

**INVOLUNTARY ORIENTING OF ATTENTION
TO IRRELEVANT TASK GOALS**

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Psychology)
in The University of Michigan
2010

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Acknowledgements

I would first like to thank my committee members for their valuable feedback and insight. Daniel, my chair, deserves special thanks for embarking on a line of research with me that was new to both of us. Additionally, I am grateful he members of the Attention and Cognitive Control lab (Josh, Joe, Jerome, and Kamin) for their feedback on my presentations and writing, as well as their insights into experimental design and analysis.

My family provided me with limitless support both before this process and throughout it. Throughout my life my parents have given me all of the educational opportunities and encouragement possible. Equipped with the skills and preparation they provided, the decision to embark on a Ph.D. was an easy one. Even in graduate school they were helpful consultants with both the mechanics and content of my writing and research. My sisters have also guided me through this process with endless advice, and served as role models as they completed their graduate work before me. I am also grateful to the Moore family for treating me as a daughter/sister and for being true cheerleaders of my career.

The person who deserves the most thanks of all is my husband, Bradley Moore. His support and encouragement have been unconditional and forever enthusiastic. He was also my #1 troubleshooter and coach in graduate school, providing me with the best advice of anyone whenever I encountered an obstacle. I could not have imagined a better

partner to have while undertaking my Ph.D. or the rest of my academic career. Brad's help was especially appreciated at the final stages of this process.

Finally, I could not have completed this research without the help of numerous undergraduate research assistants. They each deserve recognition for their contributions:

- *Clare Porter* aided in many stages (design, data collection, analysis) of the Chapter 2 investigation.
- *Marshall O'Moore* helped me set up the first versions of Experiment 1 in Chapter 3 (we learned how to use Presentation software together), which laid the groundwork for the rest of the dissertation.
- *Amanda Lai* collected most of the data for Experiments 1 & 2 of Chapter 3, and also helped with stimulus selection and data analysis. Amanda helped present this work at the Vision Sciences Society conference in May 2009.
- *Jillian Steinberg* collected all of the data for Experiment 3 of Chapter 3.
- *Patricia Chen* assisted in data collection for experiments in Chapters 3 & 4, and contributed to additional investigations not included in the dissertation. Patricia also helped present this work at the Vision Sciences Society conference in May 2009.
- *Anna Grummon* collected and analyzed data for the first versions of Experiment 1 in Chapter 4, and assisted with stimulus creation.
- *Melanie Sottile* collected and analyzed data for both experiments in Chapter 4, and helped with the design of Chapter 5.
- *Erika Pinsker* assisted in data collection for experiments in Chapters 3 & 4, and led additional investigations not included in the dissertation.

- *Elise Darling* helped design the Chapter 5 investigation, and collected all of the data for this experiment. She assisted with analysis strategies as well. Elise also helped present this work at the Psychonomics Society conference in November 2009 and the Vision Sciences Society conference in May 2010.
- *Timothy Hinkey, Frederick Mark Holt, Zenaida Rivera, and Jennifer Lyu* each contributed to related work not included in this dissertation.

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Abstract

Attention overcomes processing limitations by enhancing information relevant to task goals and suppressing distraction. Although researchers agree that task goals are stored in memory, it is unclear how attention and memory are linked at the moment that a goal-related stimulus is detected, thereby capturing attention. We predicted that 1) attention capture leads to an involuntary orientation of attention to the related goal in memory; and 2) only a single goal can be attended during attention capture, consistent with a memory model that posits a “focus of attention” possessing a capacity limit of one. Our findings in Chapter 2 support our first prediction: participants oriented attention to the wrong task goal when instructed by an irrelevant but salient stimulus to do so. The set-specific capture phenomenon identified in Chapter 3 is also consistent with the first prediction, and supports the second. When participants searched for visual targets matching either of two current goals (e.g., identify both green and orange letters), identification accuracy was much lower when the target and an immediately preceding distractor were different target colors (e.g., green and orange) than when they were the same color (e.g., green). In Chapter 4, we reported that this set-specific capture cost could be eliminated when participants focused attention on the goal related to the target (e.g., green) prior to the appearance of a distractor relating to a different goal (e.g., orange). In line with the second prediction, this result suggests that only one goal can be enhanced at a time. Chapter 5’s results provided direct support for our second hypothesis: only the most recently attended goal influenced current target identification,

whereas previously attended goals did not. This result is only explained by the focus of attention model, and cannot be explained by an alternative graded, limited-resources model. Collectively, these studies provide a novel link between attention and memory when multiple goals guide behavior.

Chapter 1

General Introduction

Goal-directed attention is essential for most everyday cognitive operations, such as carrying on a conversation in a noisy bar, searching for a friend in a crowd of people, or doing homework while a roommate watches television in the next room. In each of these situations, attention boosts the signals of the incoming information relevant to current goals, while suppressing signals arising from irrelevant information.

Most models agree that goal-oriented or top-down attention is mediated by a fronto-parietal network (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta & Shulman, 2002; Hills, 2006; Mesulam, 2004). Dorsolateral frontal regions maintain representations of current goals, also known as attentional sets. These regions communicate with parietal regions, which distribute limited resources to behaviorally relevant stimuli and tasks (Banich, et al., 2000; Corbetta, et al., 1998; Hopfinger, Buonocore, & Mangun, 2000). This fronto-parietal network allocates resources by biasing sensory regions of the brain (e.g., visual or auditory cortices) to facilitate the processing of relevant stimuli and to suppress input from irrelevant information (Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Kanwisher & Wojciulik, 2000; Kastner, De Weerd, Desimone, & Ungerleider, 1998; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999).

Though attention usually helps us achieve our objectives, it can sometimes lead us astray. A commonly studied way in which attention leads us away from our goals occurs

when we erroneously direct attention to irrelevant information in the environment, as in the case of contingent attentional capture. This phenomenon is so named because distractors that share features with a current attentional set capture attention, demanding limited resources. In capture studies using visual search tasks, the presence of target-like distractors in a display slows participants' search (Lavie & de Fockert, 2005; Olivers, 2008; Theeuwes, 1992). In spatial cuing tasks, capture is observed as a moderate benefit when a target-like distractor appears just before a target in the same location (thereby directing attention to that location), and as a cost when they appear in different locations (Downing, 2000; Folk & Remington, 2008; Folk, Remington, & Johnston, 1992; Gibson & Kelsey, 1998). Finally, in capture studies with rapid serial visual presentation (RSVP) displays, participants are less likely to identify a briefly presented target when it appears shortly after a target-like distractor than when it appears after a stimulus not sharing features with an attentional set (Folk, Ester, & Troemel, 2009; Folk, Leber, & Egeth, 2002; Folk, Leber, & Egeth, 2008; Moore & Weissman, in press). In an everyday example of contingent attentional capture, it is harder to find one's friend in a crowd when there are many others who look like him/her (e.g., similar height, hair color, outfit) than when his/her features are unique.

Another behavioral cost arising from top-down attention occurs when one implements the wrong task goal. This can occur when an attentional set that was previously but not currently relevant continues to guide behavior (Leber, Kawahara, & Gabari, 2009; Thompson, Underwood, & Crundall, 2007), or when a participant switching among multiple tasks accidentally loads the wrong one (Moore, Porter, & Weissman, 2009; Yeung, Nystrom, Aronson, & Cohen, 2006). To take another example

from every day, a worker who changes jobs and adopts a new commute may have difficulty loading the task goal to drive to the new location, because the task goal to drive to his/her old job may still influence behavior.

Understanding the limits of attention when multiple goals guide behavior is especially important in an increasingly multi-tasking society (Carrier, Cheever, Rosen, Benitez, & Chang, 2009), but these limits remain unclear. On the one hand, some studies indicate that we can manage multiple task goals efficiently and without behavioral costs (Dux, et al., 2009; Maquestiaux, Lague-Beauvais, Ruthruff, Hartley, & Bherer, 2010; Schumacher, et al., 2001). Intuition from personal experience coheres with these results—it seems safe, under most conditions, to talk on one’s cell phone while driving. On the other hand, numerous studies demonstrate severe multi-tasking costs (Dejong, 1993; Pashler, 1994; Tombu & Jolicoeur, 2003; Van Selst, Ruthruff, & Johnston, 1999), and cell phone use while driving is known to be a major cause of accidents (Laberge-Nadeau, et al., 2003; Neyens & Boyle, 2007).

The present studies examine involuntary orienting to task goals in working memory; collectively, they aim to understand attentional mechanisms when multiple goals guide behavior. In these investigations, we draw upon an existing model of memory to explain behavioral costs due to attention, thereby providing a new link between attention and memory.

The first study (Chapter 2) uses functional magnetic resonance imaging (fMRI) to demonstrate that irrelevant instructions can cause involuntary orienting of attention to a currently inappropriate task. When participants maintain two goals in working memory with the expectation of performing either task on any given trial (e.g., “look at the

screen” or “listen to the headphones”), irrelevant instructions presented closely in time with relevant instructions can cause the attentional network to enhance the wrong goal set, as indexed by an increase in activity to the wrong sensory cortex. Though the interval between the instructions and target presentation is sufficiently brief to avoid a behavioral cost, the imaging results provide clear evidence that irrelevant stimuli in the environment can cause an involuntary shift of attention to the wrong task.

The second study (Chapter 3) again demonstrates that an irrelevant stimulus can cause a task goal in memory to become enhanced, and it invokes a limited-capacity focus of attention model from the working memory literature to account for this enhancement. In this study, participants search for letters appearing in either of two target colors (e.g. “green” and “orange”) in a rapid serial visual presentation (RSVP) stream. Replicating prior findings of contingent attentional capture, participants are less likely to identify targets when the targets are preceded by irrelevant, target-colored distractors than when targets are preceded by distractors that are not target-colored. Critically, contingent capture is two to three times larger when the distractor (e.g., green) and subsequent target (e.g., orange) match different attentional sets than when they match the same attentional set (e.g., both orange). Additional experiments demonstrate that this effect, which we call *set-specific capture*, is not due to bottom-up perceptual priming or feature interference. We suggest that participants involuntarily enhance the attentional set that matches the distractor (e.g., “identify green letters”). They do so by placing the set in the focus of attention, a structure in working memory that is limited to a single item.

The third study (Chapter 4) explores how set-specific capture costs can be reduced in an RSVP task similar to that in Chapter 3. To accomplish this, irrelevant

stimuli (e.g., a green digit) guide participants to focus attention on the appropriate attentional set (e.g., “identify green letters”) prior to distraction related to a different goal (e.g., an orange peripheral letter). This procedure results in preserved target identification performance when the target’s color matches the same attentional set as the first stimulus (e.g., green), and matches a different attentional set than the peripheral distractor. In addition to showing how set-specific capture can be eliminated, this study contributes to the evidence supporting the focus of attention model proposed in Chapter 3.

The fourth study (Chapter 5) compares the focus of attention model to an alternative, limited-resources account of the set-specific capture findings from Chapters 3 and 4; it finds that only the focus of attention model can explain set-specific capture. In this study, participants maintain three search sets for colored letters (e.g., orange, green, and lavender) that appear in an RSVP stream. Up to three targets appear on each trial, and participants are to identify all of them. When the first two targets (T1 & T2) match different attentional sets (e.g., orange and lavender) and are both correctly identified, participants are equally likely to identify the third target (T3) when it is the same color as T1 (e.g., orange) as when it is a third color (e.g., green); thus, T1’s corresponding attentional set is not still enhanced when T3 is presented. However, if T2 is not identified, participants are more likely to identify T3 when it is the same color as T1, which indicates lingering enhancement of T1’s corresponding set. Taken together, these results demonstrate that only one attentional set (i.e., that of the most recently-identified target) can be enhanced in the focus of attention at a time. The findings support the focus of attention model.

Chapter 2

Consciously perceived, irrelevant instructional cues can hijack the attentional network

Abstract

Functional neuroimaging studies of endogenous cued attention suggest that a fronto-parietal attentional network keeps track of current task objectives in working memory and enhances activity in posterior sensory regions that underlie the perceptual processing of behaviorally relevant stimuli. Relatively little is known, however, about whether consciously perceived, irrelevant instructional cues can hijack the attentional network, leading to an enhancement of the perceptual processing of irrelevant stimuli. Using a cross-modal attentional cueing task in combination with functional magnetic resonance imaging, we found that such irrelevant cues can indeed hijack the attentional network, as indexed by increased activity in (a) frontal regions that control attention and (b) sensory cortices that underlie the perceptual processing of task-irrelevant stimuli. Furthermore, we found that in left ventrolateral (but not dorsolateral) prefrontal regions, the magnitude of this increased activity varies with whether an irrelevant instructional cue is presented simultaneously with (versus after) a relevant instructional cue. These findings show that consciously perceived, irrelevant instructional cues can activate inappropriate task objectives in working memory, resulting in a hijacking of the attentional network. Moreover, they reveal different time courses of hijacking effects in ventrolateral and dorsolateral prefrontal regions, consistent with models in which these regions make distinct contributions to cognitive control.

Introduction

The ability to voluntarily and flexibly orient attention toward behaviorally relevant stimuli is a fundamental aspect of human cognition. Some models posit that this ability is enabled by a fronto-parietal attentional network (Corbetta, et al., 2000; Corbetta & Shulman, 2002; Hills, 2006; Mesulam, 2004), in which lateral prefrontal regions of the brain keep track of current task objectives in working memory (Banich, et al., 2000; Milham, Banich, & Barada, 2003; Miller & Cohen, 2001) and communicate those objectives to parietal regions that allocate attention to behaviorally relevant stimuli (M. Corbetta, et al., 1998; Hopfinger, et al., 2000). The attentional network is also thought to bias activity in sensory regions of the brain to favor the perceptual processing of upcoming relevant stimuli (Kanwisher & Wojciulik, 2000; Kastner, et al., 1998; Kastner, et al., 1999). Consistent with this model, cueing humans to attend to an upcoming behaviorally relevant feature of the task environment (e.g., a specific color or spatial location) leads to a relative enhancement of activity in frontal and parietal regions of the attentional network as well as in sensory regions that underlie the perceptual processing of the behaviorally relevant feature (Hopfinger, et al., 2000; Kastner, et al., 1999; Shulman, et al., 1999).

While often beneficial, the cognitive flexibility that allows us to voluntarily direct our attention can have costs. One such cost is attentional capture, a phenomenon in which attention is drawn to irrelevant stimuli that share critical features (e.g., color) with target stimuli as defined by task objectives (Downing, 2000; Folk, Leber, & Egeth, 2002; Folk, et al., 1992) or that, for other reasons, stand out in the environment (Theeuwes, 1994; Yantis & Hillstrom, 1994). Presenting irrelevant stimuli that capture attention greatly impairs the identification of target stimuli that are presented soon afterwards

(Folk, et al., 2002). As an everyday example, while searching for a friend in a red shirt at a crowded sporting event, the appearance of a stranger wearing a red shirt may capture one's attention and interfere with one's ability to locate the friend.

A second cost that derives from this cognitive flexibility is that representations of previously relevant task objectives sometimes remain activated in working memory even when they are no longer relevant, resulting in increased attention to irrelevant stimuli and in slower and/or less accurate performance (Yeung, et al., 2006). Drawing again from everyday experience, if the goal of playing offense remains activated in a basketball player's working memory for too long after the other team steals the ball, then the player may be unable to quickly switch to playing defense in order to prevent the other team from scoring. Disruptions of attention associated with the activation of irrelevant task objectives in working memory are also prominent after brain damage to the lateral prefrontal cortex (Berger & Posner, 2000) and in numerous clinical syndromes, such as drug addiction (Ventura, Alcaro, & Puglisi-Allegra, 2005), and attention deficit and hyperactivity disorder (Casey, et al., 1997; Max, et al., 2005). For these reasons, there has been growing interest in understanding under what circumstances irrelevant task objectives become activated in working memory.

The authors of two recent studies used variants of attentional cueing tasks, in combination with functional magnetic resonance imaging (fMRI), to directly investigate some of the conditions under which irrelevant task objectives become activated in working memory, and the behavioral and neural consequences of experimentally inducing such activation (Brass & von Cramon, 2004b; Lau & Passingham, 2007). In both studies, a relevant instructional cue directed participants to perform one of two

possible tasks on an upcoming target stimulus, while an irrelevant instructional cue signaled either the same task (congruent cues) or a different task (incongruent cues). Brass and von Cramon (2004b) reported increased error rates to identify targets that followed incongruent (versus congruent) cues (i.e., a behavioral cue congruency effect). However, they observed no difference in brain activation for incongruent and congruent cues (i.e., a neural cue congruency effect). Thus, this initial study revealed a behavioral deficit associated with activating irrelevant task objectives in working memory, but shed no light on the neural underpinnings of that deficit.

Lau & Passingham (2007) also manipulated cue congruency to investigate the behavioral and neural consequences of activating irrelevant task objectives in working memory. Similar to Brass and von Cramon (2004b), they reported slower and less accurate behavioral performance for targets that followed incongruent (versus congruent) cues. However, they also observed significantly greater activation for incongruent than for congruent cues in the mid-dorsolateral prefrontal cortex (DLPFC), a neural structure that is thought to play a key role in maintaining task objectives in working memory (Banich, et al., 2000; Hopfinger, et al., 2000; Milham, et al., 2003; Miller & Cohen, 2001). One interpretation of this neural cue congruency effect is that incongruent cues led to the activation of both relevant and irrelevant task objectives in working memory while congruent cues led to the activation of only relevant task objectives (Lau & Passingham, 2007). Consistent with this interpretation, activity in posterior cortical regions underlying performance of the irrelevant task was greater for incongruent than for congruent cues. These findings suggest that activating irrelevant task objectives in working memory impairs behavioral performance by hijacking the attentional network

into enhancing the processing of currently irrelevant task representations, including representations of irrelevant stimuli.

Of importance, such hijacking differs from various distracter interference effects that are more traditionally reported in the selective attention literature. For example, while hijacking leads to the activation of an irrelevant task goal in working memory, contingent attentional capture results in a shift of spatial attention toward irrelevant stimuli whose features match a relevant task goal (Folk, et al., 1992; Serences, et al., 2005). Similarly, distracters in selective attention tasks (e.g., the Stroop and flanker tasks) often impair performance because they activate competing responses that are associated with a relevant task goal (MacLeod, 1991). Thus, hijacking effects differ from various other types of distracter effects because they stem from the activation of an irrelevant goal in working memory, rather than from the activation of a relevant goal.

A key finding in Lau and Passingham's (2007) study was that cue congruency effects in the dorsolateral prefrontal cortex were observed only when irrelevant instructional cues were not consciously perceived. This finding concurs with evidence indicating greater distraction from irrelevant stimuli that are unconsciously (versus consciously) perceived, an effect that may occur because unconsciously perceived stimuli sometimes fail to be inhibited by attentional control mechanisms (Tsushima, Sasaki, & Watanabe, 2006). However, it conflicts with a vast literature indicating that consciously perceived, irrelevant stimuli robustly interfere with the performance of selective attention tasks by activating irrelevant semantic and response representations in working memory (MacLeod, 1991). From the perspective of this latter literature, it is perplexing that both Brass and von Cramon (2004b) and Lau and Passingham (2007) did not observe neural

evidence indicating that consciously perceived irrelevant stimuli can activate irrelevant task objectives in working memory.

One possible explanation is that the simple shapes that served as irrelevant instructional stimuli in these studies (e.g., squares and diamonds) were not strongly associated with irrelevant task objectives. The degree to which a stimulus is strongly and automatically associated with an irrelevant semantic or response representation often predicts the amount of interference that it will evoke when it serves as a distracter in a selective attention task (Dunbar & MacLeod, 1984; MacLeod & Dunbar, 1988). For example, due to our extensive language training, words automatically activate irrelevant semantic and response representations in working memory which, in turn, interfere with the performance of selective attention tasks (MacLeod, 1991). Given these considerations, effects of consciously perceived cue congruency on brain activity should be most clearly visible when irrelevant instructional cues are strongly associated with irrelevant task objectives.

In which brain regions might one expect manipulations of consciously perceived cue congruency to influence activity? First, one might expect to observe cue congruency effects in posterior sensory regions whose nature is similar to the effects reported by Lau and Passingham (2007). More specifically, for congruent cues one should expect a relative enhancement of activity in task-relevant sensory regions, consistent with the existing literature on endogenous cued orienting of attention (Kanwisher & Wojciulik, 2000; Kastner, et al., 1998; Kastner, et al., 1999). For incongruent cues, however, one should expect a reduction of this enhancement, or possibly even a reversal, in which there is an enhancement of activity in task-irrelevant sensory regions (Lau & Passingham,

2007). In short, the nature of cue congruency effects in the sensory cortices should reveal whether consciously perceived, irrelevant instructional cues can hijack the attentional network.

