeded tone requiring a manual response was followed, with a variable SOA, by a matrix of red or black squares. The matrix array had to be encoded quickly because it was masked 100ms after presentation. If the speeded tone task interfered with the consolidation of the matrix pattern, this would manifest as a drop in recognition accuracy for short SOAs. Instead, the results showed little evidence of dual-task interference, suggesting that the consolidation of a visuospatial array can occur undeterred while central attention is engaged. Similar results have been found using partial report or detection as the second task (Blake and Fox, 1969; Pashler, 1991; Posner and Boies, 1971; but see Comstock, 1973).

In contrast, several studies (Dell'Acqua and Jolicoeur, 2000; Giesbrecht et al., 2001; Jolicoeur, and Dell'Acqua, 1998; 1999; Jolicoeur, 1999) have found dual-task interference between WM encoding and central attention tasks. If the first task involves the speeded response to a tone, the encoding of a task two visual array can be impaired by increased task overlap (Dell'Acqua and Jolicoeur, 2000; Jolicoeur, 1999; Jolicoeur, and Dell'Acqua, 1999). Other studies find dual-task interference in the reverse direction—if the first task involves the consolidation of a memory array for later report, RT to identify a task two auditory stimulus will be slowed at short SOAs (Jolicoeur, and Dell'Acqua, 1998; 1999). Additionally, manipulations that increase the difficulty of either the encoding or central attention task result in increased dual-task interference. These manipulations include increasing the response alternatives for the tone task (Jolicoeur, 1999), varying the stimulus-response compatibility for the tone task (Ruthruff and Pashler, 2001), and varying the number of items that have to be encoded (Jolicoeur and Dell'Acqua, 1998).

What are we to make of this discrepancy? It is important to scrutinize the methodological details of these studies. Perhaps those studies finding an interaction between encoding and central attention differ in some subtle but important way from those that do not. Dell'Acqua and Jolicoeur (2000) performed an experiment that attempted to replicate Pashler (1993). They failed to replicate his result and instead found that a speeded tone identification task interfered with matrix encoding at short SOAs. Interestingly, even though the tone task was equivalent in both studies, participants in Dell'Acqua and Jolicoeur's study responded to the tone task 25% slower than those in Pashler's study. In all of Jolicoeur's studies participants are instructed that the tone task is the important task and that accuracy and RT to the tone task should take precedence over accuracy on the encoding task. Pashler's instructions were more balanced—Participants were told that speed for the tone task was important, but they were also told to be accurate on the matrix task. Importantly, Pashler's participants performed on average slightly better at encoding the matrix array than those in Dell'Acqua and Jolicoeur (2000).

Perhaps differing task emphases might underlie the discrepancy in findings. More work is necessary to confirm that these differences are due to differing amounts of emphasis placed on the tone task. If so, it will be necessary to determine what specifically changes when participants are instructed to emphasize the tone task. De Jong and Sweet (1994) proposed that emphasis might alter task preparation such that participants only prepare in advance for the tone task if this task is emphasized. Another possibility is that emphasizing the speed of the tone task places more demand on central attention and is therefore more likely to reveal dual-task interference. The latter possibility seems more likely since dual-task interference still occurs when task two is the speeded task (Jolicoeur, and Dell'Acqua, 1998, 1999).

The conclusions about the role of attention in encoding must be tentative, since there are outstanding questions. However, there is strong evidence for a link between central attention and encoding. The studies by Jolicoeur and colleagues suggest dual-task interference between WM encoding and central attention. Does this dual-task interference reflect an isomorphism between central attention and encoding in WM? Can any consolidation occur while central attention is engaged? Future work is needed to resolve these questions as well as to ascertain the methodological conditions necessary for observing interference between central attention and encoding.

IV. WM Maintenance

1. Visuospatial Attention

Once information has been encoded into WM, it has to be stored there until the information is to be retrieved. Many researchers believe that the processes involved in WM storage are, in essence, attentional processes (Cowan, 1995; 2001, 2006; Rensink, 2000a, 2000b, 2002). Evidence for a link between visuospatial attention and WM is often considered to support these theories. This evidence is reviewed below.

Two functional magnetic resonance imaging (fMRI) studies reveal similar networks of activation for WM storage and visuospatial attention (Corbetta et al., 2002; LaBar Gitelman, Parrish, and Mesulam, 1999). However, the WM activation may have been confounded with attention. LaBar et al. compared the fMRI activation of a WM task with fMRI activation in a spatial attention task. WM activity was isolated by subtracting hemodynamic activity for an RSVP task where participants had to respond whenever a letter appeared matching the letter presented two items back (2-back task) from activity for an RSVP task where participants responded whenever they saw a target letter (control task). It was assumed that these tasks had matched attentional demands (both tasks require attending to an RSVP stream), but differed in WM demands (WM contents were constantly being updated in the 2-back task). However, the attentional demands for non-targets may not have been equivalent. In the control condition participants only need to attend to a stimulus long enough to ascertain whether it is a target. In the 2-back condition, all stimuli are relevant since they always have to be encoded. Therefore, it is not surprising that a comparison of these conditions implicated brain regions known to be involved in attention.

Using a spatial cuing task, Corbetta et al. (2002) compared the brain activity produced by initiating attention shifts to the activation for maintaining attention at a location for a seven second delay. Both activated the intraparietal sulcus and the frontal eye field. There is reason to doubt, however, that the delay condition involved a WM component. Targets would only appear within the first 3 seconds of the task. For the last four seconds of the delay condition there was no task and therefore no reason to store anything in WM. Similar activation in this condition may reflect sustained visuospatial attention rather than WM per se.

A recent study has suggested that there are common neural substrates for visual working memory and attention (Mayer, et al., 2007). In their study, hemodynamic activity in the right prefrontal cortex and bilateral insula increased additively when WM encoding and attentional search demands were increased. However, in order to conclude that these areas are involved in both WM and attention it is critical that the manipulations leading to an additive interaction selectively affect either WM encoding or visual search difficulty. Mayer and colleagues manipulated both WM and attentional demands within a single-hybrid task. To increase visual search difficulty the target of a visual search task either had a unique feature (easy search) or shared features with distractors (difficult search; Treisman and Gelade; Duncan and Humphries, 1989). To increase WM encoding difficulty, the number of items that had to be searched for and encoded was increased from one to three. The problem with the latter manipulation is that it would increase both WM encoding and search difficulty since participants have to search for one or all three targets. Indeed, an additive interaction is predicted since finding all three WM stimuli would take longer in the difficult search condition. Since the manipulations are not independent, the observed additive interaction is not strong evidence for an overlap in neural substrates for WM and attention.

Some neuroimaging evidence does suggest a similar network of activation for WM and attention tasks. Awh and Jonides (1998) reviewed the findings of several imaging studies that explored the neural correlates of either spatial WM or spatial shifts of attention. The brain areas implicated in these two tasks show a good deal of overlap. Awh et al. (1999) provided even stronger evidence for a role of attention in spatial WM; While engaged in spatial WM tasks, participants showed enhanced fMRI activation in early visual areas contralateral to the memorized locations. Similar evidence of attentional allocation to memorized locations has been found with EEG (Awh, Anllo-Vento, Hillyard, 2000; Jha, 2002). In conclusion, neuroimaging results reveal overlap in the brain regions involved in spatial WM and attention tasks. However, there is no convincing evidence for a similar overlap with object-based WM tasks.