Second, one might expect to observe larger effects of cue congruency on brain activity when a relevant and an irrelevant instructional cue are presented simultaneously than when they are presented sequentially (i.e., when the irrelevant cue is presented nearly a second after the relevant cue) in the left ventrolateral prefrontal cortex (VLPFC). The left VLPFC is thought to retrieve task sets or stimulus-response mappings from memory (Brass & von Cramon, 2004a; Bunge, 2004). Overall, the demands imposed on such retrieval processes should be greater when an irrelevant cue signals a different (versus the same) task than a relevant cue (Brass & von Cramon, 2004b; Lau & Passingham, 2007; Mattler, 2005). However, since cue-triggered retrieval of a task set from memory is usually completed in well under a second (Monsell & Mizon, 2006), any increase in the demands on task-set retrieval processes that is imposed by varying cue congruency should be maximal when a relevant and an irrelevant cue are presented simultaneously and minimal when they are presented sequentially (i.e., when the irrelevant cue is presented almost a second after the relevant cue). Drawing once again from everyday life, it is often much more difficult to retrieve from memory the mental set that is appropriate for performing a particular cognitive task (e.g., playing chess) when a distracter (e.g., a commercial on TV) simultaneously activates a competing, irrelevant task set in working memory (e.g., watching a movie) than when a distracter activates a competing task set only after the relevant task set has been retrieved.

Third, in contrast to the left VLPFC, one might expect to observe relatively similar cue congruency effects in a simultaneous and a sequential presentation condition in dorsolateral prefrontal cortex (DLPFC) regions that help to maintain task sets in working memory (Banich, et al., 2000; Miller & Cohen, 2001) and in dorsal anterior cingulate cortex (ACC) regions that detect or resolve conflict between relevant and irrelevant task sets (Luks, Simpson, Feiwell, & Miller, 2002; Orr & Weissman, 2009). In both presentation conditions, it may be harder to maintain information about the relevant task set after an irrelevant instructional cue activates a competing task set in working memory (i.e., incongruent cues) than after it activates the relevant task set (i.e., congruent cues). Similarly, in both presentation conditions incongruent cues should impose greater demands than congruent cues on processes that detect and/or resolve conflict between the relevant and the irrelevant task sets. Thus, cue congruency effects in the DLPFC and the dorsal ACC may not vary as a function of the relative timing with which a relevant and an irrelevant instructional cue are presented.

Fourth, one might expect to observe cue congruency effects in superior and/or inferior parietal regions that manage and allocate attentional resources. As we stated earlier, lateral prefrontal regions that keep track of current task objectives in working memory (Banich, et al., 2000; Milham, et al., 2003; Miller & Cohen, 2001) are thought to communicate with parietal regions that allocate attentional resources to behaviorally-relevant stimuli (Corbetta, et al., 1998; Hopfinger, et al., 2000). Thus, if irrelevant instructional cues influence activity in lateral prefrontal regions underlying working memory, they might also influence activity in parietal regions that allocate attentional resources.

With the considerations above in mind, we used a cross-modal attentional cueing task (Figure 2-1) in combination with fMRI to investigate whether consciously perceived, irrelevant instruction words can hijack the attentional network, and whether the extent of any such hijacking depends on the relative timing with which the relevant and the irrelevant instruction words are presented. In each trial, a relevant visual cue (“Look” or “Hear”) instructed participants to attend to and identify either the visual letter (“X” or “O”) or the auditory letter (“X” or “O”) within a possibly upcoming, multisensory letter pair. Accompanying the relevant visual instruction word was an irrelevant auditory word (“Look” or “Hear”) that signaled either the same task as the visual instruction word (congruent cues) or the opposite task (incongruent cues). The irrelevant auditory instruction word was presented either at the same time as the relevant visual word (simultaneous condition) or 850 ms later (sequential condition). In cue-plus-target trials, a multisensory letter pair was presented 1.875 seconds after the relevant visual cue word. Participants were asked to identify the target letter (“X” or “O”) that appeared in the cued sensory modality while ignoring the distracter letter in the other modality. The distracter letter was either the same as the target letter in the cued modality (congruent target-distracter pairs) or different (incongruent target-distracter pairs). In cue-only trials, the cue was not followed by a target. These trials allowed us to isolate the neural correlates of attentional control processes that were specific to our cue stimuli (Corbetta, et al., 2000). We note that the simultaneous condition used here was also used in a different study from our laboratory (Orr & Weissman, 2009), but that only the present study, which involved different participants, included both the simultaneous and the sequential presentation conditions.

The view that consciously perceived, irrelevant instruction words can activate irrelevant task objectives in working memory leads to four predictions. First, it predicts that the typical pattern of biasing activity in the sensory cortices for an audiovisual cued attention task (i.e., a relative enhancement of activity for “Look” versus “Hear” cue-only trials in the visual cortex, and the opposite effect in the auditory cortex) (Weissman, Warner, & Woldorff, 2004) should be observed more strongly for congruent than for incongruent cue-only trials. Second, it predicts larger effects of cue congruency in the simultaneous than in the sequential condition in left VLPFC regions that retrieve task sets from memory to guide subsequent performance (Bunge, 2004). Third, it predicts cue congruency effects in DLPFC regions that maintain task sets in working memory (Lau & Passingham, 2007) and in dorsal ACC regions that detect and/or resolve conflict between relevant and irrelevant task sets (Luks, et al., 2002; Orr & Weissman, 2009) and that the magnitude of these effects will not vary across the simultaneous and the sequential conditions. And fourth, it predicts cue congruency effects in parietal regions that allocate attentional resources to behaviorally-relevant stimuli (Corbetta, et al., 1998; Hopfinger, et al., 2000).

Materials and Methods

Participants

Twenty University of Michigan students (10 female) between the ages of 18 and 30 participated in the study. All participants were right-handed, had normal or corrected to normal vision, and had no history of neurological disorders. Each received \$20 per hour for participating, and the experiment lasted approximately 2 hours. Participants gave informed consent before the experiment in accordance with the University of Michigan Medical School Institutional Review Board.

Data acquisition

A Dell PC running Presentation software (Neurobehavioral Systems, Albany, CA) presented the experimental stimuli and recorded participants' responses. Visual stimuli were projected onto a screen at the back of the magnet's bore and were viewed through a mirror. Auditory stimuli were delivered through MR-compatible headphones. Headphone volume was adjusted for each participant separately, such that the auditory stimuli could be heard clearly over the background noise produced by the MR scanner. Participants' responses in the scanner were registered by an MR-compatible response box.

All MRI images were collected on a 3T Signa whole-body scanner equipped with a standard head coil. The blood oxygenation level-dependent (BOLD) signal was measured using a reverse spiral imaging sequence (repetition time (TR), 1250ms; echo time (TE), 30ms; field of view (FOV) 22cm; flip angle, 70°; 27 contiguous 4.5-mm-thick slices; in-plane resolution 3.44 x 3.44 mm). Anatomical images were collected in the same axial orientation as the functional images, but with a T1-weighted gradient-echo (GRE) sequence (TR, 250 ms; TE, 5.4ms; flip angle, 90°; in-plane resolution 0.86 x 086 mm). Every participant completed six runs of the experimental task, each of which consisted of 96 trials over a period of 8 minutes and 10 seconds. During each functional run, 389 brain volumes were collected. The first six images from each run contained no trials and were discarded prior to analysis.

Task

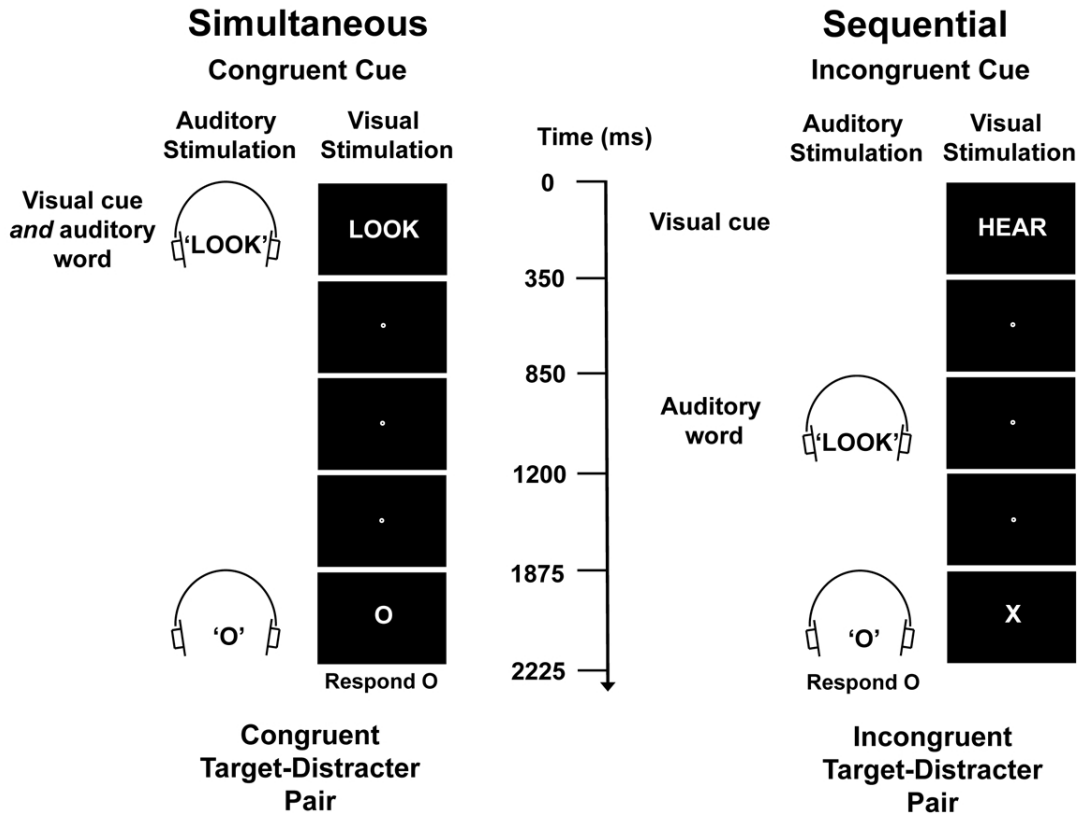


Figure 2-1: Experimental Task.

In each trial, a visual cue ('LOOK' or 'HEAR') instructed participants to attend to and identify either the visual letter ('X' or 'O') or the auditory letter ('X' or 'O') of a possibly upcoming audiovisual letter pair. An irrelevant auditory word signaled either the same task as the visual cue or the opposite task. In the simultaneous condition, the irrelevant auditory word was presented at the same time as the visual cue. In the sequential condition, the irrelevant auditory word was presented 850 ms after the visual cue. In cue-plus-target trials, an audiovisual target-distracter letter pair was presented 1.875 seconds following the onset of the relevant visual cue. The distracter letter was presented in the opposite modality as the target letter and was equally likely to be the same letter as the target (congruent target-distracter pairs) or a different letter (incongruent target-distracter pairs). In cue-only trials (33%, not shown), the relevant visual cue was not followed by a target-distracter letter pair.

Participants were instructed to maintain fixation on a small white dot (0.15° x 0.17°) presented at the center of the screen throughout each run. At the start of every trial, a relevant visual cue word ("LOOK", 3.12° x 0.86°; or "HEAR" 3.12° x 0.86°) appeared on the screen for 350 ms (Figure 2-1, top). The visual cue word instructed participants either to maintain attention in the visual modality (i.e., "LOOK") or to switch attention to

the auditory modality (i.e., “HEAR”). An irrelevant (binaural) auditory word was also presented, either at the same time as the visual cue word (simultaneous condition) or 850 ms after the onset of the visual cue word (sequential condition). The irrelevant auditory word signaled either the same task as the relevant visual word (congruent cues; 50% of trials) or the opposite task (incongruent cues; 50% of trials). In cue-plus-target trials (66%), a briefly-presented multisensory letter pair (duration, 350 ms) appeared 1875 ms after cue onset (Figure 2-1, bottom). Each letter within this audiovisual letter pair was either an “X” or an “O” (in the visual modality, the “X” subtended $1.10^\circ \times 1.36^\circ$ of visual angle and the “O” subtended $1.18^\circ \times 1.38^\circ$ of visual angle). The distracter letter in the uncued modality was equally likely to be the same letter as the target (congruent target-distracter pairs; Figure 2-1, bottom left) or a different letter (incongruent target-distracter pairs; Figure 2-1, bottom right). In cue-only trials (33%), the cue was not followed by a multisensory letter pair, which allowed us to isolate brain activity that was specific to our cue stimuli (Corbetta, et al., 2000).

Participants were instructed to indicate whether the letter in the cued modality was an “X” or an “O” by pressing one of two response buttons as quickly and as accurately as possible, using either the index or the middle finger of their right hand. If a response was not detected within 1875 ms after target onset, an error was recorded. Decision-response mappings were counterbalanced across participants. In all trials, the fixation dot changed color from white to red 1875 ms after cue onset. Because this change was coincident with target presentation in cue-plus-target trials, in cue-only trials it signaled to participants that no target would occur and, hence, that they could cease

attending (Corbetta, et al., 2000). At the end of each trial (i.e., 3750 ms after trial onset), the fixation dot reverted to white.

Design

For each participant, we interleaved three runs of the sequential condition with three runs of the simultaneous condition. Half of the participants started with the sequential condition (i.e., sequential, simultaneous, sequential, simultaneous, sequential, simultaneous) while the other half started with the simultaneous condition. Prior to entering the scanner, participants completed a training session in which they briefly practiced the sequential and simultaneous task conditions. Participants were required to achieve 90% accuracy over a 32-trial block for each task condition before performing the task in the scanner. Every participant achieved this criterion on the first attempt.

In each run, there were 12 trial types (four cue-only and eight cue-plus-target), each of which was presented eight times in a randomized order. Thus, there were a total of 96 trials per run. The four cue-only trial types consisted of the four possible combinations of Cued Modality (Look, Hear) and Cue Congruency (congruent, incongruent). The eight cue-plus-target trial types consisted of the eight possible combinations of Cued Modality, (Look, Hear), Cue Congruency (congruent, incongruent), and Target Congruency (congruent, incongruent). To optimize regression estimates of the BOLD responses that were produced by each of our 12 trial types, the inter-trial interval (ITI) was varied between zero and five TRs using a nearly exponential distribution that favored short ITIs (Miezen, Maccotta, Ollinger, Peterson, & Buckner, 2000).

Data analysis

The behavioral data were analyzed using SPSS (SPSS, 2006). Next, the functional images were corrected for asynchronous slice acquisition, head movement, normalized to Montreal Neurological Institute (MNI) space (voxel size: 3.75 x 3.75 x 4.5 mm), and spatially smoothed with a three-dimensional Gaussian filter (8 mm full-width half-max) using SPM2 (Friston, 1995). Due to head movements greater than 3 mm, two participants were excluded from further analyses, leaving a total of 18 participants.

The time series for each functional run was modeled using a finite impulse response model. This model empirically derives the stimulus-locked BOLD response across time to each trial type in an event-related design without assuming a canonical hemodynamic response shape, and has been validated in prior studies (Ollinger, Corbetta, & Shulman, 2001; Ollinger, Shulman, & Corbetta, 2001). We estimated 14 TRs (17.5 s) of the BOLD response for each trial type, yielding 168 regressors (12 trial types x 14 TRs) in the design matrix. We also included six motion regressors (i.e., SPM2 estimates of translation along and rotation around the x, y, and z axes) and two regressors for the linear trend and the y-intercept term. For every participant, parameter estimates for each trial type were converted to units of percent signal change from baseline (i.e., the y-intercept term) in each run and then averaged across runs of the same type (i.e., sequential or simultaneous).

Voxelwise analyses

We performed two random effects, one-sample t-tests. The first t-test localized voxels in which the cue congruency effect (i.e., greater peak activity for incongruent than for congruent cue-only trials) was significantly larger in the simultaneous condition than in the sequential condition. Peak activity was defined as the maximum fMRI signal

between 3.75 and 6.25 seconds after stimulus onset. The second t-test localized voxels that showed significantly greater peak activity for incongruent than for congruent cue-only trials, averaging across the simultaneous and the sequential conditions. Each of these directional t-tests was thresholded at $t(17) = 3.63$, $p < 0.001$ (one-tailed).

Region of interest analyses

Regions of interest (ROIs) in the left DLPFC, the right DLPFC, and the dorsal ACC were centered on coordinates that were localized in a prior study of cross-modal attention, which used the same multisensory target stimuli (Weissman, et al., 2004). All other ROIs were defined functionally, based on average activity for all cue-only or all cue-plus-target trials. We first performed a one-way repeated-measures analysis of variance (ANOVA) across time (14 TRs) on the average stimulus-locked response to all types of cue-only trials. After the resulting F-map was height and extent thresholded ($p < 0.01$; five contiguous voxels), we defined ROIs in the right VLPFC and in the left middle/posterior VLPFC. Because we did not identify ROIs in either the superior parietal lobe (SPL) or the inferior parietal lobe (IPL) in the cue-only map, we next constructed an analogous F-map (height and extent thresholded to $p < 0.01$; five contiguous voxels) based on the average stimulus-locked BOLD response across time (14 TRs) to cue-plus-target trials. Using this map, we defined ROIs in the right SPL, the left SPL, and the left IPL (no right IPL region was identified). We also defined two ROIs in the sensory cortices: the top-activating region of visual (occipital) cortex and the top-activating region of auditory (temporal) cortex. The relatively liberal thresholds that were used to define our ROIs did not bias the outcome of our subsequent analyses because all subsequent ROI-level contrasts were orthogonal to the contrasts that we used

to create the ROIs. Each ROI consisted of a 27-voxel cube centered on a local maximum (see Table 2-1).

Region of Interest	Brodmann Area	MNI Coordinates		
		x	y	z
Left dorsolateral prefrontal cortex	9	-48	15	31
Right dorsolateral prefrontal cortex	9	48	19	31
Left ventrolateral prefrontal cortex	9/44	-41	8	32
Right ventrolateral prefrontal cortex	9/44	53	12	36
Dorsal anterior cingulate cortex	32	-2	6	52
Right superior parietal lobe	7	34	-68	45
Left superior parietal lobe	7	-15	-75	54
Left inferior parietal lobe	7	-34	-60	45
Right middle occipital gyrus	17/18	34	-90	-5
Left superior temporal gyrus	42	-53	-34	14

Table 2-1: Regions of interest in the present study.

Parameter estimates for each trial type were averaged across all voxels in each ROI. Random effects analyses were then performed to contrast peak activity for different trial types. As in the voxelwise analyses, peak activity in cue-only trials was defined as the maximum fMRI signal between 3.75 and 6.25 seconds after cue onset. To allow for both task- and participant-related variability, peak activity was estimated separately for each trial type and participant.

Results

Behavior

Mean reaction time and mean accuracy were analyzed in separate repeated-measures analyses of variance (ANOVAs) with four within-participants factors: Condition (simultaneous, sequential), Cued Modality (visual, auditory), Cue Congruency (congruent, incongruent), and Target Congruency (congruent, incongruent). Two significant main effects replicated our findings from a prior study (Weissman, et al., 2004). First, participants were both faster (864 ms vs. 939 ms, $F(1,17) = 59.01$, $p < 0.0001$) and more accurate (97.8% vs. 96.5%, $F(1,17) = 11.79$, $p < 0.003$) when responding to congruent (versus incongruent) target-distracter pairs. Second, participants were both faster (865 ms vs. 938 ms, $F(1,17) = 44.18$, $p < 0.0001$) and more accurate (98.1% vs. 96.2%, $F(1,17) = 8.789$, $p < 0.009$) when responding to targets in the visual (versus the auditory) modality.