Behavioral results also suggest that dual-task interference between WM and attention is largely confined to memory for spatial information. The rate at which items are searched in a visual search task is slowed while participants are maintaining a spatial WM load (Oh and Kim, 2004; Woodman and Luck, 2004). This effect may be specific to spatial WM; Search rate is not affected if the WM task involves object identity (Woodman, Vogel, and Luck, 2001)[1]. A similar interaction has been found for detection tasks and WM. Participants are quicker at identifying targets presented in locations that are stored in spatial WM (Awh, Jonides, and Reuter-Lorenz, 1998). If participants are asked to memorize letter identity instead of spatial location, the location of a visually presented memory stimulus does not affect a subsequent detection task. Dual-task interference between visuospatial attention and spatial WM appears quite robust and bidirectional. Engaging in shifts of attention or controlled saccades can impair concurrent spatial WM (Awh et al., 1998; Pearson and Sahraie, 2003; Postle, Idzikowski, Della Sala, Logie, and Baddeley, 2006; Smyth, 1996; Smyth and Scholey, 1994).

Verbal WM is similar to object WM in that the effect of concurrent memory load does not interact with the demands of a visual search task (Logan, 1978). Logan had participants perform a search task either during the retention interval of a verbal WM task or in a single-task situation. Based on additive factors logic (Sternberg, 1969), Logan reasoned that if verbal WM requires attention, manipulations of the attentional demands of search should produce greater behavioral effects in conditions of WM load than in single-task conditions. Instead, using search RT as the dependent measure, Logan found that memory load did not interact with search array size or with a variety of manipulations of visual search difficulty (e.g. cue vs. no cue, mask vs. non-masked). The effect of memory load on search RT was constant across search conditions. This pattern of additivity suggests that performance in a verbal WM task does not depend on visuospatial attention. Instead, the main effect of WM load may be due to reduced preparation in the dual-task condition (Logan, 1978; 1979; see Woodman et al., 2001, for a similar conclusion for object WM). Logan's findings complicate interpreting dual-task interference based on the addition of a WM load. For example, Jonides (1981) found that a concurrent verbal WM load disrupted congruency effects in a spatial cuing task (for central but not peripheral cuing). It is possible that this effect arose because WM load increases the amount of preparation needed for a task. Alternatively, the effect of verbal WM on central precuing may have occurred because the verbal WM load slowed interpretation of the central cue. It is important to note however, that a recent study has failed to replicate the effect of verbal WM load on central cuing (Thornton and Raz, 2006). At the present time, it is not known why Jonides found interference between visuospatial attention and verbal WM while other studies did not find this pattern.

According to some theories of visual WM, attention is not needed to store individual features, but is required when feature-conjunctions need to be maintained (Delvenne and Bruyer, 2004; Wheeler and Treisman, 2002). Initially, the available evidence did not support

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[1] There is good evidence for distinct object and spatial WM stores (Courtney, Ungerleider, Keil, & Haxby, 1996; Pickering, 2001; Smith et. al., 1995)

this view. For example, neither shifts of visuospatial attention (Yeh, Yang, and Chiu, 2005), nor the engagement of executive attention (Allen, Baddeley, and Hitch, 2006) specifically disrupted memory for feature-conjunctions. However, the shifts of visuospatial attention in Yeh et al.'s study may have been too transient, and engaged too little attention, to reveal an effect. Giving support to this view, recent evidence suggests that a more demanding sustained attention task can specifically disrupt the binding of color and location (Fougnie and Marois, in press). Fougnie and Marois had participants perform a multiple object tracking (MOT) task during the retention interval of a visual WM task. MOT is an attentionally demanding task requiring the tracking of a number of unpredictably moving targets among similar looking distractors (Pylyshyn and Storm, 1988; Sears and Pylyshyn, 2000). Fougnie and Marois instructed participants to remember different visual properties in different experimental blocks. In one block type participants had to remember feature-conjunctions of color and shape. In another block type participants had to remember the color and shape of objects but they were only tested on one of these features. There were also color and shape blocks involving memory for one feature only. The principal finding was that the tracking task showed the largest interference on WM performance when color and shape conjunctions needed to be maintained.

Finding evidence of dual-task interference does not necessarily imply that WM and attention share the same underlying capacity limit. If WM capacity is due solely to attentional capacity, then interference between these two tasks should be equivalent to the interference produced by concurrently performing two visual WM tasks. A recent experiment tested whether WM and attention share the same capacity limit (Fougnie and Marois, 2006). The procedure involved the addition of a second task with a variable load during the retention interval of a task one visual WM load. The amount of dual-task interference produced by various task pairings is indicative of the amount of processing shared between the two tasks. Consistent with other work (Cocchini, Logie, Della Sala, MacPherson, and Baddeley, 2002), visual WM task pairings produced substantial dual-task interference, but only minor interference was found when a visual WM task was paired with verbal WM. Of importance, when an attention-demanding task was performed during visual WM storage, there was greater dual-task interference than was observed when task two was a verbal WM task, but significantly less than when task two involved visual WM. Indeed, while increased tracking load resulted in increased dual-task interference, these costs were similar to the costs associated with increased verbal WM load. A similar story was also revealed by the combined capacity across the two tasks (i.e. the total number of items that were stored/tracked). Combined task capacity was no greater than single task capacity for the dual visual WM task combination. However, task capacity was greater than single task capacity when tracking and visual WM were combined. This provides further evidence that the same capacity limit does not underlie tracking and visual WM.

Recently, Cowan and Morey (2007) have questioned the nature of the modality-specific dual-task costs observed by Fougnie and Marois (2006). They suggested that the interference between two visual WM tasks may have occurred during encoding, and not storage. Specifically, they proposed that it might have been difficult to encode a visual display while retaining another visual display in memory. To demonstrate this empirically, Cowan and Morey had participants perform a dual-task WM experiment similar to the procedure used by

Fougnie and Marois. Unique to their task was a postcue that would appear after the WM displays. The postcue would instruct participants as to whether one or both WM sets were task-relevant. The results revealed that presenting participants with two visual displays produced interference, even when the postcue indicated that only one display was task-relevant. It was suggested that this demonstrated the presence of encoding costs in dual-task designs. However, interference during encoding cannot explain the capacity results of Fougnie and Marois (2006) since combined dual-task capacity never suffered relative to single-task capacity. In addition, there is strong evidence that participants can concurrently encode and store visual information without cost (Woodman and Vogel, 2005). How are we to reconcile these points with the results raised by Cowan and Morey? In a recent paper (Fougnie and Marois, submitted) we questioned whether the proposed "encoding", or postcue, costs occur during encoding or storage. The number of items that participants can store in visual WM is limited to four items (Cowan, 2001; Vogel, Woodman, and Luck, 2001), yet the procedure used by Cowan and Morey requires participants to store six stimuli for several hundred milliseconds before a postcue appears. It is plausible that postcue costs reflect a participant's inability to memorize both displays due to inherent capacity limitations. Indeed, we found that postcue costs occurred only when visual WM capacity was exceeded and that difficulties performing this task occurred even when both displays were presented simultaneously (Fougnie and Marois, submitted). Thus, we suggested that the modality-specific postcue costs reported by Cowan and Morey (2006) occurred due to modality-specific limits in VWM storage capacity.

While attention is involved in the storage of information in visual WM, the evidence suggests that attention does not limit WM storage capacity. This fits well with change detection experiments demonstrating accurate detection in the absence of attention. As mentioned previously, several change detection studies manipulate attention within a display via saccades or by having participants shift attention. Of relevance to the current topic is what happens when participants shift from one part of the display to another. If the contents of WM are limited to what is attended, then no memory of a previously attended object will remain. To test this, Hollingworth (2004) had participants saccade to various display locations (by following a moving dot). Initiating eye movements is known to be preceded by shifts of visuospatial attention, which move exclusively to the saccade target (Hoffman and Subramaniam, 1995; McConkie and Rayner, 1976; Peterson et al., 2004). In contrast to the assumption that representations require constant attention, the results showed good change detection performance for the last two recently fixated items. Similar results have been reported using slightly modified procedures (Hollingworth, 2001; Irwin and Andrews, 1996; Irwin and Gordon, 1998; Irwin and Zelinsky, 2002).

Together, the current results suggest that visual WM storage is partially separate from attention. Evidence for interactions between visuospatial attention and WM seem primarily limited to WM for spatial locations and feature bindings. Below I mention two possible causes of this interference cited in the literature.

Perhaps the most straightforward explanation for the observed interference is that attention and WM interfere when both tasks require use of similar codes (Dutta, Schweickert, Choi, and Proctor, 1995; Navon and Miller, 1987). The interference between spatial WM and spatial attention may occur because both tasks utilize spatial information and this maximizes the chances of cross-talk between the tasks. Memory for feature-conjunctions may also require spatial codes. Feature-conjunctions may be represented by different feature stores referencing a 'master map' through location tags (Treisman and Gelade, 1980).

Awh and colleagues have proposed that visuospatial attention can be used to rehearse spatial information; similar to the way speaking aloud can help rehearse verbal information (Awh et al, 2000; Awh and Jonides, 2001; Awh et al., 1999; Awh et al., 1998). Specifically, visuospatial attention may shift to memorized locations thereby acting as a location marker. While code-based interference and attention-based rehearsal accounts propose different mechanisms to explain the interference, the two accounts are close to isomorphic in terms of the predicted outcomes. One distinction is that the code-based interference account emphasizes the overlap between the type of attention task and the nature of the stored information. This would predict that a non-spatial form of visual attention, such as feature-based attention (Saenz, Buracas, and Boynton, 2002; Saenz, Buracas, and Boynton, 2003), would interfere with object WM. Empirical testing of this prediction may resolve whether interference is limited to spatial information, or whether it occurs whenever there is overlap in task-relevant representations.

Storage in WM may not interfere with goal-driven shifts of attention, but it may affect the ability to prevent stimulus-driven shifts of attention towards task-irrelevant items. Lavie and de Fockert (2005) found increased attentional capture in a visual search task when it was performed with a concurrent digit WM load. Attentional capture was defined as the slowing of visual search RT caused by the presence of an irrelevant color singleton (Theeuwes, 1992). While interesting, these results may reveal more about the limits in attentional control settings (Folk et al., 1994) than about an increase in distractibility under WM load. It is known that participants can be engaged in two types of search: singleton-detection, in which distinctive items are checked first, or feature-based, in which items matching a target template are checked first (Bacon and Egeth, 1994; Leber and Egeth, 2006). The effect of the WM load may be to cause more participants to default into singleton detection mode, thereby resulting in increased attentional capture. More work on this topic would be beneficial.

Proposed dual-task interference between WM and attention is not the only evidence that has been offered to suggest an isomorphism between visuospatial attention and WM. Some researchers believe that the contents of WM serve as templates that guide visuospatial attention (Chelazzi, 1995; Chelazzi, Miller, Duncan, and Desimone, 1993; Desimone and Duncan, 1995; Downing, 2000; Duncan and Humphries, 1989). There appears to be a neural signature for this—neurons in inferior temporal cortex and prefrontal cortex that are selective for a target will continue firing during a retention delay (Chelazzi et al., 1993; Rainer, Asaad, and Miller, 1998). It is quite clear that in some instances the search target must be stored in WM. What is less clear is whether storing an item leads to the automatic orienting of attention to similar items. Duncan (1996) proposed that selection in different cognitive functions is unified, such that competition in one, e.g. maintaining object identity in WM, may influence selection in another, e.g. visuospatial attention. Evidence for automatic orienting to stored representations was offered by Downing (2000). In his study, participants were given a face to memorize at the beginning of a trial. While storing the face representation, they also had to perform a discrimination task on a visual probe shown either on the left or right side of the display. Immediately before the probe presentation, two task-irrelevant faces, one of which matched the face stored in memory, flashed briefly on screen. If the WM-matching face appeared at the location of the subsequent probe, performance on the probe task improved. One way to account for these results is to conclude that visuospatial attention was automatically drawn to the matching face (because it matched a template stored in WM) and that the subsequent probe task benefited from the increased attention. Conceptually similar results have been reported (Huang and Pashler, 2007; Olivers, Meijer, Theeuwes, 2006; Pashler and Shiu, 1999; Pratt and Hommel, 2003; Soto, Heinke, Humphreys, and Blanco, 2005).

However, the standard interpretation of these accounts has been recently criticized (Varakin, 2006; Woodman and Luck, 2007). These authors question whether the shifting of attention in these studies is truly obligatory. Shifting attention to WM-matching items may allow a participant to encode more details or to refresh a fading representation. Demand characteristics may also play a role. Participants may be curious about the matching face and may shift their attention voluntarily because they believe that they are expected to. Downing's results have not always replicated when voluntary orienting is discouraged (Downing and Dodds, 2004; Varakin, 2006; Woodman and Luck, 2007). However, a recent study observed WM-based orienting towards objects that 1) matched the WM load only by a task-irrelevant feature and 2) were never the target (Soto et al., 2005). The discrepancy in results may depend on the amount of time between the WM stimuli and the search array (Han and Kim, submitted; Varakin, 2006) or on the difficulty of the search task (Han and Kim, submitted). Since automatic orienting depends on the task parameters used, it does not provide strong evidence for a single selection mechanism.

One reason that the connection between WM and visual attention may not be as strong as once thought is that the target of a search task may only be stored as a template in WM if it changes on a trial-by-trial basis (Woodman and Chun, 2006). In support of this, Woodman and Chun point out that object WM does not interfere with the efficiency of visual search when the target remains constant. While a concurrent object WM load slows search RT, it does not affect the rate that items are searched (Woodman et al., 2001). Following up on this, Woodman, Luck, and Schall (2007) have shown that WM loads can lead to increased search rates if the target of the search varies from trial to trial.

While a close relationship between WM and attention is often suggested, the evidence argues that WM storage and visuospatial attention are more distinct than often thought. Convincing evidence of dual-task interference between attention and WM is present only for spatial location or feature-conjunction WM. Even this interference does not suggest a common underlying capacity—Interference between attention and WM is less than the interference produced by combining two WM tasks. In addition, the relationship between object WM and attentional orienting does not appear to be as straightforward as envisioned by Downing (2000). Indeed, target templates may not be used at all if a search target remains stable over time.

2. Central Attention

Maintaining items in WM is generally believed to be attentionally demanding. This belief has been influenced by the harmful effect memory loads have on general cognitive functions such as comprehension, learning, and reasoning (Baddeley, 1986; Baddeley and Hitch, 1974). However, these are complex cognitive abilities. Dual-task effects may occur simply because comprehension, learning, and reasoning all require memory.