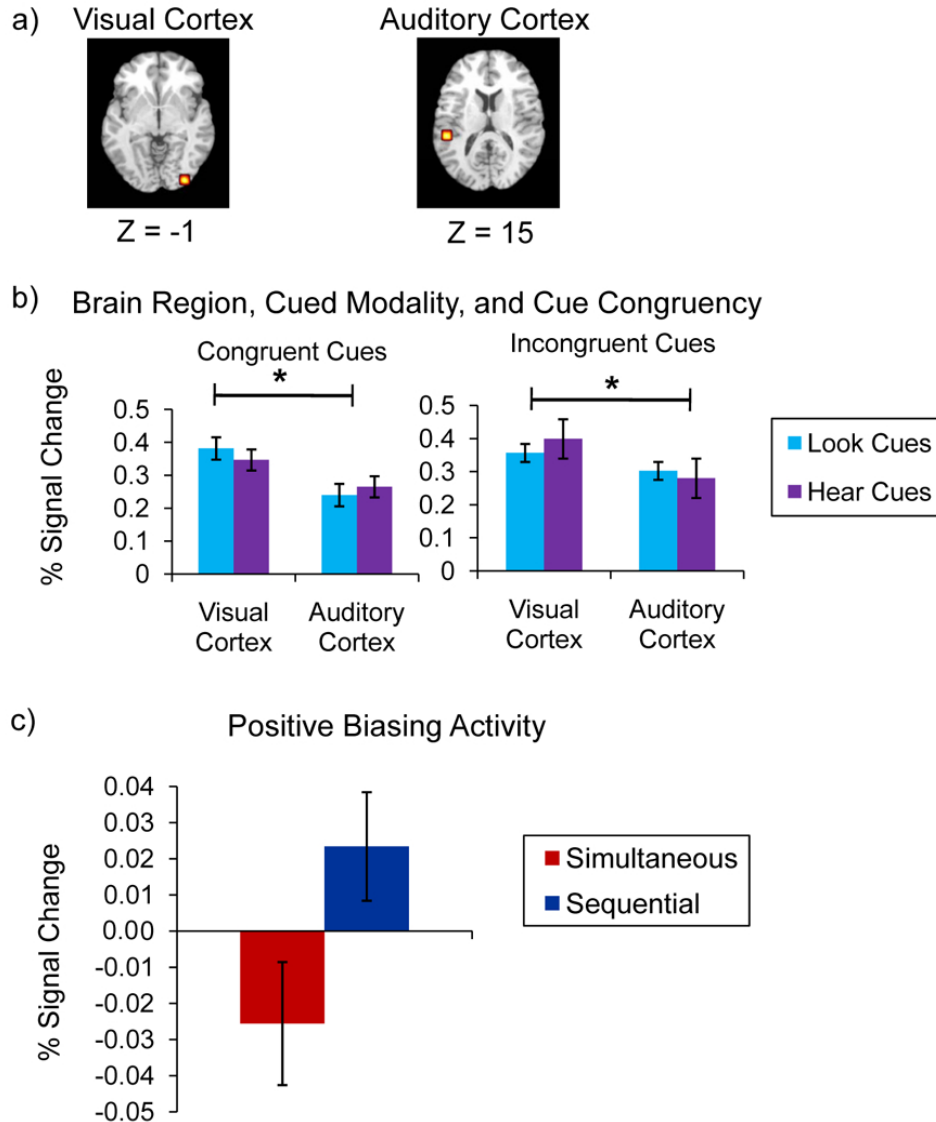


Figure 2-2: Peak activity in cue-only trials in visual and auditory cortex regions of interest.

(a) Axial slices of visual and auditory cortex regions of interest overlaid on an MNI-normalized anatomical brain. In this and subsequent figures, z coordinates refer to MNI space. (b) Peak activity in cue-only trials as a function of Brain Region (visual cortex, auditory cortex), Cued Modality (visual, auditory) and Cue Congruency (congruent cues, incongruent cues) averaged across the simultaneous and the sequential conditions. Asterisks indicate significant simple effects or interactions. Notice that the pattern of biasing activity that is typical for an audiovisual cued attention task (i.e., greater activity for “Look” than for “Hear” cues in the visual cortex and greater activity for “Hear” than for “Look” cues in the auditory cortex) was observed for congruent cues while the reverse pattern was observed for incongruent cues. (c) Positive biasing activity in the visual cortex (i.e., activity for “Look” cue-only trials minus activity for “Hear” cue-only trials) averaged with positive biasing activity in the auditory cortex (i.e., activity for “Hear” cue-only trials minus activity for “Look” cue-only trials), plotted separately for the simultaneous and the sequential conditions. Notice that there was significantly more positive biasing activity in the sequential condition than in the simultaneous condition.

We also observed a significant interaction between Target Congruency (congruent, incongruent) and Cued Modality for accuracy, $F(1,17) = 5.85, p < 0.027$. Accuracy for congruent targets was always numerically higher than accuracy for incongruent targets, but this difference was significantly larger when participants were cued to “Hear” (97.3% vs. 95.1%; $F(1,17) = 17.47, p < 0.001$) than when they were cued to “Look” (98.4% vs. 97.7%; $F(1,17) = 1.93, p > 0.18$). No other behavioral effects were significant.

FMRI

Sensory Regions

Our first prediction was that the typical pattern of biasing activity in the sensory cortices for an audiovisual cued attention task (Weissman et al., 2004) would be observed more strongly in congruent than in incongruent cue-only trials. Specifically, for congruent cues we predicted an interaction between Cued Modality (visual, auditory) and Brain Region (visual cortex ROI, auditory cortex ROI) indicating a relative enhancement of activity in the visual cortex for “Look” versus “Hear” cue-only trials, and a relative enhancement of activity in the auditory cortex for “Hear” versus “Look” cue-only trials. For incongruent cues, however, we predicted that this pattern would be significantly less pronounced, or possibly even reversed, consistent with a hijacking of the attentional network (Lau & Passingham, 2007). We tested these predictions in the regions of visual and auditory cortex that were most highly activated by our stimuli (Figure 2-2a; see *Materials and Methods*).

Consistent with our first prediction, we observed a significant three-way interaction among Cue Congruency (congruent, incongruent), Cued Modality (visual,

auditory) and Brain Region (visual cortex ROI, auditory cortex ROI), $F(1,17) = 9.36$, $p < 0.0071$ (Figure 2-1b). For congruent cues we observed a significant two-way interaction between Cued Modality and Brain Region, $F(1,17) = 5.18$, $p < 0.036$. As expected, this interaction reflected a relative enhancement of activity in the visual cortex for “Look” versus “Hear” cue-only trials, and a relative enhancement of activity in the auditory cortex for “Hear” versus “Look” cue-only trials (Figure 2-1b, left). Neither of the simple effects associated with this interaction was significant (both $p > 0.06$, one-tailed). However, the nature of the significant interaction clearly indicates a relative shift of activity toward the sensory cortex corresponding to the cued modality. For incongruent cues, we also observed a significant interaction between Cued Modality and Brain Region, $F(1,17) = 7.15$, $p < 0.016$. As expected, this interaction reflected a relative enhancement of activity in the visual cortex for “Hear” versus “Look” cue-only trials, and a relative enhancement of activity in the auditory cortex for “Look” versus “Hear” cue-only trials (Figure 2-1b, right). Neither of the simple effects associated with this interaction was significant (both $p > 0.12$, two-tailed). However, the nature of the significant interaction clearly indicates a relative shift of activity toward the task-irrelevant sensory cortex signaled by the irrelevant auditory word. These findings support our hypothesis that consciously perceived, irrelevant instruction words that signal a competing task set can hijack the attentional network, leading it to enhance the perceptual processing of irrelevant stimuli.

We also investigated whether the magnitude of the cue congruency effects above varied in the simultaneous and sequential conditions. The four-way interaction among Condition (simultaneous, sequential), Cued Modality (visual, auditory), Cue Congruency

(congruent, incongruent), and Brain Region (visual ROI, auditory ROI) did not achieve significance, $F(1,17) < 1$. Therefore, cue congruency effects in the sensory cortices did not differ for the simultaneous and the sequential conditions.

Finally, we investigated whether merely presenting the irrelevant auditory word simultaneously with (as compared to 850 ms after) the relevant visual cue might distract participants in a relatively general way, causing them to orient less attention to the cued sensory modality. To test this prediction, we defined an overall measure of positive biasing activity, which was the average of positive biasing activity in the visual cortex (i.e., activity for “Look” cue-only trials minus activity for “Hear” cue-only trials) and positive biasing activity in the auditory cortex (i.e., activity for “Hear” cue-only trials minus activity for “Look” cue-only trials). As expected, we found significantly less positive biasing activity in the simultaneous condition than in the sequential condition, $F(1,17) = 5.29$, $p < 0.034$ (Figure 2-1c). Thus, independent of cue congruency, presenting the irrelevant auditory word simultaneously with (versus after) the visual cue interfered with orienting attention to the cued sensory modality.

Frontal Regions

Our next two predictions concerned activity in frontal regions. Our second prediction was that left VLPFC regions that retrieve task sets from memory would show a cue congruency effect that was significantly larger in the simultaneous than in the sequential condition. Our third prediction was that activity in DLPFC regions involved in maintaining task sets in working memory and activity in dorsal ACC regions that detect or resolve conflict between relevant and irrelevant task sets would be greater for

incongruent than for congruent cue-only trials, and that the magnitude of these effects would not differ for the simultaneous and the sequential conditions.

Voxelwise Analyses

To test our second prediction about the left VLPFC, we performed a voxelwise t-test to locate brain regions in which the cue congruency effect was significantly larger in the simultaneous than in the sequential condition. This analysis revealed no significant activations, $t(17) = 3.63$, $p < 0.001$ and 8 contiguous voxels. We chose this threshold and cluster size from our previous investigation (Orr & Weissman, 2009).

To test our third prediction about the DLPFC and the dorsal ACC, we performed a voxelwise, random-effects t-test to localize brain regions that showed greater activation for incongruent cue-only than for congruent cue-only trials, averaging across the simultaneous and the sequential conditions, $t(17) = 3.63$, $p < 0.001$ and 8 contiguous voxels. This analysis revealed two activations in the left posterior superior temporal gyrus (center of mass coordinates in MNI space: $x = -57$, $y = -42$, $z = 8$, Brodmann Area (BA) 22, cluster size, 10 voxels; center of mass: $x = -65$, $y = -53$, $z = 10$, BA 22, cluster size, 8 voxels) and one activation in the culmen (i.e., anterior vermis) of the cerebellum (center of mass: $x = 9$, $y = -42$, $z = -10$; cluster size, 8 voxels). No other activations were observed.

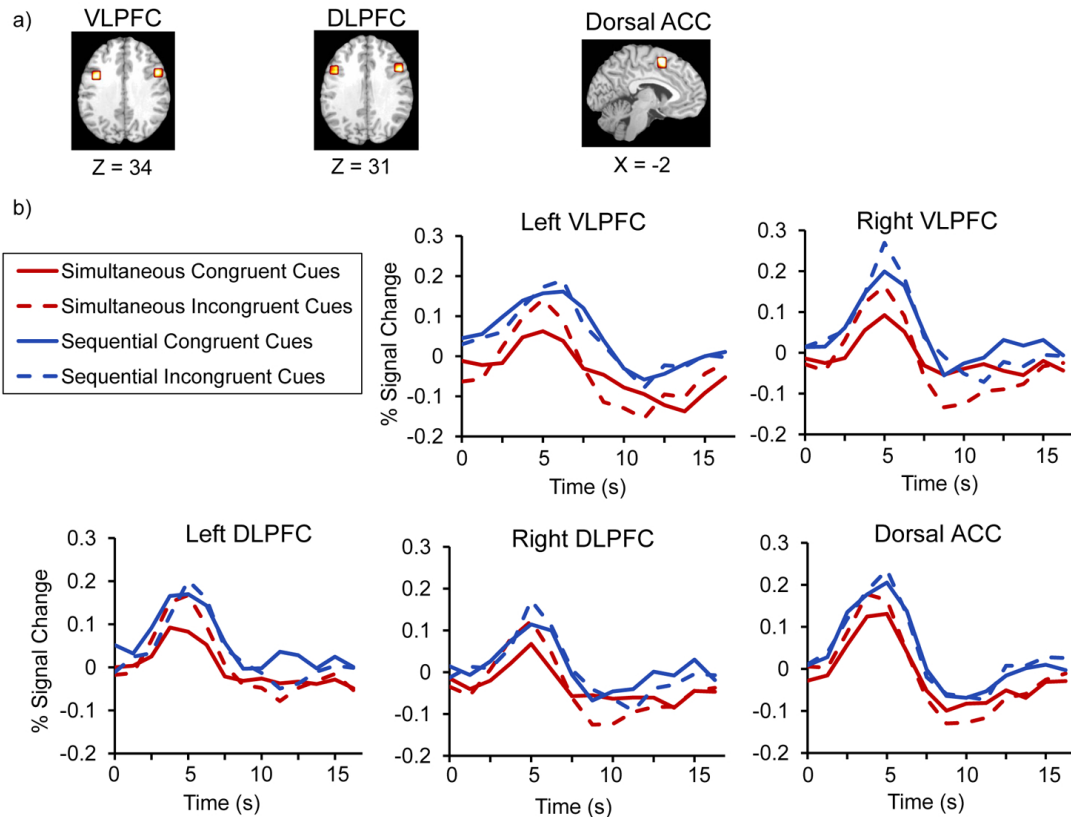


Figure 2-3: Activity in cue-only trials plotted in frontal and parietal regions of interest.

(a) Axial slices showing regions of interest on the MNI-normalized brain. These regions include the left VLPFC, the right VLPFC, the left DLPFC, the right DLPFC, and the dorsal ACC. (b) Activity in cue-only trials plotted as a function of Condition (sequential, simultaneous) and cue congruency (congruent, incongruent) in each region of interest. In the left VLPFC (but not in the other regions), cue congruency effects were significantly larger in the simultaneous condition than in the sequential condition.

ROI Analyses

As noted above, our voxelwise analyses did not reveal significant activations in either frontal or parietal regions. Thus, we functionally defined ROIs in bilateral regions of the middle/posterior VLPFC, the left superior parietal lobe (SPL), the right SPL, and the left inferior parietal lobe (IPL) and defined ROIs in bilateral regions of the DLPFC and the dorsal ACC using coordinates from one of our prior studies (Weissman, et al., 2004) (see *Materials and Methods*, and Figure 2-3). To correct for multiple comparisons

in the following analyses, we considered significance levels to be p-values that were less than 0.01.

Consistent with our second prediction, in the left middle/posterior VLPFC (Figure 2-3b, top left) we observed a significant interaction between Cue Congruency (congruent, incongruent) and Condition (simultaneous, sequential), $F(1,17) = 9.24$, $p < 0.008$. As hypothesized, this interaction occurred because there was significantly greater peak activity in incongruent than in congruent cue-only trials in the simultaneous condition, $t(17) = 2.80$, $p < 0.0062$, but not in the sequential condition, $t(17) = 1$. In the right VLPFC (Figure 2-3b, top right), which may play a role in inhibiting irrelevant task sets (Brass & von Cramon, 2004a), we observed significantly greater peak activity in incongruent than in congruent cue-only trials, $t(1,17) = 3.08$, $p < 0.004$ (averaged across the simultaneous and the sequential conditions), but there was no significant interaction between Cue Congruency and Condition, $F(1,17) = 1.22$, $p > 0.28$. Thus, as predicted, cue congruency effects in the left VLPFC were significantly larger in the simultaneous than in the sequential condition, in line with models suggesting a role for this region in retrieving task sets from memory.

We observed weak evidence to support our third prediction. First, we found a trend towards greater peak activity in incongruent than in congruent cue-only trials in bilateral regions of the DLPFC (left DLPFC: $t(17) = 1.88$, $p < 0.04$; Figure 2-3b, bottom left; right DLPFC: $t(17) = 1.87$, $p < 0.04$; Figure 2-3b, bottom middle). As expected, the size of the cue congruency effect did not vary significantly across the simultaneous and the sequential conditions (left DLPFC: $F(1,17) = 2.28$, $p > 0.149$; right DLPFC: $F(1,17) < 1$). We also observed a similar pattern in the dorsal anterior cingulate cortex (Figure

2-3b, bottom right). Specifically, there was a trend towards greater peak activity in incongruent than in congruent cue-only trials, $t(17) = 1.75$, $p < 0.05$ (averaged across the simultaneous and the sequential conditions), and the size of this effect did not vary significantly across the simultaneous and the sequential conditions, $F(1,17) < 1$. These findings are consistent with those suggesting a role for the DLPFC in maintaining task sets in working memory and with those suggesting a role for the dorsal ACC in detecting or resolving conflict between relevant and irrelevant task sets.

Parietal Regions

Our fourth prediction was that cue congruency effects would be observed in superior and inferior parietal regions that allocate attentional resources to behaviorally relevant stimuli (Corbetta, et al., 1998; Hopfinger, et al., 2000). However, ROI analyses in parietal regions revealed neither an overall cue congruency effect (i.e., averaged across the simultaneous and the sequential conditions) nor an interaction between Cue Congruency (congruent, incongruent) and Condition (simultaneous, sequential). Exploratory analyses, which should be interpreted with caution, revealed significant effects of Cue Congruency in the simultaneous condition (left SPL: $t(17) = 1.827$, $p < 0.043$; right SPL: $t(17) = 1.880$, $p < 0.039$; left IPL, $t(17) = 2.078$, $p < 0.027$), but not in the sequential condition (left SPL, $t(17) < 1$; right SPL, $t(17) < 1$; left IPL, $t(17) < 1$).

Discussion

We often become distracted from performing a primary task (e.g., reading) when an irrelevant stimulus (e.g., a television commercial) activates representations of an irrelevant task in working memory (e.g., watching a movie). Consistent with such everyday experiences, current models of selective attention posit that a major source of

distraction during task performance stems from the activation of irrelevant task objectives in working memory (MacLeod, 1991; Wagner, Maril, Bjork, & Schacter, 2001). In line with such models, we found that consciously perceived, irrelevant instructional cues that were strongly associated with an irrelevant task hijacked the attentional network, as indexed by heightened activity in (a) frontal regions that control attention and (b) sensory cortices that underlie the perceptual processing of irrelevant stimuli. Moreover, we found that effects of irrelevant instructional cues on activity in the left middle/posterior VLPFC varied with whether a relevant and an irrelevant instructional cue were presented simultaneously or sequentially. These findings have important implications for our understanding of the functional neuroanatomy of selective attention (Ventura, et al., 2005).

Consistent with our first prediction, we observed strong evidence in the sensory cortices that consciously perceived, irrelevant instructional stimuli can hijack the attentional network. Cueing participants to attend for a possibly upcoming target that is defined by its spatial location (Hopfinger, et al., 2000; Woldorff, et al., 2004), color (Giesbrecht, Woldorff, Song, & Mangun, 2003), or sensory modality (Weissman et al., 2004) often leads to a relative enhancement of activity in sensory regions that process the attended attribute, even before the target is presented (Corbetta & Shulman, 2002). In line with such findings, we observed a relative enhancement of activity in the sensory cortex corresponding to the cued modality for congruent cues, in which the relevant visual cue and the irrelevant auditory word signaled the same task (e.g., “Hear”). However, for incongruent cues, in which the irrelevant auditory word (e.g., “Look”) signaled the opposite sensory modality as the relevant visual cue (e.g., “Hear”), we

observed a relative enhancement of activity in the sensory cortex corresponding to the modality that was signaled by the irrelevant auditory word. Since the irrelevant auditory words were played at the same volume as the auditory targets that participants successfully identified, our findings show that consciously perceived, irrelevant instructional stimuli can hijack the attentional network.

Other results in the sensory cortices indicated that merely presenting the irrelevant auditory word simultaneously with (versus after) the visual cue interfered with attention-orienting processes in a relatively general way that did not depend on cue congruency. Specifically, regardless of cue congruency, there was significantly less positive biasing activity in the sensory cortices (i.e., greater activity for “Look” than for “Hear” cue-only trials in the visual cortex and greater activity for “Hear” than for “Look” cue-only trials in the auditory cortex) in the simultaneous than in the sequential presentation condition. This finding fits nicely with prior work indicating that presenting any sort of task-related information at an irrelevant stimulus dimension can be distracting (Milham, et al., 2002).

In line with our second prediction, in the left middle/posterior VLPFC we observed a significantly larger cue congruency effect when the irrelevant auditory word was presented simultaneously with (versus after) the relevant visual cue. This result is highly consistent with models in which the left middle/posterior VLPFC participates in retrieving from memory either (a) task sets or (b) stimulus-response mappings that are associated with task sets (Brass & von Cramon, 2004a; Bunge, 2004). Given that a task set can be retrieved in well under a second (Monsell & Mizon, 2006), such retrieval processes likely operate relatively early in the cue-target interval. Moreover, demands on such processes are likely greater when a simultaneously presented irrelevant instructional

cue signals a competing (versus the same) task set as a relevant cue. In light of the hijacking effects that we observed in the sensory cortices, the larger cue congruency effect in the simultaneous (versus sequential) condition might also index the retrieval of both the relevant and the irrelevant task set into working memory (Lau & Passingham, 2007). Future studies might therefore be aimed at determining whether cue congruency effects in the left middle/posterior VLPFC reflect processes that work harder to retrieve a relevant task set under conditions of distraction or, alternatively, processes that erroneously retrieve an irrelevant task set.