Some of the first evidence suggesting that WM storage requires central attention comes from experiments that measured the effect of secondary tasks on recall for sequentially presented verbal stimuli. Attention-demanding secondary tasks, if performed between list presentation and recall, disrupt list memory (Brown, 1958; Peterson and Peterson, 1959; Salthouse, 1975; Watkins, Watkins, Craik, and Mazuryk, 1973). For example, Watkins et al. presented participants with five nouns to memorize. During retention, participants could either ignore an auditory tone sequence, or they had to select one of four manual responses to each tone. The rate of forgetting was much larger for the condition that involved the selecting and executing of responses, arguing that engaging central attention may interfere with maintenance processes in WM. In another experiment, Watkins et al. showed that secondary task interference occurs primarily for recent list items. The secondary task disrupted the recency effect (the improved recall rate for the items most recently presented). These results seem robust across a variety of secondary tasks including backwards counting, number shadowing, and mental rotation. In addition, secondary tasks can disrupt both verbal and spatial WM (Phillips and Christie, 1977; Watkins et al., 1973). The traditional explanation is that attention-demanding secondary tasks disrupt the rehearsal of items in WM. However, there have been challenges to this interpretation. Some have argued that recency effects such as those found by Watkins et al. are not diagnostic of a temporary memory store and instead can be explained by distinctiveness in LTM (e.g. Crowder, 1982). This view is supported by the preservation of recency effects in serial recall when a distracting task occurs between each memory stimulus (Bjork and Whitten, 1974; but see Koppenaal and Murray, 1990 for an argument against recency effects in LTM). Another complication is that the interference in WM caused by an attention-demanding task develops over time. The first couple of trials show no effect of secondary task load. Interference in subsequent trials may reflect proactive interference rather than disruption of rehearsal (Keppel and Underwood, 1962).

The disruption of WM maintenance by central attention may depend on the nature of the secondary task employed. If the secondary task requires attending to items that are similar to the stored information then a significant amount of interference is produced (Salthouse, 1975). Instead, if the secondary task differs in modality from the contents of WM (or involves an amodal task demand such as random generation) there are much smaller (Allen et al., 2006; Klauer and Zhao, 2004; Salthouse, 1975) or even negligible dual-task costs (Bruyer and Scailquin, 1998; Tresch, Sinnamon, and Seamon, 1993). This suggests that the relationship between central attention and WM storage involves two components: a central, amodal component and one that is information/modality specific. The modality specific effect is generally interpreted to reflect the involvement of distinct memory stores for different modalities (e.g. Klauer and Zhao, 2004). While the source of the amodal deficit is not definitively known, several things can be concluded from it. For one, we can reject the possibility that WM storage depends entirely on central attention. If this were true, engaging central attention tasks would be devastating for WM storage and increased interference would not be expected when the WM and central attention task overlap in modality. Second, this reveals a distinction between the effects of visuospatial and central attention on WM maintenance. The dual-task interference observed between verbal or object WM and central attention stands in stark contrast to the relative lack of evidence for dual-task interference with visuospatial attention. Indeed, unlike visuospatial attention, an amodal central attention task interferes with memory for object features to the same degree as memory for feature-bindings (Allen et al., 2006; but see Miyake, Friedman, Rettinger, Shah, and Hegarty, 2001). Overall, this suggests that the pattern of interference on WM storage caused by a secondary task depends on whether that task engages visuospatial, central, or both forms of attention.

Experimental studies looking at the effect of a WM load on central attention tasks also reveal a nuanced relationship. According to Lavie and colleagues, high WM loads disrupt selective attention and therefore lead to increased distractor processing (de Fockert, Rees, Frith, and Lavie, 2001; Lavie et al., 2004; see also Thornton and Raz, 2006). In these studies, selective attention is typically measured by presenting a visual display containing both relevant and irrelevant information (e.g. flanker tasks). Participants are instructed to attend to the relevant information and to ignore the irrelevant information. Their ability to do so can be inferred from the RT difference between trials in which the irrelevant information is response incongruent from where it is congruent (larger congruency effects imply less selective attention). The general finding is that an increase in WM load leads to increased congruency effects. This method of assessing selective attention is not ideal for dissociating visuospatial and central components of attention since both can potentially play a role. There is, however, good reason to believe that the congruency effects in Lavie's studies arise at a central processing stage. For one, the pattern of the results is the same whether the congruent and incongruent information is spatially separate (Lavie et al., 2004) or overlapping (de Fockert et al., 2001). In addition, the work of Santee and Egeth (1982) suggests that RT costs from flankers occur at a response stage.

A subsequent study has argued that the effect of WM storage on selective attention may depend on the relation between the stored information and stimuli in the attention task (Kim, Kim, and Chun, 2005; see also Park, Kim, and Chun, 2007). Kim et al. (2007) suggest that increased WM loads lead to decreased selective attention only when the task-relevant stimuli of a flanker task are similar to the items stored in WM. The increase in flanker effects reported in previous studies, such as those by Lavie and colleagues, may be attributable to a shared requirement for verbal processing for the WM and attention tasks. The results of Kim et al. accord well with the studies on secondary tasks during WM storage. Both suggest that some of the proposed interference between WM and attention tasks is due to overlap in content-specific processing.

There is also evidence that storing information in WM does not always slow central attention tasks. Oberauer (2002) had participants memorize two lists of numbers. During the WM retention interval, mathematical operations needed to be performed on the numbers in one of the lists (active list). In contrast, the passive list only required storage in WM. The time required to perform the mathematical operations was affected by the setsize of the active list but not the passive list. Mathematical operations took longer if they needed to be performed on a number different from the last one tested. This switch cost was strongly affected by the setsize of the active list (Garavan, 1998; Oberauer, 2002, 2003) but not the passive list

(Oberauer, 2002; see also Logan, 2004). These results suggest a distinction between the storage of items that need to be accessed during a memory delay and those that can be maintained passively. This passive store within WM may operate relatively independently of central attention while the active store may not. This framework provides an economical way of accommodating the various findings mentioned in this section. When items simply have to be maintained in WM, they may be stored in both the active and passive portions of WM (assuming that the active portion of WM is otherwise unoccupied). When a task requiring central attention is required, dual-task interference may occur. However, the effect of the attention task will be modest since items can be maintained in the passive store without interference.

Such an account is speculative, and perhaps too simple to capture the complex relationship between central attention and WM storage. It should also be mentioned that this account is not completely novel and shares many similarities with other models (Cowan, 1995, 2006; McElree, 2001; Oberauer, 2001, 2002). Regardless of whether this framework is accurate, the studies discussed in this section reveal several interesting patterns. Contrary to the oft-mentioned similarity between attention and WM, dual-task interference between central attention and WM maintenance is limited. Only under specific conditions, such as when the items stored in WM overlap with the processing involved in the central attention task, is substantial dual-task interference observed. Additionally, unlike with visuospatial attention, there is little evidence that the interference between central attention and WM storage is restricted to memory for spatial information or feature-conjunctions.

V. Manipulation/Updating of WM

In addition to the offline storage of information, a task may require the manipulation, or updating of stored information, or may engage simultaneous processing and storage of items. For the sake of brevity, I will collectively refer to these as executive WM processes. Unlike the previous sections, which present data that is best explained by viewing attention and WM as related but functionally distinct constructs, one might predict that the executive components of WM would be interchangeable with attention. The brain regions found to activate for executive WM load show remarkable correspondence with those regions activated in central attention tasks (D'Esposito et al., 1999; Jiang, Saxe, and Kanwisher, 2004; Szameitat, Schubert, Müller, and van Cramon, 2002). Indeed, many models of WM (e.g. Baddeley, 1996; Baddeley and Logie, 1999; Kane and Engle, 2002) group executive and central attention functions. I will agree that the data is consistent with this assertion. Deviating from previous sections, the subsection for central attention has been placed prior to the section for visuospatial attention. My motivation for this is pragmatic: A discussion of the relationship between executive WM and visuospatial attention will benefit from a prior discussion of central attention and executive WM.

1. Central Attention

If there is a close connection between executive WM and central attention, then having to perform both concurrently should result in strong dual-task interference. The evidence supports this (Berti and Schröger, 2003; Mitchell, Macrae, and Gilchrist, 2002; Oberauer, 2002, 2003; Roberts, Hager, and Heron, 1994). Recall the findings of Oberauer (2002, 2003) discussed earlier—the time needed to perform an arithmetic operation on an item in WM was affected by the setsize of the active, but not the passive list. Thus, while storing an item may not affect the speed of central processing, if the list items need to be updated, this can interfere with central processing.

An executive WM load also impairs performance in the antisaccade (AS) task. AS tasks require making a saccade to the side of the screen opposite a visually presented cue. To perform quickly and accurately, participants must suppress the prepotent response of attending to the cued location. This response selection difficulty makes the AS task useful for assessing the effects of executive WM load on central attention. Indeed, AS are delayed in the PRP paradigm while prosaccades are not (Pashler, Carrier, and Hoffman, 1993). Two studies have varied the executive load of a WM task performed concurrently with an AS task (Mitchell et al., 2002; Roberts et al., 1994). One study varied WM load by using an N-back task (Mitchell et al., 2002). They found that AS performance was affected by a concurrent 1-back or 2-back task and that the interference was greater in the 2-back condition. Roberts et al. (1994) also report that an executive WM load impaired AS performance. The executive component in their study involved constantly updating a WM item to reflect the result of an addition task. Importantly, while the concurrent task affected AS performance in these studies, it did not affect prosaccade performance (Mitchell et al., 2002; Roberts et al., 1994).

Also relevant are studies that measure the behavioral and neurophysiologic effects of task-irrelevant information under conditions of executive WM load (Berti and Schröger, 2003; Fougnie and Marois, 2007; Spinks, Zhang, Fox, Gao, and Hai, 2004). In contrast to Lavie's studies discussed in section IV, executive WM load appears to reduce distractibility to task-irrelevant information. Berti and Schröger found that task-irrelevant deviations in tone length in a tone-monitoring task led to pronounced EEG components (mismatch negativity and P300) and also produced behavioral interference. When the executive demands of the task were increased (by forcing participants to base their current response on the previous tone) this reduced both the P300 and the behavioral interference caused by the tone deviations. Importantly, executive load did not affect the sensory processing of the tones as measured by mismatch negativity amplitude. Similar results have been reported by Spinks and colleagues (Spinks, et al., 2004), however, their study is difficult to interpret. Unlike in Berti and Schröger's study, Spinks et al.'s result may have been due to effects in sensory processing. Executive load was manipulated by having participants subtract either three (low load) or thirteen (high load) from a number presented on screen. Participants were distracted from this task by the presentation of a task-irrelevant onscreen character. Unfortunately, the number and the task-irrelevant character were presented simultaneously and therefore the behavioral interference on the subtraction task could be due to capture of visuospatial attention by the character.

The findings of Berti and Schröger may indicate that central attention and executive WM load draw on similar processes. If participants are engaged in a demanding executive WM task, these processes may not be available for processing task-irrelevant information. This is in contrast to the effects of information load on central attention (see section IV), but caution is required in generalizing from these results. For one, the methodology used to assess selective attention is different across the two sets of studies. In Berti and Schröger's study, the tone length deviations were a property of the attended stimuli and may have been impossible to suppress (but see Remington and Folk, 2001). It is unknown whether these methodological differences might have played a role in the discrepant results. Another concern is whether these results would generalize to all manipulations of executive WM load. Kim et al. (2005) suggest that a WM load may reduce task-irrelevant information when the content of the WM task overlaps with the content of the task irrelevant information. This was true of Berti and Schröger's study, however manipulations of executive load may not have the same effect as increases in stored information. There is some evidence that increased executive load can lead to reduced processing of task-irrelevant information even if the two tasks differ in modality. Fougnie and Marois (2007) found that participants were more likely to be inattentionally blind to a task-irrelevant, novel visual stimulus if they were manipulating consonants in verbal WM. Perhaps a WM storage demand produces content-dependent interference, while an executive WM load always results in reduced task-irrelevant processing. Future studies are needed that manipulate both WM storage load and executive load in a WM task, and that measure the effect of these manipulations on central attention tasks that do not overlap in content with the WM task.

If executive WM and central attention are fundamentally linked, then performance in one may predict a person's ability on the other. Several measures have been developed to measure executive WM capacity. These tests measure the ability to simultaneously perform storage and processing tasks. For example, the operation-span task presents an alphanumeric string containing both a mathematical operation plus a word to memorize (Turner and Engle, 1989). Variations on this procedure include the reading-span (Daneman and Carpenter, 1980) and counting-span (Case, Kurland, and Goldberg, 1982). While these procedures measure both the storage and processing of information, it is the executive demands of the tasks, rather then domain-specific storage, that have been shown to predict performance on an array of complex cognitive abilities (Conway, Kane, and Engle, 2003; Engle, Tuholski, Laughlin, and Conway, 1999; Turner and Engle, 1989). Relevant to the current topic, participants with high working memory capacity[2] (WMC) have been shown to perform significantly better than low WMC individuals on a variety of central attention tasks (Conway, Cowan, Bunting, 2001; Heitz and Engle, 2007; Kane, Bleckley, Conway, and Engle, 2001; Kane and Engle, 2003; Long and Prat, 2002; McCabe, Robertson, and Smith, 2005; Unsworth, Schrock, and Engle, 2004).

The results of these studies converge with the dual-task interference studies. Just as participants perform poorly on an AS task if given a concurrent executive WM load, low WMC individuals are slower and less accurate on AS tasks than are high WMC individuals (Kane et al., 2001; Unsworth et al., 2004). Low WMC individuals are also poor at blocking out distracting information in dichotic listening and stroop tasks. Conway et al. (2001) presented two auditory messages to participants (one message to each ear). When participants were asked to repeat one of the messages and ignore the other one they could effectively

[2] Individuals were considered to have high working memory capacity if they scored high (usually top quartile) in the operation span task. Individuals with low working memory capacity were those that scored lower (usually bottom quartile).

ignore the irrelevant stream, as indicated by the fact that none of the participants detected a yoked name. However, if the ignored stream contained the participant's name almost half detected it, replicating the well-known cocktail party effect (Moray, 1959; Wood and Cowan, 1995). The important result was that more low capacity (65%) than high capacity (20%) individuals noticed their name. Low WMC individuals are more susceptible to stroop interference than individuals with high WMC (Kane and Engle, 2003; Kiefer, Ahlegian, Spitzer, 2005; Long and Prat, 2002; McCabe, Robertson, and Smith). Interestingly, this difference seems to depend on the proportion of trials in which the text color and word are incongruent. An increased proportion of congruent trials results in increased stroop interference (Logan and Zbrodoff, 1979, 1998) and the effect of this increased stroop interference appears larger for individuals with low WMC.

There is also evidence that low WMC individuals have larger flanker effects, particularly if they are forced to respond under time pressure (Heitz and Engle, 2007; Redick and Engle, 2006). If participants are forced to respond to a flanker display within the first 300ms of presentation, accuracy tends to be low and can even drop below chance in incongruent trials (this would indicate a response based off the incongruent letters). As time pressure is relaxed performance gradually improves. Heitz and Engle argued that this occurs because the visuospatial attentional window initially comprises all flanker stimuli, however, over time the attentional window shrinks to include only the target letter.