Our results in the left middle/posterior VLPFC may also be accounted for by models in which this region selects relevant semantic information in the context of competing semantic distracters (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2007). Indeed, such models readily account for our finding that cue congruency effects were larger in the simultaneous condition, in which the relevant task representation needed to be selected in the context of a competing task representation, than in the sequential condition, in which the relevant task representation could be selected before the irrelevant task representation was retrieved. Also consistent with such models, the specific region of left VLPFC that we have identified is highly proximal to a region of the left middle/posterior VLPFC that has previously been linked to semantic selection (Badre, et al., 2005). Future studies will be needed to determine whether cue congruency effects in the left middle/posterior VLPFC reflect processes that retrieve task sets from memory (Bunge, 2004) or processes that operate on such task sets after they are retrieved in order to select relevant task sets among competing ones (Badre, et al., 2005; Badre & Wagner, 2007).

We found weak but suggestive evidence to support our third prediction. There were trends towards cue congruency effects in bilateral regions of the DLPFC and the dorsal ACC. We also found a significant cue congruence effect in the right VLPFC. For none of these effects did the magnitude significantly differ in the simultaneous and the sequential conditions. Cue congruency effects in the DLPFC may reflect increased demands on processes that maintain relevant representations in working memory after an irrelevant stimulus activates competing representations (Sakai & Passingham, 2002; Sreenivasan & Jha, 2007). Given the hijacking effects that we observed in the sensory cortices, cue congruency effects in the DLPFC may also index the maintenance of both a relevant and an irrelevant task set in incongruent cue-only trials (Lau & Passingham, 2007). Cue congruency effects in the dorsal ACC may reflect processes that detect or resolve conflict between relevant and irrelevant task sets (Luks, et al., 2002; Orr & Weissman, 2009). Finally, cue congruency effects in the right VLPFC may reflect increased demands on processes that inhibit irrelevant task sets that become activated in working memory during the processing of incongruent cues (Brass & von Cramon, 2004a). Future studies will be necessary to distinguish among these and other possible interpretations of the cue congruency effects that we have observed. Nonetheless, our findings are important because they provide some initial insight into which frontal regions are hijacked by consciously perceived, irrelevant instructional cues. Moreover, they both replicate and extend our findings from a prior experiment with different participants, the design of which included only a simultaneous presentation condition (Orr and Weissman, 2009), by demonstrating that cue congruency effects in the DLPFC

and the dorsal ACC do not vary with whether relevant and irrelevant task cues are presented simultaneously or sequentially.

In line with our fourth prediction, we also observed cue congruency effects in bilateral regions of the superior parietal lobe and in the left inferior parietal lobe. More specifically, exploratory analyses in these regions revealed greater activity for incongruent than for congruent cue-only trials in the simultaneous (but not the sequential) condition. Parietal regions are thought to allocate attention to behaviorally relevant stimuli (Corbetta, et al., 1998; Hopfinger, et al., 2000). Thus, cue congruency effects in parietal regions may index the effect of activating irrelevant task objectives in frontal regions on processes that orient attention.

Finally, we observed cue congruency effects in the left posterior superior temporal gyrus and in the anterior vermis (i.e., culmen) of the cerebellum. Activity in the left posterior superior temporal gyrus (BA 22) is thought to increase with demands on phonological processes (Graves, Grabowski, Metha, & Gupta., 2008; Rumsey, et al., 1997). To the extent that participants sub-vocalized the visual cue word, demands on phonological processes were likely greater in incongruent than in congruent cue-only trials. Indeed, only in incongruent cue-only trials did the irrelevant auditory word activate phonological representations that conflicted with those needed to sub-vocalize the relevant visual word. Activity in the anterior vermis is thought to underlie processes related to response preparation and response inhibition (Desmond, Gabrieli, Wagner, Ginier, & Glover, 1997; Simmonds, Pekar, & Mostofsky, 2008). We speculate that incongruent cue-only trials imposed greater demands than congruent cue-only trials on inhibitory processes that prevented participants from subvocalizing the irrelevant

auditory word. In sum, we observed cue congruency effects in left posterior superior temporal and anterior vermis regions which underlie, respectively, phonological and motor processes that were likely recruited by our verbal cue stimuli.

Our finding that consciously perceived, irrelevant instructional cues can hijack the attentional network stands in stark contrast to the findings from two previous fMRI studies (Brass & von Cramon, 2004b; Lau & Passingham, 2007). In these studies, hijacking occurred only when the irrelevant instructional cues that signaled an irrelevant task were presented below the threshold of conscious perception. Notably, the simple geometric forms (e.g., squares and diamonds) that served as irrelevant instructional cues in these prior studies were not strongly associated with the irrelevant task objectives they were meant to activate in working memory. It is well known, however, that consciously perceived distracters in selective attention tasks produce the greatest interference when they are strongly associated with irrelevant semantic and response representations (MacLeod, 1991). For example, irrelevant words in the Stroop task are thought to produce especially large interference effects because words have been automatically associated with their meanings and vocal responses through extensive language training. The present finding that consciously perceived auditory words (“Look” and “Hear”) can hijack the attentional network is thus highly consistent with the existing literature on selective attention, but future research will be required to fully understand the boundary conditions in which hijacking occurs.

Our data indicating that cue congruency effects in the left VLPFC were more pronounced in the simultaneous than in the sequential presentation condition is also generally consistent with the literature on selective attention. A predominant finding in

this literature is that interference from irrelevant stimuli is greater when those stimuli are presented simultaneously with (versus after) target stimuli (for a review, see MacLeod, 1991). Such data clearly indicate that temporal overlap in the processing of relevant and irrelevant stimuli plays an important role in determining the efficiency of selective attention when only a single task set is activated. Here, we have shown that temporal overlap in the processing of relevant and irrelevant stimuli can also influence whether irrelevant stimuli can activate irrelevant task sets in working memory. Thus, our findings further underscore the importance of temporal factors in determining the efficiency of selective attention.

A limitation of the present study is that we did not observe significant effects of cue congruency on behavioral measures of performance. The lack of such behavioral effects makes it difficult to determine whether frontal and parietal regions whose activity is influenced by cue congruency participate in “protecting” a relevant task set from distraction (Jha, Fabian, & Aguirre, 2004; Sakai & Passingham, 2002) or, alternatively, in orienting attention to irrelevant stimuli (Lau & Passingham, 2007). Given that behavioral performance following incongruent (versus congruent) cues is impaired for only about 300 ms (Mattler, 2005), the absence of behavioral cue congruency effects in the present study (which featured a 1.875 second cue-target interval) is unsurprising. Due to the relatively short temporal duration of behavioral cue congruency effects, brain imaging techniques that offer higher temporal resolution than fMRI, such as, for example, magnetoencephalography (MEG), may be especially useful for dissociating brain regions that “protect” a relevant task set under conditions of distraction from brain regions that orient attention to irrelevant stimuli.

In conclusion, we have found that irrelevant instructional cues can hijack the attentional network even when they are consciously perceived. Moreover, we have found that the relative timing with which relevant and irrelevant instructional cues are presented influences the extent of this hijacking in certain regions of the attentional network. Future studies will be important for advancing our understanding of how irrelevant task objectives become activated in working memory and for revealing the behavioral and neural consequences of activating such representations in both neurologically-intact and clinical populations.

Chapter 3

Involuntary transfer of a top-down attentional set into the focus of attention: Evidence from a contingent attentional capture paradigm

Abstract

We investigated whether involuntarily directing attention to a target-colored distractor causes the corresponding attentional set to enter a limited-capacity focus of attention, thereby facilitating the identification of a subsequent target whose color matches the same attentional set. As predicted, in Experiment 1 contingent attentional capture effects from a target-colored distractor were only one half to one third as large when subsequent target identification relied on the same (versus a different) attentional set. In Experiment 2, this effect was eliminated when all target colors matched the same attentional set, arguing against bottom-up perceptual priming of the distractor's color as an alternative account of our findings. In Experiment 3, this effect was reversed when a target-colored distractor appeared after the target, ruling out a feature-based interference account of our findings. We conclude that capacity limitations in working memory strongly influence contingent attentional capture when multiple attentional sets guide selection.

Introduction

In order to protect limited-capacity information processing systems, attention is posited to direct processing resources toward stimuli that are important for achieving current behavioral goals (Desimone & Duncan, 1995; Posner & Rothbart, 2007). Such goal-directed attention is thought to be made possible by representations of behavioral goals, which specify the attentional settings that are needed to optimize the processing of behaviorally-relevant stimuli (Folk, et al., 1992). For example, the goal of searching for a lemon at the grocery store is usually linked to searching for the color yellow. Once such attentional settings are specified, top-down signals are posited to bias sensory processing in favor of stimuli whose features match these settings (Corbetta & Shulman, 2002), thereby enhancing the ability of relevant stimuli to gain access to limited-capacity systems.

While selective attention usually helps to prevent irrelevant stimuli from gaining access to limited-capacity systems, sometimes it has the opposite effect. For example, when one is searching for a lemon at the grocery store, all yellow items in the fruits and vegetables section—including lemons, peppers, and squash—may attract attention. Put another way, attention is often involuntarily directed to an irrelevant stimulus that possesses a feature (e.g., a particular color) that matches a top-down attentional set. In the laboratory, *contingent attentional capture* refers to a phenomenon in which involuntarily directing attention to an irrelevant stimulus that possesses a task-relevant feature impairs the identification of a subsequent target stimulus (Folk, et al., 1992). Contingent capture effects have been observed in spatial cuing (Bacon & Egeth, 1994; Folk, et al., 1992; Gibson & Kelsey, 1998), visual search (Olivers, 2008), and rapid serial

visual presentation (RSVP) paradigms (Folk, et al., 2002; Folk, et al., 2008; Leblanc, Prime, & Jolicoeur, 2008; Serences, et al., 2005), and are thought to arise because a distractor whose properties match an attentional set is processed more deeply, as though it were a target (Folk, et al., 2002). Because this deeper processing is serial and capacity-limited, it impairs the identification of a target that appears later in time or at a different location. Thus, while selective attention usually limits the processing of irrelevant stimuli, it sometimes enhances such processing.

Although the phenomenon of contingent attentional capture is firmly established in the literature, relatively little is known about such capture in the context of maintaining multiple attentional sets. Current models of working memory posit that up to four representations can be maintained simultaneously (Cowan, 2001; Jonides, et al., 2008; Oberauer, 2002). Consistent with such models, participants can maintain rules for at least three tasks in task switching experiments (Mayr & Keele, 2000; Monsell, 2003). Moreover, in visual attention tasks contingent capture effects can be produced by irrelevant stimuli that match either of two concurrently maintained attentional sets (Adamo, Pun, Pratt, & Ferber, 2008; Ansorge & Heumann, 2003). Nonetheless, it remains unclear whether some contingent attentional capture effects are different when participants maintain multiple attentional sets than when they maintain just a single attentional set.

Evidence to suggest that contingent attentional capture effects may indeed differ in these two situations comes from numerous findings indicating that it is possible to focus attention on only one representation in working memory at a time (Oberauer, 2002, 2003). First, when multiple items are maintained in working memory, the time it takes to

identify the most recently presented or rehearsed item is much shorter than the time needed to identify other items, suggesting that this item is alone in the focus of attention (McElree, 2001). Second, in experiments that investigate the updating of multiple counters, participants are faster when updating the same counter sequentially than when switching between counters, indicating that only one counter can be focused at a time (Berti, 2008; Garavan, 1998). Third, task switching studies show that participants are faster and more accurate when repeating the same task than when switching from one task to another, suggesting that participants can only focus on one task set at a time (Hsieh & Allport, 1994; Monsell, 2003). And fourth, participants experience a smaller “attentional blink” (i.e., decreased accuracy when identifying the second of two rapidly presented targets) when the same attentional set is used to identify the two targets than when different attentional sets are used, regardless of whether the attentional sets are defined by conceptual category (e.g., letters vs. digits) (Juola, Botella, & Palacios, 2004) or by location (Vachon, Tremblay, & Jones, 2007). These findings suggest that voluntarily directing attention to a particular stimulus or task causes the corresponding attentional set to enter the limited-capacity focus of attention, thereby enhancing future behaviors that rely on the same set.

In the present study, we investigated whether *involuntarily* directing attention to a distractor that possesses a target-defining color also causes the corresponding attentional set to enter the focus of attention. According to this *enhancement hypothesis*, an integral component of deeply processing a target-colored distractor is moving that item’s attentional set into the focus of attention until the item has been successfully identified. In line with this possibility, various theories of visual search posit that detecting a

potential target leads to the recruitment of working memory processes that attend, identify, or otherwise consolidate that item (see Dux & Marois, 2009). And, consistent with this view, it has been shown that information about distractors is transferred into working memory during the performance of capture tasks (Belopolsky, Kramer, & Godijn, 2008). However, none of the existing contingent attentional capture studies requiring participants to maintain multiple attentional sets has explored whether one set ever becomes prioritized, or enhanced, over the others during the time course of a single trial (Adamo, et al., 2008; Ansorge & Heumann, 2003).

The enhancement hypothesis predicts that contingent attentional capture effects caused by deeply processing a target-colored distractor should be smaller when a target appearing soon afterwards matches the same (versus a different) attentional set. Deeply processing a target-colored distractor should always impair the identification of a subsequent target. However, this impairment should be reduced when target identification relies on the same attentional set and, therefore, does not involve loading a different attentional set into the focus of attention. This view is consistent with the findings from working memory, task switching, and attentional blink studies that we reviewed earlier, all of which demonstrate a relative enhancement in performance when a target can be identified using the attentional set that is currently inside the focus of attention. As an everyday example, when one is searching for both lemons and garlic at the grocery store, deeply processing a yellow pepper may cause the “lemon” attentional set to temporarily enter the focus of attention. While the “lemon” attentional set is prioritized, it could become comparatively easier to notice a nearby lemon than a garlic

bulb, even though it may still be harder to notice either item than if the yellow pepper had not captured attention.

The enhancement hypothesis may appear to contradict previous findings from visual search tasks indicating that the manner in which attentional sets are used in one trial can influence how they are used in the next trial (Belopolsky, Schreij, & Theeuwes, 2010). Specifically, although inter-trial priming of attentional sets is not always observed (Ansorge & Horstmann, 2007; Ansorge, Horstmann, & Carbone, 2005), in some studies identifying a distractor that possesses a target-defining feature (e.g., a particular color) in one trial is associated with a decreased attentional bias toward that feature in the next trial (Lleras, Kawahara, & Levinthal, 2009). The present experiments differ from these prior studies, however, because they investigate within-trial changes to attentional control settings. Thus, as we will argue in greater detail in the General Discussion, the enhancement hypothesis does not contradict prior findings regarding inter-trial priming effects in visual search tasks.

It is also important to note that the enhancement hypothesis makes no explicit assumptions about the manner in which multiple attentional sets are maintained during active search for a target stimulus (i.e., *before* an item possessing a target-defining feature is detected). In some models, attentional sets are maintained in working memory (e.g., (Olivers & Meeter, 2008)). However, there is also evidence that attentional sets can influence visual search even when they are not actively maintained in working memory (e.g., Thompson, et al., 2007). In either case, the enhancement hypothesis posits that the detection of a potential target (including a distractor that possesses a target-defining

feature) leads the attentional set corresponding to that item to enter the limited-capacity focus of attention.

Finally, although the enhancement hypothesis posits an interaction between attention and working memory, it does not speak directly to an active debate concerning this interaction. Specifically, there is an ongoing controversy over whether people automatically orient attention to stimuli whose features match the contents of working memory, *but which are not the targets of an ongoing search task* (e.g., Houtkamp & Roelfsema, 2006; Olivers, 2009; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman & Luck, 2007). In contrast, the enhancement hypothesis assumes that people automatically orient attention to stimuli whose features match the contents of working memory (i.e., an attentional set within the focus of attention), *and which are the targets of an ongoing search task*. As others have noted (Olivers, 2009), this assumption is not related to the current debate and data to support this assumption have been reported in numerous prior studies of contingent attentional capture (e.g., Folk, et al., 2002; Folk, et al., 1992; Leblanc, et al., 2008; Serences, et al., 2005).

Experiment 1

In Experiment 1, we tested the enhancement hypothesis by instructing participants to search a central RSVP stream for letters that were presented in either of two possible target colors (e.g., orange and green). The presence of irrelevant colors in the central RSVP stream made it necessary for participants to maintain two attentional sets, one for each target color. Some targets in the central RSVP stream were preceded by a colored distractor that appeared in either of two peripheral RSVP streams. As in prior studies, we

defined contingent attentional capture as lower target identification accuracy when a target-colored (e.g., orange) distractor preceded a target than when a non-target-colored (e.g., lavender) distractor preceded a target (Folk, et al., 2002; Folk, et al., 2008; Serences, et al., 2005; Visser, Bischof, & Di Lollo, 2004). Consistent with the enhancement hypothesis, we predicted that contingent attentional capture effects would be smaller when a target-colored distractor's color (e.g., green) matched the same attentional set as the color of an upcoming target (e.g., green) than when it matched a different attentional set (e.g., orange).

Methods

Participants

Twenty-eight University of Michigan students (fifteen female) participated in exchange for course credit or \$10. All participants (age range: 18-30 years) reported normal or corrected vision and no history of neurological injury or disease. Each gave informed written consent in accordance with the University of Michigan Behavioral Sciences Institutional Review Board requirements.

Procedure and Design

Our task was similar to other contingent attentional capture experiments that have made use of RSVP displays (Folk, et al., 2002; Folk, et al., 2008; Serences, et al., 2005).

Participants viewed three RSVP streams. In the central stream,

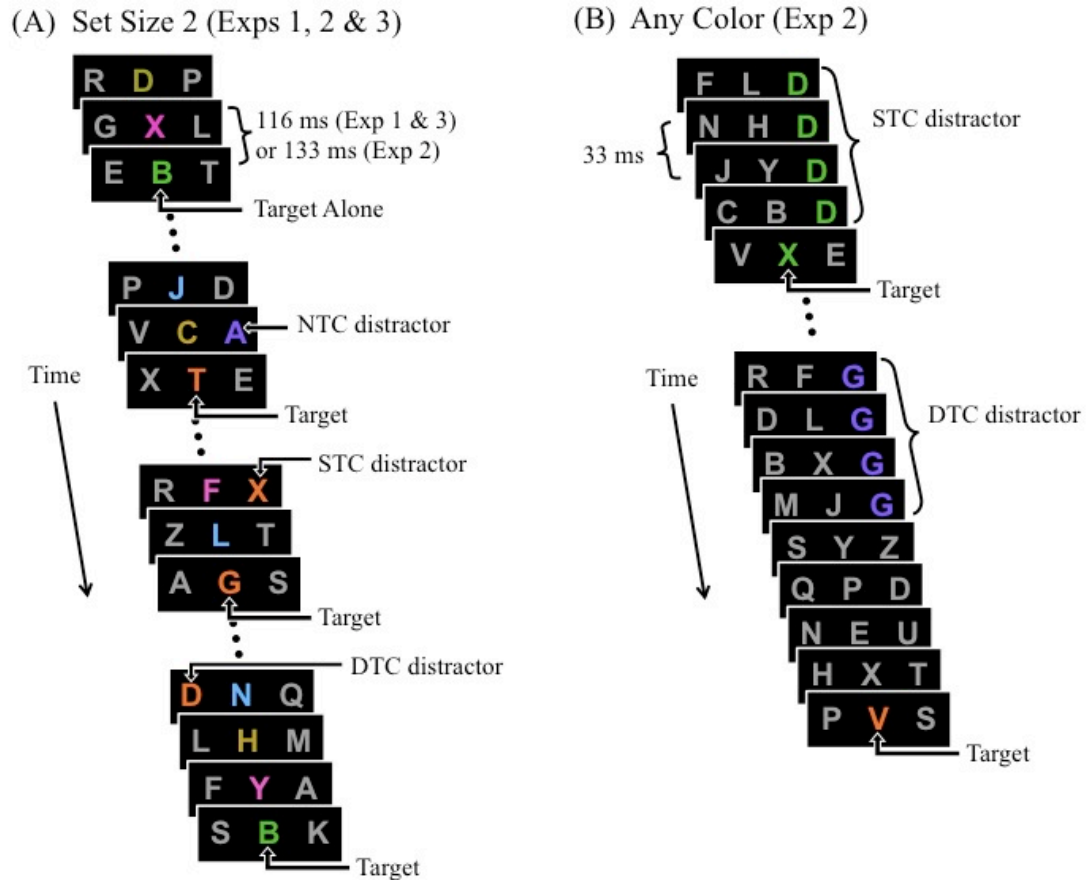


Figure 3-1: The contingent attentional capture tasks that we used in the present study.