In a series of experiments, they manipulated time pressure in a flanker task by imposing response deadlines of various durations. Participants with high WMC improved at a faster rate as time pressure was relaxed. Heitz and Engle argued that individuals with high WMC could more rapidly adjust the size of their attention window. There is reason to doubt, however, that this effect is due to different rates of attentional constraint. For one, the location of the target stimulus is known, so it seems likely that visuospatial attention could focus in advance. Also, because the letters were spaced apart by only .5º of visual angle, if attention was able to shrink to 1º of visual angle (Eriksen and St. James, 1986) the window would still include distractor information. I propose that performance in this task is largely due to post-perceptual/central selection and that the reason that high WMC individuals outperform low WMC individuals is because high WMC individuals are better at making an accurate selection in the presence of competing activation.

The evidence for a close link between executive WM and central attention is quite strong. The only caveat is that the central attention tasks that are interfered by executive WM load or are predicted by WMC do not cover the full spectrum of central attention tasks. Many of these tasks involve a prepotent response or require distractor suppression. This may indicate that executive WM requires inhibitory control (Hasher and Zacks, 1988; Lustig, Hasher, and Tonev, 2001) instead of a general central attention capacity. One way to resolve this is to test whether WMC also predicts performance on central attention tasks that do not involve inhibitory control.

For example, participants with high WMC might show less of an effect of task overlap in PRP tasks. Until the prerequisite experiments are carried out, it is difficult to conclude whether a close relationship between executive WM and central attention generalizes beyond the type of tasks discussed in this section.

2. Visuospatial Attention

Theories of visuospatial attention often liken attention to the beam of a flashlight (Posner, Snyder, and Davidson, 1980). Consistent with this metaphor, models of visuospatial attention generally assume a contiguous area of selection (LaBerge, 1983; Posner et al. 1980; Eriksen and St. James, 1986). Several studies have argued, however, that visuospatial attention can select noncontiguous regions (Awh and Pashler, 2000; Bichot, Cave, and Pashler, 1999; Egly and Homa, 1984). Egly and Homa had participants split their attention between a letter detection task at fixation and a letter localization task. For the localization task, a letter could appear at any of 24 positions on three concentric rings of different radii around fixation. One ring was cued at the beginning of a trial. The target usually, but not always, appeared along this ring. If attention acts as a beam, then it would be impossible to attend to both fixation and an outer ring without also attending to inner regions. Instead, Egly and Homa found that accuracy suffered on invalid trials regardless of whether the target appeared inside or outside the cued ring. Bleckley and colleagues (Bleckley, Durso, Crutchfield, Engle, and Khanna, 2003) extended the results of Egly and Homa to determine whether this ability to flexibly allocate visuospatial attention would be present in both high and low WMC individuals. Only high WMC individuals showed the pattern found by Egly and Homa. Low WMC individuals performed just as well on invalid trials as valid trials when the target appeared inside the cued ring. This shows that WMC is predictive of the ability to attend to noncontiguous regions of space.

WMC has been less successful at predicting performance on more standard visuospatial attention tasks. Fan and colleagues (Fan et al., 2002) developed the attention network test as a means of dissociating performance on three types of attention: alerting, orienting, and executive. In this test, participants are asked to respond quickly and accurately to the direction of an arrow. Executive attention is assessed by manipulating the compatibility of flanking distractor arrows. Orienting attention is assessed by comparing trials in which the location of the arrow was validly versus invalidly cued. Alerting is assessed by comparing a non-spatial precue versus a no-cue condition. Redick and Engle (2006) tested participants of both high and low WMC on the attention network test to determine which types of attention could be predicted by WMC. Differences in executive attention were found between the two WMC groups, consistent with the prior discussion of a role for WMC in mediating flanker interference. However, WMC did not predict performance on the orienting (or alerting) component of the task. This implies that there is no difference between high and low WMC individuals in their ability to shift and hold visuospatial attention in a spatial cuing task.

WMC is also not predictive of visual search performance (Kane et al., 2006). Participants of either high or low WMC performed a variety of visual search tasks (feature-presence, feature-absence, feature-conjunction, etc). High and low WMC individuals searched through these arrays at statistically indistinguishable rates. Interestingly, while WMC does not predict search performance, an executive WM load may interfere with visual search (Han and Kim, 2004). Han and Kim had participants perform a visual search task during the retention interval of WM tasks. They found that the search rate was slowed (compared to single task) when the WM task involved an executive load (backward counting or alphabetical reordering) but not when the WM task merely involved storage (digit or alphabet remembering). The differing results for dual-task interference and WMC suggest that one should be cautious in generalizing from one to the other, although, in other paradigms these generalizations have proved constructive (e.g. Kane et al., 2001). Perhaps those with low WMC still have enough attentional capacity to perform a visual search task but those under dual-task loads do not.

Interference between visual search and executive WM load is suggestive of a link between visuospatial attention and the executive component of WM. However, more work is required to determine what aspect of visual search is being interfered with. Peterson and colleagues attempted to provide an answer for this by monitoring eye movements in a search task while participants were given a concurrent executive WM load (Peterson, Beck, and Wong, 2008). Their data suggest that executive load did not result in slowed saccade rates, but instead resulted in an inability to inhibit preprogrammed saccades. This may have played a role in Han and Kim's study since they did not monitor eye movements, although, it is not clear why this should lead to overadditive effects with array size. Another possibility is that executive WM load disrupts the tendency to avoid repeatedly checking already searched locations (inhibition of return). There is evidence that spatial WM disrupts inhibition of return (Castel, Pratt, Craik, 2003) but no study has examined the effect of executive load on inhibition of return. Currently, there is simply not enough data to determine why executive WM load interferes with visual search.

While executive load disrupts visual search, it doesn't disrupt the perceptual processing of distractors (Yi, Woodman, Widders, Marois, and Chun, 2006). Yi et al. tested if increasing the difficulty of an N-back task would result in less processing of task-irrelevant background scenes. Increasing the perceptual difficulty of the task resulted in attenuated scene processing, perhaps because there was less visuospatial attention available for the background scenes. However, scene processing was not affected by an increase in the executive load of the N-back task. This is evidence that visuospatial attention resources are independent of executive WM resources.

The available evidence suggests a pattern: visuospatial attention and executive WM operate independently except when the visuospatial attention task is fairly complex. WMC was found to predict the ability to attend to noncontiguous regions of space, but it did not predict visuospatial attention performance in other tasks. Dual-task interference has been observed when a visual search task needs to be performed during an executive WM task. However, an executive WM load does not appear to restrict the availability of visuospatial attention resources for processing task-irrelevant information.

VI. Discussion

Perhaps the most striking conclusion supported by this review is that, in contrast to previous theories, the distinction between attention and WM is quite strong. This suggests that the existing frameworks relating attention and WM must be modified. I will briefly describe three influential theories that propose a close connection between attention and WM. These theories fit well with some findings, but cannot account for all of the empirical work.

One of the main themes of this review is that further work is necessary in order to have a better understanding of the relationship between WM and attention. Nevertheless, I will outline what properties a successful theory relating the two constructs would have to explain. Based on these properties, I will sketch a simple model of how attention and WM interact. The last part of this discussion will comment on the different methodologies mentioned in this review. I will outline the pros and cons of different methodologies to facilitate the design of future studies.

Duncan's integrated competition hypothesis proposed that there is one selection mechanism that acts to select items for both attention and working memory systems (Duncan, 1996, Duncan et al., 1997). Specifically, while separate attention and WM processes may exist, these systems interact and converge to select a single item. A strong prediction of the integrated competition hypothesis is that attentional selection will be determined by the contents of other systems, e.g. WM. The theory gained its strongest support from the finding of automatic attentional capture towards items stored in WM (Downing, 2000). However, Downing's results have been subject to criticism, and several studies have failed to observe WM-based capture when voluntary orienting is discouraged (Downing and Dodds, 2004; Woodman and Luck, 2007). The integrated competition hypothesis has trouble explaining a number of findings. For one, it cannot account for the lack of interference from object or verbal WM on visual search (Logan, 1978; Woodman et al., 2001). The dissociations between visuospatial and central attention discussed in section II are also problematic for a model that proposes a unitary selection mechanism.

Cowan (1995, 1999, 2001, 2006) also proposes a close relationship between attention and WM. In his model, WM is comprised of 1) a capacity-limited focus of attention and 2) activated long-term memory representations residing outside of attention. While Cowan has suggested that the interference between visuospatial attention and WM is supportive of his framework, the evidence reviewed in section III suggests that interference is restricted to WM for spatial locations or feature-conjunctions. This does not support his theory as the focus of attention is proposed to be an amodal store. Cowan's theory is more successful at explaining the available data concerning central attention and WM. Consider the relationship between WM storage and central attention. The data revealed moderate interference when the two tasks were performed concurrently, with more potent interference if the tasks overlapped in modality/content. Cowan's theory might explain this pattern by suggesting that central attention tasks disrupt the information stored in the focus of attention, but that the focus of attention only holds a subset of the to-be-remembered items.

Rensink (2000; 2002) offers a more extreme position on the necessity of attention for WM. This theory was proposed as an explanation for our surprisingly poor ability to detect changes to scenes. Early studies revealed that very little visual information is accumulated across saccades (Grimes, 1996; McConkie, and Zola, 1979). This presents a paradox with the rich visual world that we subjectively experience. Perhaps this perception of a veridical external world is an illusion (Dennett, 1991; O'Regan, 1992). The reason we don't notice our inability to accumulate information across eye movements may be that we experience change when it occurs because it is accompanied by a motion signal that attracts attention. To explain these results, Rensink (2000a, 2000b, 2002) proposed that attention is necessary to see change. Consistent with this, if the motion signal that normally accompanies a change is disrupted (Levin and Simons, 1997; O'Regan, Rensink, and Clark, 1999; Rensink et al., 1997) change detection is quite poor. According to Rensink's coherence theory, representations formed by the perceptual system are volatile and have limited coherence over time unless they are attended. If attention is removed, representations return to their preattentive volatile state[3]. Coherence theory connects the capacity limit of WM with the capacity of attention. However, not only are the capacity limits of attention and WM distinct (Fougnie and Marois, 2006) but his theory cannot explain the good change detection performance for objects that are no longer attended (Hollingworth, 2004; Irwin and Zelinsky, 2002). In opposition to coherence theory, the evidence suggests that we can retain representations in visual WM when they are no longer attended.

The findings reviewed here suggest that the existing frameworks relating attention and WM must be modified. The following aim will be to determine what attributes a model of attention and WM must possess. For one, it appears necessary to distinguish between visuospatial attention and central attention—A theory will be incomplete if it presupposes a unified view of attention. This evidence for this distinction is strongest for WM maintenance. Visuospatial attention and WM maintenance seem largely independent unless spatial locations or feature-conjunctions are being stored. In contrast, central attention and verbal or object WM do result in dual-task interference. This is true even if there is no overlap of content in the two tasks, but the interference is stronger in the presence of overlap.

Visuospatial and central attention are more involved in WM encoding than WM storage. Jolicoeur and colleagues have provided evidence that central attention tasks interfere with encoding and that encoding slows central processing. Similarly, visuospatial attention acts to prioritize items for encoding, even when the capture of attention is not predictive of what needs to be stored. In some respects this is a surprising conclusion. In Irwin and Gordon's (1998) report procedure, the attended item is often not the item most relevant for the memory test. In this case, the optimal approach would be to execute the saccade while encoding letters from the other side of the display. Instead, the results suggest that WM encoding and visuospatial attention cannot be disentangled. A theory of WM must explain the close relationship between attention and encoding, while also explaining the more qualified relationship between attention and WM storage. It seems unlikely that a theory viewing encoding and maintenance as stages of a single process could account for these results. Woodman and Vogel (2005) have also argued that consolidation and maintenance involve separate processes. As further evidence of this, the amount of information that needs to be encoded, but not the amount of information that needs to be stored, prolongs the AB (Marois, et al., in preparation).

Many WM models distinguish between the storage of items that need to be accessed from the storage of items that only need to be maintained. This review reinforces the utility of this distinction. Studies that combine central processing and executive WM load all observe dual-task interference, while the same is not true for central processing and WM storage. The interference between central attention and executive WM is perhaps not surprising—it is

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[3] In this way coherence theory differs from object-file theory (Kahneman, Treisman, and Gibbs, 1992). Wolfe and colleagues (Wolfe, Klempen, Dahlen, 2000) have also suggested the importance of attention for continued perceptual coherence. However, Wolfe et al. argue that a memory of the coherent representation may be preserved even if attention is removed (pp. 693).

often difficult to draw the line between central processing and executive load. Whenever the contents of WM need to be manipulated or updated this may engage central stages of processing. The evidence that WM encoding engages central attention is less strong, but also has some support. This suggests a common mental workspace for WM encoding, WM manipulation, and central attention. It is possible that this workspace is also capable of storing items in WM, particularly if the storage requirement is high.

Just as visuospatial and central attention are distinct, perhaps central attention is a mixture of diverse types of attention. By using a broad definition of central attention, I may have blurred important distinctions that would have been apparent had a more narrow definition been adopted. This raises the question, what more restrictive definitions would have been appropriate. Taxonomies for central/executive processing have been developed (Miyake, Friedman, Emerson, Witzki, Howerter, and Wager, 2000; Oberauer, Süb, Wilhelm, and Wittman, 2003) but there is disagreement between them. Perhaps the most promising division is between tasks that stress inhibitory control (like stroop) and those that stress only processing speed (like the PRP). Indeed, evidence for interference between executive WM and central attention was mostly limited to tasks that required inhibition of task-irrelevant information (but see Oberauer, 2002). However, this may not imply that inhibition of task-irrelevant information is necessary to observe interference with executive WM. The current literature suggests only that empirical work has emphasized inhibitory control tasks. Also, this division may be more apparent than real. Both stroop and the PRP involve making a speeded response under conditions that tax central processing. Selecting a response may be more difficult in the presence of a competing alternative (stroop) or when response selection for two tasks overlap (PRP). Central attention may be best defined broadly if it reflects the existence of an amodal, task-generalized central processing capacity. Another problem is that even if this broad definition were blurring important distinctions, there doesn't seem to be enough data at present to describe the relationship between central attention and WM at a finer grained level of analysis. This is a topic best addressed by future research.