(A) Participants searched for target-colored letters that appeared within a heterogeneously-colored, central rapid serial visual presentation (RSVP) stream while ignoring occasional colored distractors that could appear in either of two peripheral RSVP streams. Performance was measured in three types of task blocks. In one (Set Size 2, Experiments 1-3), participants searched for two target colors (e.g., orange and green) in the central RSVP stream. In Experiments 1 & 2, targets in the central RSVP stream appeared alone or 1-4 items after a colored peripheral distractor (see text for details). In Experiment 3, targets appeared alone, 1-2 items after a colored peripheral distractor, or 1-2 items *before* a colored peripheral distractor (not shown). Colored peripheral distractors were Non-Target-Colored (NTC) (e.g., a lavender “V”), Same-Target-Colored (STC), in which case the peripheral distractor’s color (e.g., an orange “X”) matched the same attentional set as the subsequent target’s color (e.g., an orange “G”), or Different-Target-Colored (DTC), in which case the peripheral distractor was target-colored (e.g., an orange “D”), but matched a different attentional set than the subsequent target’s color (e.g., a green “B”). In the second type of task block (Set Size 1, Experiment 1, not shown), participants searched for only one target color in the central RSVP stream. Set Size 1 included the same trial types as Set Size 2 with the exception of the DTC trial type. In both set sizes, non-target letters in the central stream were also colored to ensure that participants were required to search for letters in the central RSVP stream that possessed the specific target color(s). Non-distractor items in the peripheral streams were grey. (B) In the third type of task block (Any Color, Experiment 2), participants identified any colored letter in the central RSVP stream. Non-target letters in the central RSVP stream were grey as were non-distractor letters in the peripheral RSVP streams.

letters appeared in five or six different colors (see Apparatus and Stimuli). In two peripheral RSVP streams, most of the letters were grey. Depending on the block, participants searched for letters in the central RSVP stream that appeared in one target color (Set Size 1) or in either of two possible target colors (Set Size 2). Participants indicated whether target-colored letters in the central RSVP stream were from the first or the second half of the alphabet, respectively, by pressing the “J” or “K” key on a computer keyboard with the index or middle finger of their right hand. The first key press logged within 2200 ms following a target was recorded as the response to that target. The time between target-colored letters in the central RSVP stream varied randomly from 2320 ms to 4060 ms. Every 32 trials, participants were given a self-paced break. Figure 3-1A provides a schematic of the task.

Both set size blocks contained the following trial types: (1) Target Alone, in which a target was not preceded by a distractor, (2) Same-Target-Colored (STC) distractor, in which a target was preceded by a distractor of the same color, and (3) Non-Target-Colored (NTC) distractor, in which a target was preceded by a non-target-colored distractor. Set Size 2 had an additional trial type: Different-Target-Colored (DTC) distractor, in which a target was preceded by a target-colored distractor whose color differed from that of the target. In STC, NTC, and DTC trials, the distractor appeared one to four frames before the target which corresponded, respectively, to stimulus onset asynchronies (SOAs) of 116 ms, 233 ms, 350 ms, and 466 ms.

Of importance, our design ensured that any performance differences between STC and DTC trials would reflect varying amounts of contingent attentional capture rather than varying amounts of response congruency in these trial types. Specifically, in all trial

types with distractors (i.e., STC, NTC, and DTC), whether the target-colored distractor and the upcoming target were from the same or different halves of the alphabet was orthogonal to whether the target-colored distractor and the target had the same or different colors. Thus, potential effects of response congruency in the present design were not confounded with our measures of attentional capture.

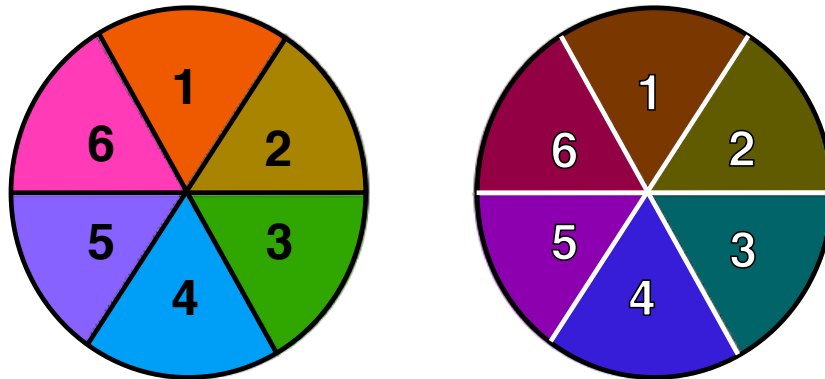
In addition to the critical trial types above, occasional catch trials (in which the display paused for 1000 ms on an item) measured whether participants were successfully maintaining the target color(s) in each set size block. In Target Catch trials, the display paused on a target-colored letter that participants were supposed to identify. In Non-Target Catch trials, the display paused on a non-target-colored letter that participants were not supposed to identify. The main purpose of the catch trials was to ensure that participants were equally capable of maintaining one and two target colors. With the display paused for 1000 ms, we eliminated the encoding limitations that were imposed by the rapid speed and immediate masking of targets in the RSVP stream, thereby providing a relatively pure test of color memory. We reasoned that if participants maintained one and two target colors equally well, then a difference in the amount of contingent capture measured in Set Size 1 and Set Size 2 could not be attributed to an underlying difference in the ability to maintain one and two attentional sets.

There were 288 trials in Set Size 1: 48 Target Alone, 48 catch (24 target, 24 non-target), 96 NTC (4 SOAs, 24 per SOA), and 96 STC (4 SOAs, 24 per SOA). There were also 288 trials in Set Size 2: 48 Target Alone, 48 catch, 64 NTC (4 SOAs, 16 per SOA), 64 STC (4 SOAs, 16 per SOA), and 64 DTC (4 SOAs, 16 per SOA).

Each set size block began with instructions explaining the task followed by 48 practice trials. During the practice trials, the display began slowly (250 ms per item), but gradually accelerated to full speed (116 ms per item) by the 24th trial. The order in which the different set size blocks were performed was counterbalanced across participants.

Apparatus and Stimuli

Stimuli were displayed on a 19" Viewsonic CRT monitor with a 60 Hz refresh rate, controlled by a Dell PC running Windows XP. The experiments were programmed using Presentation® software (Neurobehavioral Systems, Inc.). A viewing distance of 80 cm was enforced by a chin rest. Three RSVP streams containing letters ($2.07^\circ \times 1.88^\circ$) were presented simultaneously on a black background: one stream appeared at fixation while two others appeared 4.22° to the left and 4.22° to the right of fixation. Letters appeared successively in each RSVP stream for 100 ms, followed by a blank gap lasting 16 ms. Target-colored letters and colored peripheral distractors were drawn from the beginning (A, B, C, D, and G) and the end (T, V, X, Y, and Z) of the alphabet to minimize demands on decision-making processes and, consequently, to provide a sensitive measure of contingent attentional capture. Other letters in the display were drawn from the entire alphabet except I, O, and W.



Color	Light Color Wheel		Dark Color Wheel	
	Name	RGB values	Name	RGB values
1	Orange	239, 90, 0	Brown	122, 55, 0
2	Tan	169, 132, 0	Olive	96, 90, 0
3	Green	48, 166, 0	Teal	0, 100, 104
4	Turquoise	0, 159, 247	Blue	55, 29, 216
5	Lavender	135, 98, 255	Purple	140, 0, 175
6	Magenta	250, 59, 184	Red	147, 0, 67

Figure 3-2: Two color wheels to generated colored letters.

All six colors in each wheel had the same lightness (L^*) value in CIELAB space. In Set Size 1 and Set Size 2, three equally-spaced colors from a single wheel (numbers 2, 4, and 6) served as irrelevant colors in the central rapid serial visual presentation (RSVP) stream. Among the remaining three colors (1, 3, and 5), either one (Set Size 1) or two (Set Size 2) served as the target color(s) while the third served as the non-target color for colored distractors in the peripheral RSVP streams. A control experiment established that, for each color wheel, all possible pairings of the target and non-target colors (numbers 1, 3, and 5) were equally discriminable. Nonetheless, we counterbalanced which specific colors (numbers 1, 3, or 5) served as target and non-target colors across participants. All grey letters in the display had the same lightness value in CIELAB space (L^*) as colored letters appearing in the same task block. In Experiments 1 and 2, the specific color wheel that was assigned to a particular task block (Set Size 1 or Set Size 2 in Experiment 1, Set Size 2 or Any Color in Experiment 2) was counterbalanced across participants. In the Any Color condition of Experiment 2, only three equally-spaced colors (numbers 1, 3, and 5) from a single color wheel appeared in the central and peripheral RSVP streams. In Experiment 3, only the light color wheel was used because performance was measured in just a single task block (Set Size 2).

Because contingent attentional capture can be influenced by bottom-up salience (Yantis & Egeth, 1997) and by the relative discriminability of target and distractor stimuli

(Anderson & Folk, In press), we attempted to match our colors across several important dimensions. First, we attempted to equate the perceptual salience (i.e., luminance and saturation) of all colors in each set size block. Second, within each set size block, we attempted to make the target colors equally discriminable from each other and from the color of the non-target-colored distractor. To accomplish these objectives, we created two 6-color wheels in CIELAB color space (see Figure 3-2), one dark ($L^* = \text{approx. } 40$) and one bright ($L^* = \text{approx. } 70$). The colors in each wheel were chosen to be as psychologically different (i.e., discriminable) from each other as possible.

A control experiment verified that our selection of colors was appropriate for testing our hypotheses about contingent attentional capture. In each trial, participants viewed a central RSVP stream containing 10 letters, which was presented at the same speed as in the main experiment (116 ms per item). All of the letters in the RSVP stream had the same lightness value (L^*) in CIELAB color space. Although most of the letters in the RSVP stream were grey, the second and ninth letters were assigned either the same color or two different colors from one of the color wheels. Participants judged as quickly as possible whether the colored letters were the same or different. Because participants take longer to judge two stimuli as being “different” when those stimuli are somewhat similar than when they are very different (Farell, 1985; Posner & Mitchell, 1967), we were able to determine how psychologically different each color was from other colors in the same wheel.

Critically, we found three non-adjacent colors in each wheel to be equally discriminable. That is, mean reaction times to respond “different” to any two of these three colors did not significantly differ (all $p > 0.4$, $n = 35$). These three colors from each

wheel served as the target color(s) and the Non-Target-Colored (NTC) distractor color in one set size block. The precise mapping of each of these three colors to the target and NTC distractor stimuli was counterbalanced across participants. The remaining three colors in each wheel were randomly assigned to non-target items that appeared in the heterogeneously-colored, central RSVP stream within the same set size block. A different color wheel was used in each set size block in order to avoid proactive interference or practice effects from prior attentional sets (Leber & Egeth, 2006; Thompson, et al., 2007). The color wheel assigned to each set size block was counterbalanced across participants.

Results

Mean accuracy was the dependent measure in all analyses. At the outset, we excluded four participants whose performance indicated that they were unable to consistently identify target-colored letters in the central RSVP stream. Specifically, each of these participants failed to respond correctly in at least 90% of target catch trials and/or produced false alarms in more than 10% of non-target catch trials in one or both set size blocks. Among the remaining 24 participants, catch trial accuracy was equivalent across set size (Set Size 1 hits vs. Set Size 2 hits: 96.7% vs. 96.4%, $t(23) = 0.419$, $p = 0.679$; Set Size 1 false alarms vs. Set Size 2 false alarms: 5.1% vs. 4.1%; $t(23) = 0.707$, $p = 0.487$). Furthermore, performance in Target Alone trials did not significantly differ in Set Size 1 and Set Size 2 [86.2% vs. 82.4%, $t(23) = 1.68$, $p = 0.11$]. Thus, it would appear that participants maintained one and two attentional sets equally well.

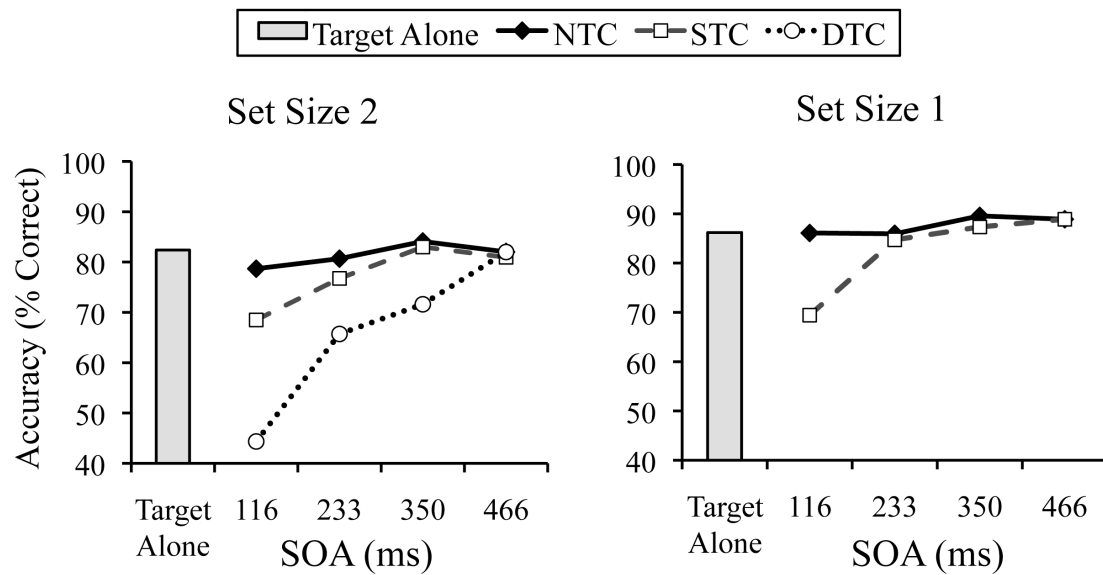


Figure 3-3: Data from Experiment 1.

Mean target identification accuracy is plotted as a function of SOA and distractor type in Set Size 2 and Set Size 1. In each set size, target identification accuracy at short SOAs was lower when a target was preceded by a Same-Target-Colored (STC) versus a Non-Target-Colored (NTC) distractor, indicating the presence of contingent attentional capture. The magnitude of this effect did not differ in Set Size 1 and Set Size 2. However, consistent with the enhancement hypothesis, target identification accuracy in Set Size 2 was lower when a target was preceded by a Different-Target-Colored (DTC) distractor than when it was preceded by a STC distractor.

To test the enhancement hypothesis, we performed a repeated-measures ANOVA with distractor type (STC, DTC) and SOA (116 ms, 233 ms, 350 ms, 466 ms) as factors using the data from Set Size 2. First, in line with prior research (Folk, et al., 2002; Folk, et al., 2008), there was a main effect of SOA [$F(3,69) = 31.08, p < 0.0001$] indicating that participants performed more poorly at shorter than at longer SOAs. Second, consistent with the enhancement hypothesis, there was a main effect of distractor type [$F(1,23) = 43.56, p < 0.0001$] indicating that performance was better in STC than in DTC trials. Third, and also consistent with the enhancement hypothesis, there was an interaction between distractor type and SOA [$F(3,69) = 7.93, p < 0.0001$] because performance

recovered more quickly in STC than in DTC trials (Figure 3-3, left). In sum, the data from Set Size 2 were highly consistent with the enhancement hypothesis.

We also determined whether the magnitude of contingent attentional capture as it is traditionally defined (i.e., worse performance in STC than in NTC trials) interacted with set size. To do so, we performed a repeated-measures ANOVA with the factors set size (1, 2), distractor type (STC, NTC), and SOA (116 ms, 233 ms, 350 ms, 466 ms). First, replicating prior studies of contingent attentional capture (Folk, et al., 2002; Folk, et al., 2008), we observed main effects of distractor type [$F(1,23) = 36.73, p < 0.0001$] and SOA [$F(3,69) = 23.64, p < 0.0001$], as well as an interaction between distractor type and SOA [$F(3,69) = 9.47, p < 0.0001$]. In short, performance was worse in STC than in NTC trials, and this performance decrement was larger at shorter than at longer SOAs (Figure 3-3). Second, a main effect of set size [$F(1,23) = 8.60, p < 0.007$] indicated better performance in Set Size 1 than in Set Size 2. Third, and critically, although contingent attentional capture was present within each set size block [Set Size 1: $F(3,69) = 11.08, p < 0.0001$; Set Size 2: $F(3,69) = 11.15, p < 0.0001$], its magnitude did not vary with set size. Neither the two-way interaction between set size and distractor type nor the three-way interaction among set size, distractor type, and SOA was close to achieving significance ($F < 1$ in both cases). Thus, we found no evidence to suggest that the magnitude of contingent attentional capture differed in Set Size 1 and Set Size 2.

Finally, whether the peripheral distractor and subsequent target were from the same or different halves of the alphabet did not affect the results. Specifically, when response congruency was included as a within-participants factor in our analyses, we observed no main effects or interactions involving this factor (all $p > 0.5$).

Discussion

Experiment 1 yielded two principal results. First, in line with the enhancement hypothesis, contingent attentional capture effects in Set Size 2 were significantly smaller in STC than in DTC trials. That is, when participants searched for two target colors, target identification accuracy was higher when a target was preceded by a peripheral distractor that possessed the same (versus a different) target color. Second, the magnitude of contingent attentional capture did not vary with the number of attentional sets that participants maintained. This result is consistent with our analyses of catch trial performance, which suggested that participants were able to maintain one and two attentional sets equally well.

We now consider two possible accounts of the enhancement effect (i.e., better performance in STC than in DTC trials). First, in line with the enhancement hypothesis, deeply processing a peripheral target-colored distractor may cause the corresponding attentional set (e.g., identify orange letters) to enter the focus of attention, thereby facilitating the identification of a subsequent target whose color matches the same attentional set (e.g., another orange letter) as compared to a different attentional set (e.g., a green letter). Second, and more trivial, a target-colored peripheral distractor may prime a subsequent target's color in a bottom-up fashion, such that the visual system is more prepared to see a target in that color than in a different color (Henson, 2003). We could not distinguish between these accounts in Experiment 1 because the relationship between a peripheral distractor's color and a subsequent target's color (same or different) was

confounded with whether these colors matched the same or different attentional sets. Thus, we conducted a second experiment.

Experiment 2

In Experiment 2, we sought to distinguish between the enhancement and priming accounts of our findings in Experiment 1 by measuring performance in two task blocks. In one block (Set Size 2 from Experiment 1), participants searched for letters that appeared in either of two colors within the central RSVP stream. Because distractor items in the central RSVP stream were heterogeneously colored, participants needed to maintain two attentional sets, one for each target color. In the other block (Any Color), participants searched for letters that appeared in any color (except grey) within the central RSVP stream. Because all of the distractor items in the central RSVP stream were grey, participants could maintain just a single attentional set (i.e., identify any colored letter). We reasoned that if the enhancement effect in Set Size 2 is due to bottom-up perceptual priming of the target's color, then it should also be observed in Any Color. On the other hand, if the enhancement effect in Set Size 2 stems from the fact that deeply processing a peripheral target-colored distractor leads the corresponding attentional set (e.g., identify orange letters) to enter the focus of attention, then this effect should be absent in Any Color, a result that would be consistent with prior findings from a similar paradigm (Folk et al., 2008). Indeed, because all colors match the same attentional set in Any Color, the entry of that attentional set into the focus of attention should not be associated with relatively less capture in STC than in DTC trials.

Methods

Participants

Forty new individuals who had not been in Experiment 1 (twenty-three female) participated in Experiment 2 for \$10. Participants (age range: 18-30 years) reported normal or corrected vision and reported no history of neurological injury or disease. Each consented in accordance with the University of Michigan Behavioral Sciences Institutional Review Board requirements.

Apparatus, Stimuli, and Procedure

Experiment 2 used the same apparatus and stimuli as Experiment 1. In the Set Size 2 task block, participants performed the Set Size 2 task from Experiment 1 with two minor changes. First, all catch trials were replaced by Target Alone trials because we were no longer comparing retention of the attentional sets in Set Size 2 to that in Set Size 1. Second, the RSVP streams were slowed slightly to 133 ms per item in order to match the duration of distraction to that in the Any Color task block described below.

In the Any Color task block, participants searched for any colored letter among grey items in the central RSVP stream, making the same judgment about target letters as they did in Set Size 2. Because reducing the heterogeneity of an RSVP stream results in higher target identification accuracy (Folk, et al., 2002), we increased the speed of the RSVP streams in the Any Color block to 33 ms per item (with no blank space) to avoid ceiling effects. Thus, each target was presented for just 33 ms. To equate the duration of distraction in Any Color and Set Size 2, peripheral colored distractors in the Any Color block lingered for four frames, or 133 ms (Figure 3-1B). To equate the temporal intervals during which distraction occurred in Any Color and Set Size 2, peripheral

colored distractors in the Any Color block were presented 0-133 ms, 133-266 ms, 266-400 ms, or 400-533 ms before central targets.

There were 288 trials in the Any Color block: 96 Target Alone, 128 Different-Target-Colored (DTC) (4 SOAs, 32 per SOA) and 64 Same-Target-Colored (STC) (4 SOAs, 16 per SOA). This trial distribution matched that in Set Size 2, in which one third of the trials with distraction were STC. A 48-trial practice session began slowly (100 ms per frame) and accelerated gradually to 33 ms per frame by the 24th trial.

Analogous to Experiment 1, we counterbalanced across participants the order in which the two blocks (Set Size 2 and Any Color) were performed as well as the color wheel that was assigned to each block.

Results

Mean accuracy was the dependent measure in all analyses. At the outset, six participants (three female) were eliminated due to low accuracy (i.e., below 70% in Target Alone trials in either block). In the remaining 34 participants, mean accuracy in Target Alone trials did not significantly differ in the Any Color (89.9%) and Set Size 2 (87.6%) task blocks, $p = 0.2$, suggesting that participants maintained the target colors

equally well in these blocks.

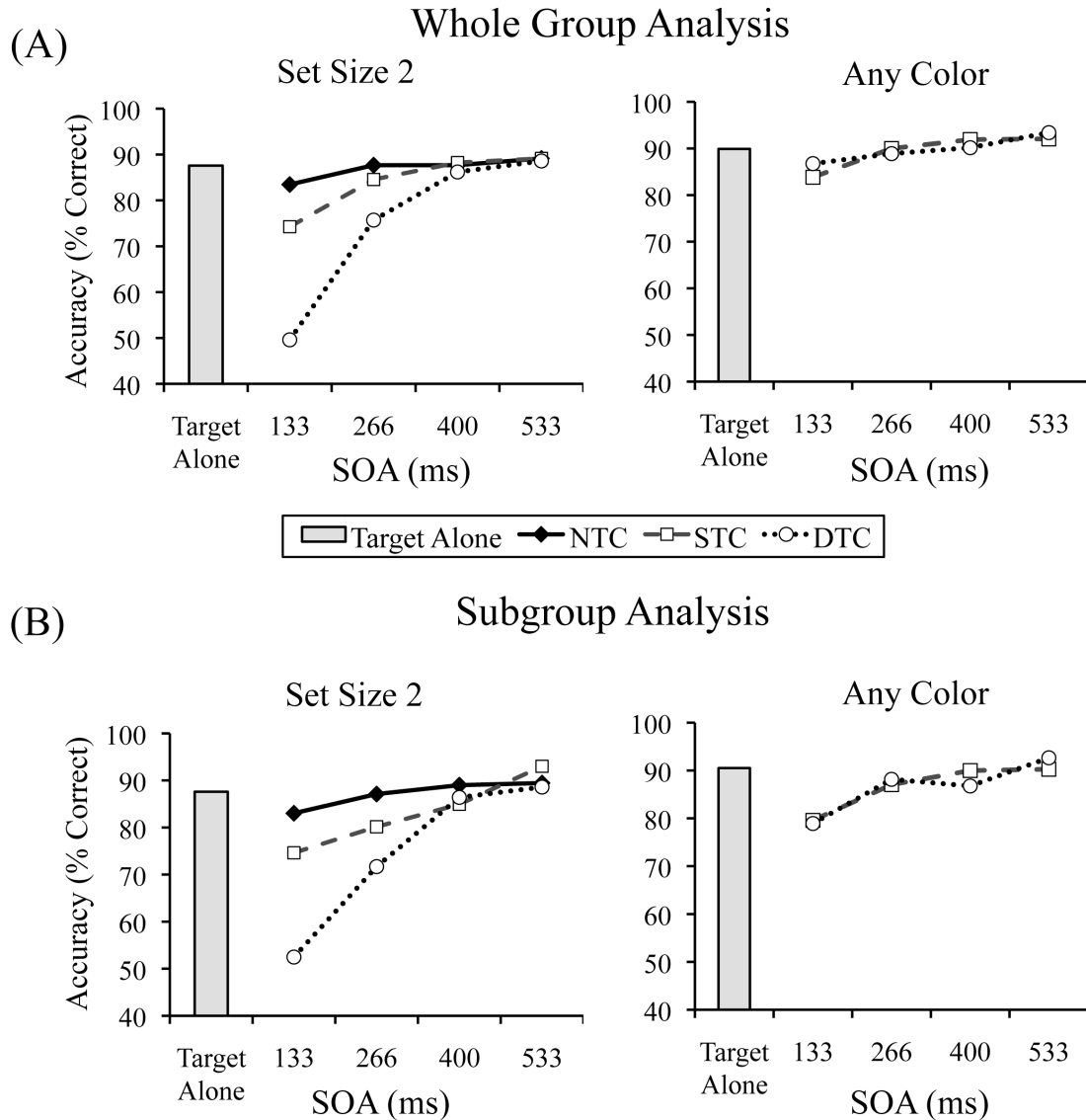


Figure 3-4: Data from Experiment 2.

Mean target identification accuracy is plotted as a function of SOA and distractor type in Set Size 2 and Any Color. (A). Consistent with the enhancement hypothesis, target identification accuracy was worse in Different-Target-Colored (DTC) distractor trials than in Same-Target-Colored (STC) distractor trials in Set Size 2, but not in Any Color (B). Critically, this effect was still observed in a subgroup of participants in whom the magnitude of attentional capture in Any Color (i.e., mean accuracy in Target Alone trials minus accuracy in STC and DTC trials) did not differ from an equivalent measure of attentional capture in Set Size 2 (i.e., mean accuracy in Target Alone trials minus mean accuracy in STC trials).

The results from Set Size 2 replicated our findings from Experiment 1. First, we observed evidence of contingent attentional capture as it is traditionally defined (i.e., worse performance in STC than in NTC trials; Figure 3-4A, left). Indeed, a repeated-measures ANOVA with distractor type (STC, NTC) and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors revealed (a) a main effect of distractor type [$F(1,33) = 7.23, p < 0.011$] because performance was worse in STC than in NTC trials, (b) a main effect of SOA [$F(3,99) = 17.1, p < 0.0001$] because performance was worse at shorter than at longer SOAs, and (c) an interaction between distractor type and SOA [$F(3,99) = 4.46, p = 0.006$] because the difference in performance between STC and NTC trials was greater at shorter than at longer SOAs. Second, a repeated-measures ANOVA with distractor type (STC, DTC) and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors revealed an enhancement effect (Figure 3-4A, left). More specifically, we observed (a) a main effect of distractor type [$F(1,33) = 54.66, p < 0.0001$] indicating better performance in STC than in DTC trials, (b) a main effect of SOA [$F(3,99) = 62.9, p < 0.0001$] indicating worse performance at shorter than at longer SOAs, and (c) an interaction between distractor type and SOA [$F(3,99) = 24.02, p < 0.0001$] indicating that performance recovered from distraction more quickly in STC than in DTC trials.

We next examined performance in the Any Color block to determine whether the results supported the enhancement or the priming hypothesis. As expected, the data supported the enhancement hypothesis (Figure 3-4A, right). In particular, the enhancement effect found in Set Size 2 was not observed in Any Color as indexed by (a) the absence of a main effect of distractor type [$F(1,33) = 0.22, p = 0.64$] and (b) the

absence of an interaction between distractor type (STC, DTC) and SOA [$F(3,99) = 1.5, p = 0.22$].

Critically, we did observe evidence of attentional capture in Any Color. First, there was a main effect of SOA [$F(3,99) = 11.52, p < 0.0001$] indicating that performance was worse at shorter than at longer SOAs. Second, mean accuracy at the shortest SOA in trial types with target-colored distractors (i.e., mean accuracy in STC and DTC trials at the 133 ms SOA, 85.3%) was significantly worse than mean accuracy in Target Alone trials (89.9%), [$t(33) = 2.80, p < 0.008$]. Thus, as predicted, attentional capture was observed in Any Color, even though the enhancement effect was not observed.

Given these results, we next investigated whether the enhancement effect was larger in Set Size 2 than in Any Color by performing a repeated-measures ANOVA with block (Set Size 2, Any Color), distractor type (STC, DTC), and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors. As expected, a two-way interaction between block and distractor type [$F(1,33) = 18.63, p < 0.0001$] indicated a significantly larger enhancement effect in Set Size 2 than in Any Color. Moreover, a three-way interaction among block, distractor type, and SOA [$F(3,99) = 11.93, p < 0.0001$] revealed that the tendency for the enhancement effect to be larger at shorter than at longer SOAs was more pronounced in Set Size 2 than in Any Color. These differences are apparent when comparing the data from Set Size 2 to the data from Any Color in Figure 3-4A.

Finally, as in Experiment 1, whether the distractor and target letters were from the same or different halves of the alphabet did not affect the results. In particular, there were no main effects or interactions involving response congruency (all $p > 0.4$).

Subgroup Analysis

One might wonder whether the enhancement effect was present in Any Color, but could not be observed statistically because the overall magnitude of attentional capture was close to floor. Indeed, attentional capture at the shortest SOA in Any Color (i.e., mean accuracy in Target Alone trials minus mean accuracy in STC and DTC trials) was associated with only about a 5% reduction in target identification accuracy. In contrast, an equivalent measure of attentional capture at the shortest SOA in Set Size 2 (i.e., capture arising from a distractor whose color matched the same attentional set as the target's color; that is, mean accuracy in Target Alone trials minus mean accuracy in STC trials) was linked to about a 15% reduction in target identification accuracy. Thus, it is possible that we failed to observe an enhancement effect in Any Color simply because target-colored distractors did not strongly capture attention.

To evaluate this possibility, we performed additional analyses on a subgroup of our participants. The members of this subgroup were chosen as follows. First, we ranked each participant in terms of the overall size of his or her overall attentional capture effect in Any Color at the shortest SOA (i.e., mean accuracy in Target Alone trials minus mean accuracy in STC and DTC trials). Second, we selected participants for the subgroup analysis if their overall capture effect in Any Color exceeded the median capture effect for the entire group. Confirming that our criteria for forming the subgroup were adequate, in this subgroup the magnitude of attentional capture at the shortest SOA (133 ms) was highly significant in Any Color [$t(16) = 5.19, p < 0.0001$] (Figure 3-4B, right). Moreover, the magnitude of attentional capture in Any Color (10.9%) was similar to the equivalent measure of attentional capture in Set Size 2 defined in the preceding paragraph

(12.5%). In short, we successfully created a subgroup of participants in which the attentional capture effect in Any Color was relatively large.

We recognize that, due to regression of the mean, an equally large capture effect in Any Color might not be observed in a follow-up experiment involving this particular subgroup of participants. However, the goal of the subgroup analysis was simply to assess whether an enhancement effect in Any Color could be observed when attentional capture effects were relatively large and, consequently, any potential ceiling effects on the size of the enhancement effect were removed. Thus, the subgroup analysis was appropriate for achieving this objective.

It is also important to note that our selection criteria for membership in the subgroup and our subsequent analyses of the enhancement effect were orthogonal. Selection into the subgroup was based on having a large overall capture effect in the Any Color condition, as defined by the difference between Target Alone performance and the average of STC and DTC performance at the shortest SOA. In contrast, the enhancement effect was defined by the difference between the STC and DTC trial types. Thus, our method of choosing individuals for the subgroup analysis did not bias the results of our subsequent analyses of the enhancement effect in these participants, either in Any Color or in Set Size 2.

As expected, the subgroup analysis replicated the main findings from the overall analysis. First, a repeated-measures ANOVA with distractor type (STC, DTC) and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors and mean accuracy in Any Color as the dependent measure revealed (a) no main effect of distractor type [$F(1,16) = 0.009, p = 0.925$] and (b) a main effect of SOA [$F(3,48) = 15.43, p < 0.0001$] because performance

was worse at shorter than at longer SOAs. Second, a repeated-measures ANOVA with distractor type (STC, DTC) and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors and mean accuracy in Set Size 2 as the dependent measure revealed significant main effects of (a) distractor type [$F(1,16) = 13.24, p < 0.002$] and (b) SOA [$F(3,48) = 26.94, p < 0.0001$], as well as (c) an interaction between distractor type and SOA [$F(3,48) = 5.50, p < 0.002$]. In short, as in the overall analysis and consistent with the enhancement hypothesis, in Set Size 2 performance was worse in DTC than in STC trials and this difference was greater at shorter than at longer SOAs; in contrast, in Any Color no such effects were observed.

Critically, the subgroup analysis also replicated our finding of a significantly smaller enhancement effect in Any Color than in Set Size 2. A repeated-measures ANOVA with block (Any Color, Set Size 2), distractor type (STC, DTC) and SOA (133 ms, 266 ms, 400 ms, 533 ms) as factors revealed (a) a two-way interaction between block and trial type [$F(1,16) = 8.13, p < 0.012$] and (b) a three-way interaction among block, trial type, and SOA [$F(3,48) = 5.03, p < 0.004$] (Figure 3-4B). Put simply, as in the overall analysis, the difference in performance between STC and DTC trials was significantly larger in Set Size 2 than in Any Color, and this effect was more pronounced at shorter than at longer SOAs. Thus, in line with our hypothesis, the enhancement effect was significantly larger in Set Size 2 than in Any Color, even in participants who exhibited relatively large capture effects in Any Color.

Finally, as in the overall analysis, there were no main effects or interactions involving response congruency (all $p > 0.4$).

Discussion

Our findings from Experiment 2 further support the enhancement hypothesis while weighing against the possibility that the enhancement effect in Set Size 2 stems from bottom-up perceptual priming of the distractor's color. First, we replicated the enhancement effect observed in Experiment 1. That is, in Set Size 2 performance was better in STC than in DTC trials. Second, the enhancement effect was absent in Any Color, in which all colors matched the same attentional set. Third, and critically, the enhancement effect was significantly smaller in Any Color than in Set Size 2, even when the overall magnitude of attentional capture was matched in these task blocks within a subgroup of the participants. Taken together, these results indicate that the enhancement effect found in Set Size 2 was not due solely to bottom-up perceptual priming of the distractor's color. Thus, our findings in Experiment 2 further support the enhancement hypothesis.

Experiment 3

In Experiment 3, we investigated another alternative account of the enhancement effect in Set Size 2. According to this alternative account, better performance in STC than in DTC trials occurs because there is confusion about the location of the target in STC trials, but confusion about both the location and the color of the target in DTC trials. In other words, the target-colored distractor activates a representation of an incorrect location in STC trials, but activates a representation of an incorrect location *and* a representation of an incorrect color in DTC trials. Given that there are fewer sources of confusion, or interference, in STC than in DTC trials, this interference-based account

predicts better performance in STC than in DTC trials and, therefore, appears to explain our findings as well as the enhancement hypothesis.

In Experiment 3, we distinguished between these competing accounts by varying whether the target-colored distractor was presented before or after the critical target. While both accounts predict better performance in STC than in DTC trials when the critical distractor appears before the target, they make different predictions about performance in STC and DTC trials when the critical distractor appears after the target. The interference-based account still predicts better performance in STC than in DTC trials because interference is always lower in STC than in DTC trials. In contrast, the enhancement hypothesis predicts better performance in DTC than in STC trials. According to this hypothesis, detecting a potential target leads the attentional set corresponding to that item's color to enter into the focus of attention. Thus, a target-colored distractor that appears immediately after the target should be detected more readily, and hence interfere with performance to a greater degree, when its color matches the same attentional set as the target than when its color matches a different attentional set. In sum, the goal of Experiment 3 was to contrast two accounts of the enhancement effect by comparing performance in STC and DTC trials when a target-colored distractor was presented *after* a target.

Methods

Participants

Thirty-six new individuals who had not participated in either Experiment 1 or Experiment 2 (20 female) participated in Experiment 3 for \$10 or course credit.

Participants (age range: 18-25 years) reported normal or corrected vision and no history of neurological injury or disease. Each gave informed written consent in accordance with the requirements of the University of Michigan Behavioral Sciences Institutional Review Board.

Apparatus, Stimuli, and Procedure

We used the same apparatus and stimuli as in Experiments 1 and 2. Colors for the letter stimuli were drawn from the light color wheel only; the dark color wheel was not used in this experiment.

The procedure was the same as that for the Set Size 2 condition of Experiment 1 with three exceptions. First, we replaced the 350 ms and 466 ms SOA trial types with -116 ms and -233 ms SOA trial types. Thus, in half the trials the distractor appeared before the target (the 116 ms and 233 ms SOA trial types), while in the other half the distractor appeared *after* the target (the -116 ms and -233 ms SOA trial types). Second, we doubled the number of trials in each trial type to increase statistical power. Third, as in Experiment 2, we did not include catch trials, and so used Target Alone performance as a criterion for including participants. In total, there were 576 trials: 192 Target Alone, 128 NTC (32 per SOA), 128 STC (32 per SOA), and 128 DTC (32 per SOA).

Results

Mean percent correct was the dependent measure in all of our analyses. At the outset, we excluded 8 participants with poor performance (Target Alone accuracy below 50%). We set a lower threshold for exclusion in Experiment 3 than in Experiment 2 for

two reasons. First, we reasoned that participants who were less skilled at this task might experience greater capture from a target-colored distractor (either STC or DTC) that appeared after a target, an effect that needed to be present for us to test our hypotheses in Experiment 3. Second, as a group, the participants in Experiment 3 performed more poorly than those in Experiments 1 and 2.

First we conducted two separate repeated-measures ANOVAs in order to examine whether we replicated the capture and enhancement effects found in Experiments 1 and 2. The first ANOVA had two factors: distractor type (NTC, STC) and SOA (116 ms, 233 ms). This ANOVA showed that we replicated the basic contingent attentional capture effect when the target-colored distractor appeared before the target. More specifically, it revealed main effects of distractor type [$F(1,27) = 4.44, p < 0.045$] and SOA [$F(1,27) = 7.87, p < 0.009$], as well as a distractor type X SOA interaction [$F(1,27) = 4.71, p < 0.039$]. As in Experiments 1 and 2, performance was worse in STC than in NTC trials, and this difference was larger at the 116 ms SOA than at the 233 ms SOA (Figure 3-5, right).

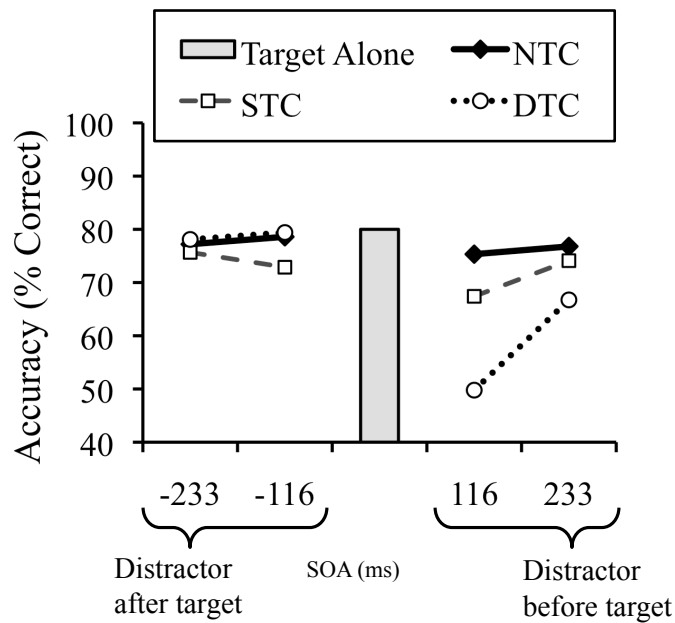


Figure 3-5: Data from Experiment 3.

Mean target identification accuracy is plotted as a function of SOA and distractor type. When the distractor appeared prior to the target (positive SOAs; right side of the figure), performance was better in NTC than in STC trials, indicating contingent attentional capture. Performance was also better in STC than in DTC trials, indicating an enhancement effect. In each of these trial types, performance was better at the longer (233 ms) than at the shorter (116 ms) SOA, likely because participants had more time to recover from distraction. When the distractor appeared after the target (negative SOAs; left side of the figure), performance was worse in STC than in either NTC or DTC trials, as predicted by the enhancement hypothesis. Performance was better at the longer (-233 ms) than at the shorter (-116 ms) SOA, probably because target identification was more likely to be completed before the critical distractor appeared at the longer than at the shorter SOA.