While the definition for central attention was purposefully inclusive, the definition for visuospatial attention was specific. Visuospatial attention was considered synonymous with sensory selection in visual space. While it may have been informative to discuss the relationship between featural attention and WM, pertinent data on this is lacking. Also not mentioned in this review is the relationship between WM and auditory attention. A strong distinction between auditory attention and WM also seems likely. One important question is whether orienting to the direction of a sound, or to a specific frequency would interfere with WM for either spatial WM or feature-conjunctions. Perhaps attending to the location of a sound would interfere with spatial WM, while attending to a specific frequency band would interfere with verbal/auditory WM.

Based on the available findings, a tentative model for the interaction between WM and attention is presented in figure 1. This model includes a passive WM store, a mental workspace for active processing, and a visuospatial attention system. Active processing is an amodal workspace required for WM manipulation, WM encoding, and central attention. The model predicts strong dual-task interference between any of these processes. Once information has been encoded into WM, it can be maintained in a passive store until it needs to be retrieved, or updated. The passive store appears to be modality specific, and may function similar to the slave systems proposed in the WM model of Baddeley and colleagues (Baddeley 1986). However, unlike Baddeley's model, I suggest that the ability to store information in the passive stores is independent of demands placed on executive/active processing (Baddeley and Logie, 1999). Interference between active processing and passive storage is only predicted to occur when the two forms of processing act on similar representations.

The model also predicts little interference from active processing and passive storage on the control of visuospatial attention. There does appear to be some evidence that visuospatial attention is impaired during active processing, particularly if a task requires coordination between active processing and visuospatial attention, such as visual search (Han and Kim, 2004). In addition, interference between visuospatial attention and passive storage does occur, but only under limited circumstances. For example, dual-task interference between attention and WM storage occurs when spatial representations are used by both tasks (Fougnie and Marois, in press; Oh and Kim, 2004; Woodman and Luck, 2004) but not when the WM task simply requires object identity (Woodman and Luck, 2001).

The proposed model owes much to previous proposals that have argued for a distinction between an active WM store that requires central attention and a passive WM store which does not (e.g. Cowan, 1995; Oberauer, 2002). Going beyond existing models, I have attempted to describe the relationship between visuospatial attention, central attention, and WM. This tentative model may prove wrong in the specifics, however, the need to acknowledge the multifaceted nature of attention and WM seems well supported by the existing literature.

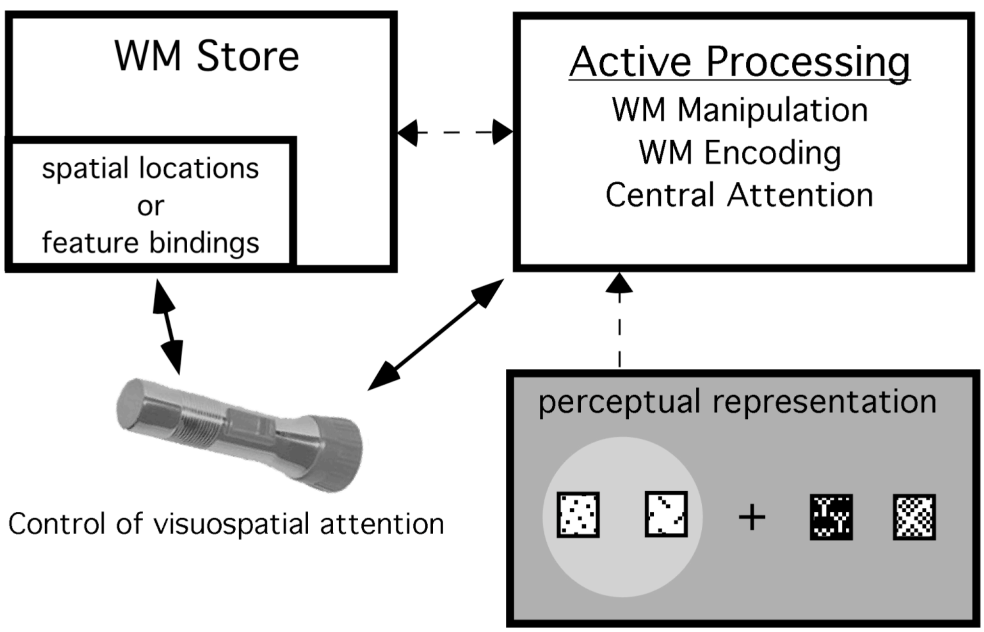

Figure 1. A proposed model for the relationship between attention and WM. This model contains four components: a workspace for active processing, a WM store, a structure for controlling visuospatial attention, and a perceptual representation in early visual cortex. Dotted arrows indicate information transfer between systems. Solid arrows indicate potential dual-task interference.

The evidence presented in this review comes from a variety of experimental techniques. Here I describe the pros and cons of different methodologies. The simplest method of studying the relationship between attention and WM is to have participants perform both tasks concurrently and to observe task performance. Dual-task interference studies comprise much of the results discussed here. One problem with interpreting dual-task costs is that interference can occur for multiple reasons. Having to perform two tasks instead of one increases the amount of preparation needed for the tasks and may result in a performance cost irrelative to the amount of task overlap. A dual-task methodology is best used along with methods to rule out non-capacity explanations for the observed interference (e.g. Fougnie and Marois, 2006; Logan, 1978; Woodman et al., 2001).

Perhaps more elegant than observing dual-task interference, is to observe strong associations or co-dependences between attention and WM. For example, Awh et al. (1999) found that storing a location in WM led to faster detection for targets presented at that location. Another example is Downing’s (2000) proposal that the storage of an item in WM leads to automatic orienting towards similar objects in the environment. This method allows an exploration of the connection between WM and attention without having to interpret dual-task costs. Unfortunately, these associations may not be straightforward to interpret either. Consider the apparent encoding benefit for items near the focus of visuospatial attention. This result may be interpreted as indicating the necessity of attention for WM encoding. An alternative possibility is that the benefit in encoding is a side effect of the improved perceptual processing afforded attended items.

Another method that has been used to explore attention and WM is to test for correlations between aspects of WM and attention. Neuroimaging approaches are often based on observing correlations—If two tasks activate the same neural regions then perhaps they involve similar processes. Another example of a correlation-based approach is using WMC to predict performance on attention tasks. The advantage of this method is that it can utilize a single-task design and compare performance across tasks. As with any conclusion based off correlational data, there is the possibility of a third variable affecting the results. Perhaps the reason that WMC predicts performance on stroop tasks is that both WM span tasks and stroop tasks require inhibition of task-irrelevant information. When using correlational data, it is wise to seek converging results with different tasks. For example, if WMC were found to predict PRP performance, this would suggest that the correlation between WMC and attention performance is not just due to high WMC individuals having better inhibitory control.

Conclusion

This review explored the relationship between attention and WM by comparing perceptual and central forms of attention to distinct processes in WM (encoding, storage, and manipulation). Contrary to widely held assumptions, the evidence suggested strong distinctions between attention and storage in WM. Dual-task interference between visuospatial attention and WM was observed only when spatial locations or feature-conjunctions were stored in WM. Interference between central attention and WM was mostly restricted to instances in which the contents of WM were being manipulated or updated. None of the discussed theories could account for all of the empirical data.

As a replacement, I proposed a simple model of how the components of WM and attention interact. I suggested more independence between attention and WM than other models predict, particularly in regard to visuospatial attention. The model predicts strong interference between tasks that engage central attention (i.e. WM manipulation, WM encoding, and central attention), and also predicts that these tasks will not interfere with simple visuospatial attention tasks. Hopefully, this model will help to stimulate work on issues that have not yet been explored or in which no clear consensus has emerged. For all the work done on this topic, the fundamental questions are still largely unanswered.

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