The second ANOVA also had two factors: distractor type (STC, DTC) and SOA (116 ms, 233 ms). This ANOVA showed that we replicated the enhancement effect when the target-colored distractor appeared before the target. Specifically, it revealed main effects of distractor type [$F(1,27) = 33.00, p < 0.0001$] and SOA [$F(1,27) = 23.65, p < 0.0001$], as well as a distractor type X SOA interaction [$F(1,27) = 15.24, p < 0.001$]. Consistent with Experiments 1 and 2, performance was better in STC than in DTC trials,

and this difference was greater at the 116 ms SOA than at the 233 ms SOA (Figure 3-5, right).

Next, we performed the critical analysis needed to distinguish between the enhancement and interference hypotheses. As uniquely predicted by the enhancement hypothesis, an ANOVA with the factors distractor type (STC, DTC) and SOA (-116 ms, -233 ms) revealed a significant *reversed* enhancement effect; that is, performance was worse in STC than in DTC trials [$F(1,27) = 7.06, p < 0.013$] (Figure 3-5, left).

It is important to note that the reversed enhancement effect above was caused by a selective performance decrement in STC trials. First, an ANOVA with the factors distractor type (NTC, STC) and SOA (-116 ms, -233 ms) revealed a significant main effect of distractor type [$F(1,27) = 7.12, p < 0.013$] because performance was significantly worse in STC than in NTC trials. Second, an ANOVA with the factors distractor type (NTC, DTC) and SOA (-116 ms, -233 ms) did not reveal a main effect of distractor type [$F(1,27) = 0.02, p = 0.874$] because performance did not differ in DTC and NTC trials. Together, these results suggest that contingent attentional capture involves both an increase of attention to a potential target's attentional set and a decrease of attention to other attentional sets.

Finally, as in Experiments 1 and 2, there were no main effects or interactions involving response congruency (all $p > 0.5$).

Discussion

The results of Experiment 3 further support the enhancement hypothesis while ruling out an interference-based account of the enhancement effect. As in Experiments 1

and 2, performance was better in STC than in DTC trials when the target-colored distractor appeared before the target, indicating an enhancement effect. Critically, however, the enhancement effect was reversed when the target-colored distractor appeared after the target. This result is inconsistent with the interference hypothesis, which predicts less interference (and thus better performance) in STC than in DTC trials regardless of whether the target-colored distractor is presented before or after the target. In contrast, this result is consistent with the enhancement hypothesis. In particular, if the target appears before the target-colored distractor, then the entry of its attentional set into the focus of attention should facilitate the detection of a subsequent distractor if its color matches the same (versus a different) attentional set. In sum, the results of Experiment 3 provide further support for the enhancement hypothesis.

General Discussion

Although selective attention usually helps to prevent irrelevant stimuli from gaining access to limited-capacity information processing systems, it occasionally has the opposite effect (Folk, et al., 1992). For example, distractors that possess a target-defining color attract attention and are deeply processed in a limited-capacity manner (Folk, et al., 2002; Serences, et al., 2005). Here, we investigated whether such deep processing of a target-colored distractor causes the corresponding attentional set to enter a limited-capacity focus of attention within working memory (Jonides, et al., 2008; Oberauer, 2002), leading to enhanced identification of a subsequent target whose features match the same attentional set. Findings from three experiments supported this enhancement hypothesis. Moreover, they weighed against two alternative accounts of our results.

In Experiment 1, we both replicated previous findings of contingent attentional capture and observed initial support for the enhancement hypothesis. First, consistent with prior studies of contingent attentional capture, in both set sizes target identification accuracy was lower when a target was preceded by a Same Target-Colored (STC) distractor than when it was preceded by a Non-Target-Colored (NTC) distractor, and this effect was larger at shorter than at longer SOAs (Folk, et al., 2002; Folk, et al., 2008). Such effects were similar in magnitude in Set Size 1 and Set Size 2, consistent with the data from catch trials suggesting that participants were able to maintain one and two attentional sets equally well. Second, in line with the enhancement hypothesis, target identification accuracy was higher when a target was preceded by a STC distractor than when it was preceded by a Different-Target-Colored (DTC) distractor, and this effect was larger at shorter than at longer SOAs. This enhancement effect suggests that deeply processing a target-colored distractor causes the corresponding attentional set to enter a focus of attention within working memory that can hold just a single item (Jonides, et al., 2008; Oberauer, 2002, 2003).

In Experiment 2, we ruled out bottom-up perceptual priming as an alternative explanation for the enhancement effect. Performance was measured in two task blocks. In one task block (Set Size 2), participants identified letters in the central RSVP stream that possessed either of two target colors while ignoring letters that possessed other colors. The presence of irrelevant colors in the central RSVP stream made it necessary for participants to maintain two attentional sets, one for each target color. In the other task block (Any Color), participants identified any colored letter in the central RSVP stream. Thus, they could maintain just a single attentional set and all colors matched the

same set. In line with the enhancement hypothesis, the enhancement effect was highly robust when different colors matched distinct attentional sets in Set Size 2, but was completely absent when different colors matched the same attentional set in Any Color. This finding weighs against the possibility that the enhancement effect stems solely from bottom-up perceptual priming of the distractor's color.

However, it is important to consider whether differences in the number of attentional sets that participants maintained in Set Size 2 (two sets) and Any Color (one set) in Experiment 2 might have caused the enhancement effect to be larger in Set Size 2 than in Any Color. For example, contingent attentional capture effects might simply scale with the number of attentional sets that participants maintain. Arguing against this possibility, in Experiment 1 we did not observe a significant difference in the magnitude of contingent attentional capture in Set Size 1 and Set Size 2. In fact, contrasting performance in STC and NTC trials revealed numerically less contingent attentional capture in Set Size 2 than in Set Size 1. For this reason, differences in the number of attentional sets that participants maintained do not appear to account for our finding that the enhancement effect was larger in Set Size 2 than in Any Color.

In Experiment 3, we ruled out an interference-based account of the enhancement effect in Set Size 2. According to this account, performance was better in STC than in DTC trials because there was confusion, or interference, with regards to the location of the target in STC trials, but with regards to both the location and the color of the target in DTC trials. To pit this interference-based account against the enhancement hypothesis, we varied whether the target-colored distractor was presented before or after the target. As in Experiments 1 and 2, when the target-colored distractor was presented before the

target in Set Size 2, performance was better in STC than in DTC trials, a result that could be explained by either hypothesis. However, when the target-colored distractor was presented after the target, performance was worse in STC than in DTC trials, a result that could only be explained by the enhancement hypothesis. Thus, our findings in Experiment 3 not only rule out an interference-based account of the enhancement effect, but also provide converging support for the enhancement hypothesis.

Although the results of Experiments 2 and 3 weigh against various alternative accounts of our findings, one might question how strongly they actually support the enhancement hypothesis. Indeed, evidence for the enhancement hypothesis was observed as a reduction of contingent attentional capture costs, rather than as an improvement in performance relative to conditions that did not contain target-colored distractors. However, it is standard practice in the literature to show that an effect is present by demonstrating that it modulates the size of a performance decrement. For example, in studies of task switching, an effect of task set reconfiguration has been revealed by showing that switch costs can be reduced, but not fully eliminated, by giving participants more time to prepare for an upcoming task switch (Meiran, Chorev, & Sapir, 2000). Analogously, in the present study of contingent attentional capture, an effect of enhancing a potential target's attentional set has been demonstrated by showing that the magnitude of capture varies with whether a distractor's color and a target's color match the same or different attentional sets. Thus, our findings support the enhancement hypothesis even though effects of enhancement manifested themselves as a reduction of contingent attentional capture costs rather than as an improvement in performance relative to conditions without target-colored distractors.

Given the robust enhancement effects that we have observed, it would appear that most prior studies have failed to appreciate the full range of contingent attentional capture effects. In almost all contingent attentional capture studies, participants maintain just a single attentional set (Folk, et al., 2002; Folk, et al., 1992; Remington, Folk, & McLean, 2001; Serences, et al., 2005; Shih & Reeves, 2007), which means that contingent capture effects arising from a target-resembling distractor are estimated when the attentional set that defines the subsequent target is already within the focus of attention. Under these conditions, such capture effects index not only a reduction of target identification accuracy that is caused by deeply processing a target-resembling distractor, but also an enhancement of target identification accuracy that is caused by the presence of the target-defining attentional set within the focus of attention. Only by requiring participants to maintain two distinct attentional sets in Set Size 2 were we able to measure contingent attentional capture effects in the absence of such enhancement. Notably, contingent attentional capture effects at short SOAs were two to three times larger when the target-defining attentional set was outside the focus of attention (i.e., in DTC trials) than when it was within the focus of attention (i.e., in STC trials) (see the data from Set Size 2 in Figure 3-3, Figure 3-4, and Figure 3-5). Thus, contingent attentional capture effects can sometimes be much more pronounced than previous studies have indicated.

The enhancement effect is consistent with other data indicating that transferring a task or attentional representation into the focus of attention enhances subsequent behaviors involving that representation. As we discussed in the Introduction, this view is supported by prior studies of working memory (Berti, 2008; Garavan, 1998; McElree,

2001), task switching (Hsieh & Allport, 1994; Monsell, 2003), and the attentional blink (Juola, et al., 2004; Vachon, et al., 2007). For example, in the attentional blink paradigm, the second of two targets is identified more accurately when it matches the same conceptual category (e.g., digits) as the first target than when it matches a different category (e.g., letters) (Juola, et al., 2004). Our findings suggest that identifying the first target causes the corresponding attentional set (e.g., identify digits) to be transferred into the focus of attention, leading to a smaller attentional blink when the second target is identified using the same (versus a different) attentional set. Moreover, they indicate that even an irrelevant, target-resembling distractor can cause an attentional set to be transferred into the limited-capacity focus of attention, from which it can enhance subsequent behaviors relying on the same set.

As mentioned previously, the enhancement effect may appear to conflict with prior data indicating that attentional sets can be primed across trials. For example, although inter-trial priming of top-down attentional sets is not always observed (Ansorge & Horstmann, 2007; Ansorge, et al., 2005), identifying a distractor that possesses a target-defining color sometimes decreases an attentional bias toward that color in the next trial (Lleras, et al., 2009). Based upon such findings, one might have predicted worse performance in the present experiments when a target possessed the same color as a preceding distractor in STC trials than when it possessed a different color in DTC trials, due to a reduction of attention to the distractor's color. However, given that the detection of a target-colored distractor initially leads that item to be deeply processed *as though it were a target* (Folk, et al., 2002), an attentional bias toward that item's color may increase for a brief time (Dux & Marois, 2009), even if it is subsequently reduced.

Converging evidence for such an increase comes from the finding that presenting a distractor just before presenting the second of two targets in an RSVP stream reduces the magnitude of the attentional blink most strongly when the distractor possesses the upcoming target's color (Nieuwenstein, 2006; Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005). Thus, any perceived discrepancy between our findings and previous work revealing inter-trial priming of top-down attentional sets (Folk & Remington, 2008; Lleras, et al., 2009) likely stems from the relatively short interval over which our within-trial effects were measured.

Although we have argued that the enhancement effect stems from a limited-capacity focus of attention, it is worthwhile to consider whether it might alternatively arise from a brief lapse of attention. This possibility is suggested by the temporary loss of control (TLC) model, which was first developed to explain various phenomena in the attentional blink paradigm (Di Lollo, Kawahara, Ghorashi, & Enns, 2005). In this model, a limited-capacity central processor biases attentional filters to detect stimuli that possess one or more target-defining features (e.g., task-relevant colors). When such a stimulus is detected, it is directed to the central processor for purposes of stimulus identification, during which time the central processor does not have sufficient resources to continue biasing the attentional filters. Thus, until the potential target is identified, these filters are exogenously reconfigured by each subsequent distractor item that appears, leading to exogenous (rather than endogenous) changes in attentional set.

Of importance, the TLC model cannot explain our finding that performance was better in STC than in DTC trials when the target-colored peripheral distractor and the subsequent target were separated by one or more colored distractors in the central RSVP

stream. The TLC model posits that by the time a target appears in such trials, attentional filters should already be reconfigured to match the color of the central RSVP stream distractor that immediately preceded the target (for similar reasoning, see Nieuwenstein, 2006). Thus, identifying the target should require a time-consuming change of attentional set in both STC and DTC trials, leading to equivalent performance in these trial types. Given that performance was better in STC than in DTC trials even when the target-colored distractor and the subsequent distractor were separated by one or more colored distractors, the TLC model does not appear able to account for the enhancement effect.

Although we have emphasized enhancement when accounting for the present data, inhibitory mechanisms may also play a role. For example, our finding that target identification accuracy was lower when the target's color matched a different (versus the same) attentional set than the preceding distractor's color may stem, in part, from a distractor-triggered inhibition of competing attentional sets. In other words, when searching for orange and green target letters, detecting an orange distractor may result not only in transferring the "orange" attentional set into the focus of attention, but also in inhibiting the "green" attentional set. Consistent with this possibility, task switching appears to involve not only loading a new task set into the focus of attention, but also inhibiting the previous task set (Mayr & Keele, 2000). Given that the present experiments were not designed to distinguish between enhancement and inhibition, however, future work will be necessary to determine the relative contributions of these processes to the enhancement effect.

Our account of the enhancement effect relies on the assumption that only a single representation can occupy the focus of attention (Oberauer, 2002, 2003). However, it is well-established that multiple items can be maintained within the focus of attention when they are chunked, or bound, into a single representation (Jonides, et al., 2008; Oberauer & Bialkova, 2009). Consistent with this view, the behavioral cost associated with switching attention between items in working memory is eliminated when those items are bound into a single object representation. For example, when updating a location and a count in working memory, participants experience no cost of switching between these representations when they are bound by imagining a moving number (Bao, Li, & Zhang, 2007). This result suggests that the enhancement effect might be absent if distinct attentional sets could be bound into a single representation. While additional studies are necessary to test this hypothesis, such a result would provide complementary evidence that contingent attentional capture effects stem from a limited-capacity focus of attention within working memory.

More broadly, the present findings may have important implications for real-world activities that involve maintaining multiple attentional sets (e.g., Most & Astur, 2007). For example, while driving to brunch on a winding highway, we may simultaneously be searching for a yellow warning sign indicating an upcoming twist in the road and a restaurant billboard that has either the same color as (e.g., yellow, Waffle House) or a different color than (e.g., blue, International House of Pancakes) the warning sign. The present findings suggest that drivers would be much more likely to miss such a warning sign when it appears in a different (versus the same) color as an immediately preceding, target-colored billboard. Given that nearly 80% of car crashes are

immediately preceded by a moment of driver inattention (Ranney, 2008), applied research should be aimed at identifying and minimizing contingent attentional capture effects in real-world settings.

In sum, our findings indicate that involuntarily directing attention to a distractor that possesses a target-defining color (e.g., orange) leads the corresponding attentional set (e.g., identify orange letters) to enter a limited-capacity focus of attention within working memory, thereby enhancing the identification of a subsequent target whose color matches the same (versus a different) attentional set. Specifically, contingent attentional capture effects were only one half to one third as large when detecting a target relied on the same (versus a different) attentional set as detecting a preceding target-colored distractor. Of importance, neither bottom-up perceptual priming nor feature-based interference could account for this modulation of contingent attentional capture effects. Future work investigating the possible influences of inhibitory mechanisms and chunking on the enhancement effect may reveal additional information about how capacity limitations in working memory contribute to contingent attentional capture effects, both in the laboratory and in real-world situations.

Chapter 4

Set-specific capture can be reduced by preemptively occupying a limited-capacity focus of attention

Abstract

Recent work has shown that contingent attentional capture effects can be especially large when multiple attentional sets for color guide visual search (Moore & Weissman, in press). In particular, this research suggests that detecting a target-colored (e.g., orange) distractor leads the corresponding attentional set (e.g., identify orange letters) to enter a limited-capacity focus of attention, where it remains briefly while the distractor is being attended. Consequently, the ability to identify a differently-colored (e.g., green) target 100-300 ms later is impaired because the appropriate set (e.g., identify green letters) cannot also enter focus of attention. In two experiments, we investigated whether such *set-specific capture* can be reduced by preemptively occupying the focus of attention. As predicted, a target-colored central distractor presented 233 ms before a target-colored peripheral distractor eliminated set-specific capture arising from the peripheral distractor. Moreover, this effect was observed only when the central distractor's color (e.g., orange) (a) matched a different set than the upcoming peripheral distractor's color (e.g., green) *and* (b) matched the same set as the upcoming central target's color (e.g., orange). We conclude that the same working memory limitations that give rise to set-specific capture can be preemptively exploited to reduce it.

Introduction

Selective attention directs limited resources to stimuli that are important for achieving behavioral goals (Yantis & Egeth, 1997). Moreover, selective attention appears to be enabled by creating and maintaining one or more attentional sets, which specify the perceptual and/or conceptual attributes (e.g., color, location, size, shape, or semantic category) that define relevant stimuli (Adamo, et al., 2008; Ansorge & Heumann, 2003; Atsunori Ariga & Yokosawa, 2008; Folk, et al., 1992; Pashler & Huang, 2007; Pashler & Shiu, 1999). Guided by such attentional sets, top-down signals enhance the processing of relevant stimuli while limiting the processing of irrelevant stimuli (M. Corbetta & Shulman, 2002).

Sometimes, however, top-down signals have the opposite effect. For example, contingent attentional capture refers to a phenomenon in which an irrelevant stimulus that possesses a target-defining attribute (e.g., a particular color) attracts attention as though it were a target (Bacon & Egeth, 1994; Folk, et al., 2002; Folk, et al., 2008; Folk, et al., 1992; Serences, et al., 2005). Because limited resources have been allocated to the irrelevant stimulus, the identification of a target that appears within a few hundred milliseconds afterwards is impaired. Such capture has been observed in a variety of paradigms including those involving spatial cuing (Bacon & Egeth, 1994; Folk, et al., 1992; Gibson & Kelsey, 1998), visual search (Olivers, 2008), and rapid serial visual presentation (RSVP) (Folk, et al., 2009; Folk, et al., 2002; Folk, et al., 2008; Leblanc & Jolicoeur, 2007; Moore & Weissman, in press; Serences, et al., 2005). Thus, attentional sets are not always helpful for limiting the processing of irrelevant stimuli.

Given that minimizing distraction is crucial for enabling purposeful behavior, it is important to investigate whether contingent attentional capture can be reduced. Support for this possibility comes from a recent study by Folk and colleagues (Folk, Ester & Troemel, 2009). In this study, participants searched for letters of a particular color (e.g., red) within a centrally-presented RSVP stream. Similar to prior studies of contingent attentional capture, a peripheral distractor impaired the identification of a subsequent target more when it was target-colored (e.g., red) than when it was not target-colored (i.e., grey). However, this effect vanished when a target-colored distractor was presented in the central RSVP stream a few hundred milliseconds before the peripheral distractor was presented. Folk et al. (2009) argued that detecting the central distractor led to the opening “of a gate between perceptual processes and higher level cognitive processes,” which allowed target-colored items in the central RSVP stream, but not at different locations, to access higher level cognitive processes. Thus, contingent attentional capture arising from the subsequent peripheral distractor was reduced.

Reducing contingent attentional capture may be even more important when multiple attentional sets guide target selection because contingent capture effects can be especially large under such conditions. For instance, in one of our recent studies (Moore & Weissman, in press), participants searched a heterogeneously-colored central RSVP stream for occasional target letters that appeared in either of two possible colors (e.g., orange or green). As in other studies of contingent attentional capture (Folk, et al., 2009; Folk, et al., 2002; Folk, et al., 2008; Serences, et al., 2005), a peripheral distractor impaired subsequent target identification more when it was target-colored (e.g., orange) than when it was not target-colored (e.g., purple). Critically, at short stimulus onset

asynchronies (SOAs) of approximately 100-300 ms, this effect was two to three times larger when the peripheral distractor's color (e.g., orange) matched a different attentional set than the upcoming target's color (e.g., green) as compared to the same attentional set (e.g., orange). We call this phenomenon *set-specific* capture.

In our prior study, we argued that set-specific capture reflects a redistribution of processing resources among the attentional sets that guide visual search (Moore & Weissman, in press). Specifically, we suggested that detecting a target-colored item (e.g., an orange letter) leads processing resources to become more strongly directed toward the corresponding attentional set (e.g., identify orange letters), consistent with prior claims that detecting a potential target leads to the recruitment of working memory processes that attend, identify, or otherwise consolidate that item (for a review, see Dux & Marois, 2009). Thus, for a brief time after a target-colored (e.g., orange) distractor is detected, it becomes harder to attend and identify a subsequent target if its color (e.g., green) matches a different attentional set than if its color (e.g., orange) matches the same attentional set.

Further support for our view comes from two additional findings in our prior study (Moore & Weissman, in press). First, although peripheral distractors captured attention in general, set-specific capture vanished when participants were instructed to search for any colored letter in a central RSVP stream containing mostly grey letters. In other words, set-specific capture was no longer observed when all possible target colors could be maintained in the same attentional set (i.e., identify any colored letter). This finding fits with our view because directing processing resources more strongly to a global attentional set for color should facilitate the identification of a subsequent target,

regardless of its exact color. Also important, this finding rules out bottom-up perceptual priming of the target's color as an alternate account of set-specific capture.

Second, set-specific capture was reversed when the peripheral distractor appeared 116 ms *after* the central target. That is, the peripheral distractor disrupted performance more when its color (e.g., green) matched the preceding target's color (e.g., green) than when its color matched the other target color (e.g., orange). This finding fits with our view because detecting a target (e.g., a green letter) should lead to a relative increase of processing resources toward the corresponding attentional set (e.g., identify green letters). Thus, a distractor that appears soon afterward should be more likely to be attended and impair performance if its color matches the same (versus a different) attentional set as the preceding target's color. This finding also shows that set-specific capture does not simply reflect interference between the peripheral distractor's color and the target's color. If that were the case, then performance should always be worse when the distractor and the target appear in different colors than when they appear in the same color. In sum, multiple findings suggest that set-specific capture reflects a redistribution of processing resources among the attentional sets that guide visual search.

This view fits nicely with a theory of working memory in which only one item or representation can be maintained in a limited-capacity focus of attention (Jonides, et al., 2008; McElree, 2001; Oberauer, 2002)¹. Support for this theory comes from a variety of sources including studies of working memory (Berti, 2008; Garavan, 1998; McElree,

¹ This theory is not inconsistent with findings indicating that about four items can be maintained in working memory (e.g. see Cowan, 2000) for a review). It simply suggests that a single item, residing in the focus of attention, is privileged in comparison to other items that are being maintained. Numerous researchers espouse this view, even though they disagree about other aspects of working memory (Jonides, et al., 2008; McElree, 2001; Oberauer, 2002, 2003; Oberauer & Bialkova, 2009).

2001), task switching (Hsieh & Allport, 1994; Monsell, 2003), and the attentional blink (Juola, et al., 2004; Vachon, et al., 2007). For example, when participants maintain separate counters in working memory corresponding to the number of times that circles and triangles have been presented, they are faster to update a particular counter (e.g., the number of circles) just after the same (versus a different) counter has been updated (Berti, 2008; Garavan, 1998). Moreover, this effect is not due to perceptual priming as it disappears when the updating task permits the counters to be bound into a single representation (Bao, et al., 2007). Thus, it has been argued that only a single item or representation can occupy the focus of attention at any given time (Berti, 2008; Garavan, 1998).

In line with this theory, we have suggested that only a single attentional set can occupy the focus of attention (Moore & Weissman, in press). Specifically, detecting a target-colored item (e.g., a green letter) leads the corresponding attentional set (e.g., identify green letters) to enter the focus of attention, where it remains for up to a few hundred milliseconds while the item is being attended (Moore & Weissman, in press). During this time, a second target-colored item may be detected. However, it is possible to attend and identify this second item only if its color (e.g., green) matches the same attentional set (e.g., identify green letters) as the first item's color. If the second item's color (e.g., orange) matches a different attentional set (e.g., identify orange letters), then it will not be identified.

Critically, our view leads to a hypothesis about how to reduce set-specific capture arising from a target-colored peripheral distractor. Namely, such capture should be reduced if a target-colored distractor is detected within a few hundred milliseconds *before*

the peripheral distractor is presented. Moreover, this reduction should occur only when the first distractor's color (e.g., orange) and the peripheral distractor's color (e.g., green) match different attentional sets. In such trials, detecting the first distractor's color (e.g., orange) should lead the corresponding attentional set (e.g., identify orange letters) to enter the limited-capacity focus of attention, where it should remain for a few hundred milliseconds while the first distractor is attended. If, during this time, a peripheral distractor that possesses a different target color (e.g., green) is detected, then the attentional set corresponding to its color (e.g., identify green letters) should be unable to enter the already-occupied focus of attention. Thus, there should be a reduction of set-specific capture arising from the peripheral distractor.

Given the sizable literature investigating interactions between attention and working memory, it is important to clarify two aspects of our view. First, we posit that it is only *after* a target-colored (e.g., orange) item is detected during a visual search task that the corresponding attentional set (e.g., identify orange letters) enters the focus of attention. In other words, active visual search *before* a target-colored item is detected does not require an attentional set to occupy the focus of attention. Consistent with this view, some researchers have argued that attentional sets are maintained in working memory during active visual search, but not necessarily in the focus of attention (e.g., (Olivers & Meeter, 2008)). Also consistent, attentional sets are able to guide visual search even when they are not actively maintained in working memory (Thompson, et al., 2007). Finally, the magnitude of contingent attentional capture that is observed when a distractor's color (e.g., orange) matches an upcoming target's color (e.g., orange) does not vary with the number of attentional sets for color that guide visual search (Moore &

Weissman, in press). This result suggests that searching for multiple target colors does not involve rapidly switching the attentional set that occupies the focus of attention. If that were the case, then the probability that an attentional set corresponding to a distractor's color occupies the focus of attention when the distractor appears would decrease with the number of sets guiding visual search, leading to smaller contingent attentional capture effects. In sum, multiple findings suggest that it is only *after* a target-colored item is detected that the corresponding attentional set enters the focus of attention.

Second, although our view posits an interaction between attention and working memory, it does not relate to a current debate regarding this interaction. Specifically, many researchers disagree about whether stimuli whose features match the current contents of working memory capture attention when they are *not* related to an ongoing visual search task (e.g., Houtkamp & Roelfsema, 2006; Olivers, 2009; Soto, et al., 2005; Woodman & Luck, 2007). In contrast, our view is that such stimuli capture attention when they *are* related to an ongoing visual search task. This view is not connected to the current debate (Olivers, 2009). Moreover, it is a non-controversial stance that has received support from numerous prior studies of contingent attentional capture (e.g., Folk, et al., 2002; Folk, et al., 1992; Leblanc, et al., 2008; Serences, et al., 2005).

Experiment 1

The goal of Experiment 1 was to investigate whether it is possible to reduce set-specific capture. Participants searched for target-colored letters within a central RSVP stream. Targets appeared unpredictably in either of two possible colors (e.g., orange and

green). In some trials, a target letter was preceded by a target-colored distractor that appeared in one of two peripheral RSVP streams. As in our prior study of set-specific capture (Moore & Weissman, in press), we expected target identification accuracy to be lower when the peripheral distractor's color (e.g., green) differed from the target's color (e.g., orange) than when it matched the target's color. Critically, a target-colored distractor in the central RSVP stream occasionally preceded the target-colored distractor in the peripheral RSVP stream. We predicted that this central distractor would reduce set-specific capture arising from the peripheral distractor if its color (e.g., green) matched a different attentional set than the peripheral distractor's color (e.g., orange), but not if its color (e.g., orange) matched the same attentional set.

Method

Participants

Thirty University of Michigan students (15 female) participated in exchange for course credit. All participants (age range: 18-25) reported normal or corrected vision and no history of neurological injury or disease. Participants gave informed written consent before the experiment in accordance with the University of Michigan Behavioral Sciences Institutional Review Board.

Procedure

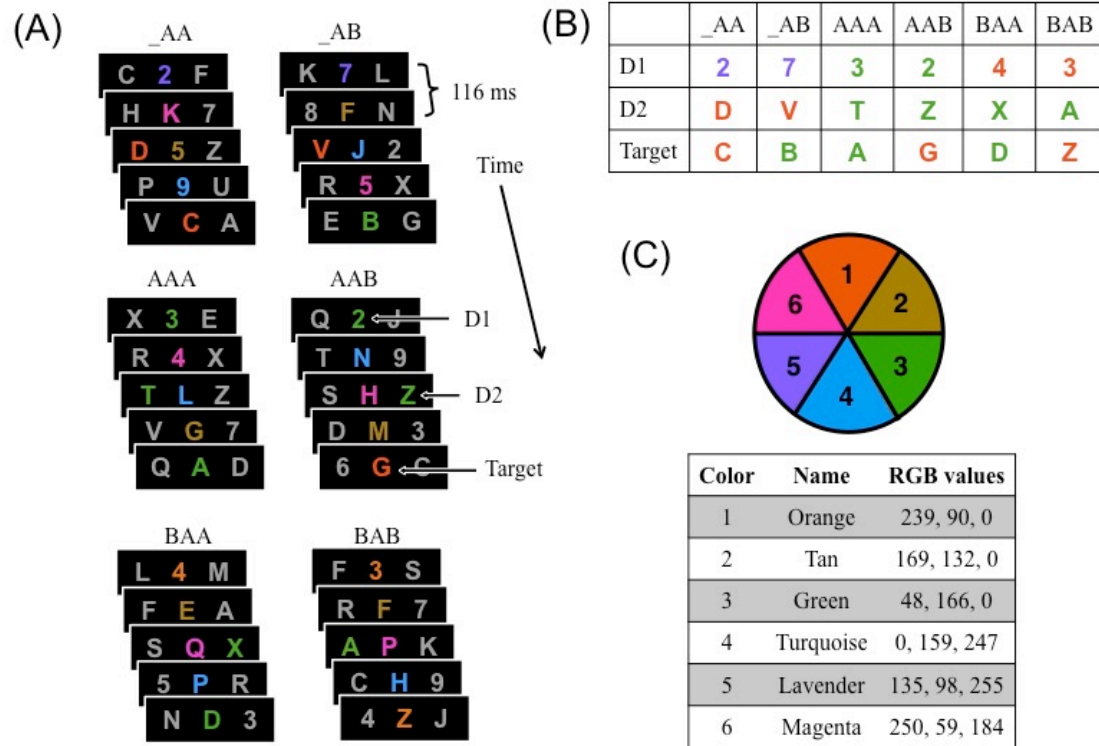


Figure 4-1: Stimuli used in Experiment 1.

A) Examples of the stimulus displays used in Experiment 1. Participants searched for target letters that could appear in either of two possible colors (e.g., orange and green) within a heterogeneously-colored, central rapid serial visual presentation (RSVP) stream while ignoring occasional target-colored distractors that appeared in either of two peripheral RSVP streams. Each frame was presented for 116 ms. D1 was a digit in the central RSVP stream, which was either non-target-colored (i.e., tan, magenta, or turquoise in the **_AA** and **_AB** trial types) or presented in one of the two possible target colors. D2 was a letter in one of the two peripheral RSVP streams. D2 appeared two frames after D1 and was always presented in one of the two possible target colors. Finally, the central target appeared two frames after D2. (B) A list of the trial types in Experiment 1, which includes an example stimulus sequence for each trial type. (C) The 6-color wheel from which stimulus colors were selected in Experiments 1 and 2. Color names and RGB values are indicated beneath the color wheel.

The task was similar to those in prior contingent attentional capture experiments that have used rapid serial visual presentation (RSVP) displays (Folk, et al., 2009; Folk, et al., 2002; Folk, et al., 2008; Moore & Weissman, in press; Serences, et al., 2005).

Participants viewed three simultaneously presented RSVP streams, each of which was composed of letters and digits (Figure 4-1A). In each of the two peripheral RSVP streams, most of the characters were grey, aside from an occasional target-colored (e.g.,

orange or green) letter distractor. In the central RSVP stream, each character appeared in one of six possible colors. Participants were instructed to identify occasional target letters in the central RSVP stream that appeared in either of two target colors (e.g., orange and green) while ignoring characters that appeared in any of the four other colors. They were also told to ignore target-colored letters in each of the two peripheral RSVP streams. As in a similar prior study (Serences et al., 2005), when a target-colored letter appeared in the central RSVP stream, participants were to indicate, via a key press, whether it was from the first half of the alphabet (J key, right index finger) or the second half of the alphabet (K key, right middle finger). Participants were not pressured to respond quickly.

As in our previous study (Moore & Weissman, in press), the three RSVP streams were presented continuously and the inter-target interval varied randomly across trials. An advantage of this procedure is that it does not allow participants to form expectations about when a target letter will appear. Thus, we reasoned that it would result in relatively low false alarm rates. To construct an appropriate set of inter-target intervals, we took into account an analysis of response times from our previous study of set-specific capture in which there was also no pressure to respond quickly (Moore & Weissman, in press). This analysis revealed that more than 95% of responses occurred within 2000 ms of target onset with an average response time of about 800 ms. Thus, we felt confident in making our shortest inter-target interval 2333 ms. Other inter-target intervals were 2916, 3500, and 4083 ms. To maintain consistent criteria for defining a target response across the four inter-target intervals, we defined a target response as the first key press logged within 2200 ms following target onset.

The experiment began with instructions explaining the task followed by 48 practice trials. During the practice trials, the rate of presentation of items in the three RSVP streams was slow at first (250 ms per item), but accelerated to full speed (116 ms per item) by the 24th trial. During the test trials, participants were given a self-paced rest break every 32 trials (about every 2 minutes).

Design

Targets in the central stream were preceded by zero, one, or two critical distractors. The first possible distractor (D1) was a digit that appeared in the central RSVP stream four frames (466 ms) prior to the target. D1 was either target-colored or non-target-colored. If it was target-colored, then it was either the same color as the upcoming target or a different color. The second possible distractor (D2) was a target-colored letter that appeared equally often in the left and right peripheral RSVP streams. D2 always appeared two frames (233 ms) prior to the target and was either the same color as the upcoming target or the other target color. As we describe next, there were nine trial types.

Three trial types did not include D1 and D2. In *target alone* trials, a target-colored letter that participants were supposed to identify appeared for a single 116 ms frame in the central RSVP stream. In *target catch* trials, a letter appeared in each RSVP stream for 1000 ms including a target-colored letter in the central RSVP stream that participants were supposed to identify. In *non-target catch* trials, a letter appeared in each RSVP stream for 1000 ms including a non-target-colored letter in the central RSVP stream that participants were *not* supposed to identify. The purpose of including catch

trials was to provide a relatively pure test of participants' ability to remember the target colors by eliminating the severe encoding limitations that were imposed by the RSVP display. In other words, these trials were included to ensure that participants were keeping track of the target colors. They were not, however, important for testing our main hypotheses.

Trial type	N, Exp1	N, Exp2
Target Alone	64	64
Target Catch	32	18
Non-target Catch	32	18
_AA	64	60
_AB	64	60
AAA	64	60
AAB	64	60
BAA	64	60
BAB	64	60
BAC	0	60

Table 4-1: The number of trials per trial type in Experiments 1 and 2.

Six additional trial types *did* include D1 and D2. To simplify our discussion of these trial types, we name each one using a three-letter sequence. In this sequence, the first letter represents D1, the second letter represents D2, and the third letter represents the target. Further, “A” and “B” represent different target colors. For example, “AAB” refers to a trial in which D1 and D2 appeared in the same target color (e.g., orange),

while the target appeared in a different target color (e.g., green). Finally, an underscore in the first position indicates that D1 appeared in a non-target color (e.g., lavender). For instance, “_AA” refers to a trial in which D1 was not target-colored (e.g., lavender) and D2 was the same color as the upcoming target (e.g., orange). Figure 4-1B indicates the three-letter label that corresponds to each of the six trial types involving distraction. It also provides an example stimulus sequence for each trial type, which is further illustrated in Figure 4-1A. Lastly, Table 4-1 indicates the number of trials that were included for each of these trial types in Experiments 1 and 2.

Finally, we controlled for effects of response congruency in our design. Specifically, whether D2 and the target were from the same or different parts of the alphabet was fully crossed with whether D2’s color and the target’s color matched the same or different attentional sets (this control was unnecessary for D1, which was a digit whose identity was not mapped to a task-relevant response). Thus, set-specific contingent attentional capture effects arising from D2 were not confounded with potential effects of response congruency.

Apparatus and Stimuli

Stimuli were displayed on a 19” Viewsonic CRT monitor with a 60 Hz refresh rate, controlled by a Dell PC running Windows XP. Presentation® software (Neurobehavioral Systems, Inc.) was used to control stimulus presentation and to record participants’ responses. A viewing distance of 80 cm was enforced by a chin rest.

Three RSVP streams containing letters and digits (character size, 2.07° x 1.88°) were presented simultaneously on a black background: one stream appeared at fixation,

while two others appeared 4.22° to the left and 4.22° to the right of fixation. A new character appeared in each RSVP stream every 100 ms, followed by a blank gap that lasted 16 ms. Target and D2 letters were drawn from the beginning (A, B, C, D and G) and the end (T, V, X, Y, Z) of the alphabet, so that target identification would not rely on a demanding decision (e.g. “is ‘M’ from the first or second half of the alphabet?”). D1 digits included 2, 3, 4, 7 and 9. Other characters in the RSVP streams included the entire alphabet except for I, O, and W, and all of the digits excluding 0 and 1 (see Figure 4-1A).

The stimulus colors were identical to those in the “light” color scheme of our prior study (Moore & Weissman, in press). These colors were drawn from a 6-color wheel (Figure 4-1C), in which each color had approximately the same CIELAB lightness value ($L^* = \text{approx. } 70$). The two target colors and single non-target color (i.e., D1’s color in _AA and _AB trials) were drawn from three non-adjacent colors in the wheel (orange, green, and lavender: colors 1, 3, and 5). A control experiment in our prior study confirmed that each of these three colors was equally discriminable from the other two colors in the triplet (Moore & Weissman, in press). The target and non-target colors were counterbalanced across participants. The remaining three colors in the wheel (tan, turquoise and magenta: colors 2, 4, and 6) were randomly assigned to other characters in the central RSVP stream. Moreover, the non-target color always appeared in the central RSVP stream once between successive targets to ensure that a non-target-colored item appeared in this stream as frequently as a target-colored item. In short, the target and non-target colors in the central RSVP stream were equated in terms of luminance, salience, and frequency of occurrence. These manipulations, in combination with the fact that target colors were drawn from non-adjacent colors on the wheel, ensured that

participants could only perform the task correctly if they maintained distinct attentional sets for each of the target colors.

Results

Mean accuracy was the dependent measure in all of our analyses (Figure 4-2). At the outset, we excluded eight participants (3 female) whose performance indicated that they were unable to keep track of the target colors. Specifically, these participants failed to correctly discriminate the target letter in more than 20% of target catch trials and/or produced false alarms in more than 20% of non-target catch trials.

Among the remaining 22 participants, we observed evidence of attentional capture. Specifically, target identification accuracy was lower when a target was preceded by a target-colored peripheral distractor (79%, *_AA* trials) than when it was not preceded by such a distractor (84.0%, target alone trials), [$t(21) = 3.80, p < 0.001$]. Although isolating contingent attentional capture requires a comparison of target identification accuracy following target-colored versus non-target-colored distractors², the contrast above typically leads to the same conclusion about the presence or absence of contingent attentional capture (Folk, et al., 2009; Folk, et al., 2002; Folk, et al., 2008; Moore & Weissman, in press; Serences, et al., 2005). As this conclusion is not critical for testing our main hypotheses, we now turn to discuss set-specific capture effects.

² In our prior study (Moore & Weissman, 2009), robust contingent attentional capture effects were revealed by this comparison. In the present study, however, we did not include trials in which a target was preceded by a single non-target-colored distractor because they were not critical for testing our main hypotheses. Moreover, we did not want to lose power by reducing the number of trials for the trial types that *were* critical for testing our hypotheses.

Of importance, the results supported our hypothesis about reducing *set-specific capture*. Replicating our previous finding of set-specific capture, *_AB* performance (71.2%) was worse than *_AA* performance (79.8%), [$t(21) = 3.80, p < 0.001$]. As predicted, however, this set-specific capture effect vanished when D1's color matched a different attentional set than D2's color. Specifically, performance did not differ in BAA (74.7%) and BAB (77.8%) trials [$t(21) = 1.71, p = 0.11$]. Further suggesting that D1 reduced set-specific capture, target identification accuracy was actually higher in BAB than in *_AB* trials [$t(21) = 2.62, p < 0.016$]. Together, these findings indicate that D1 reduced set-specific capture arising from D2 when D1's color matched a different attentional set than D2's color.

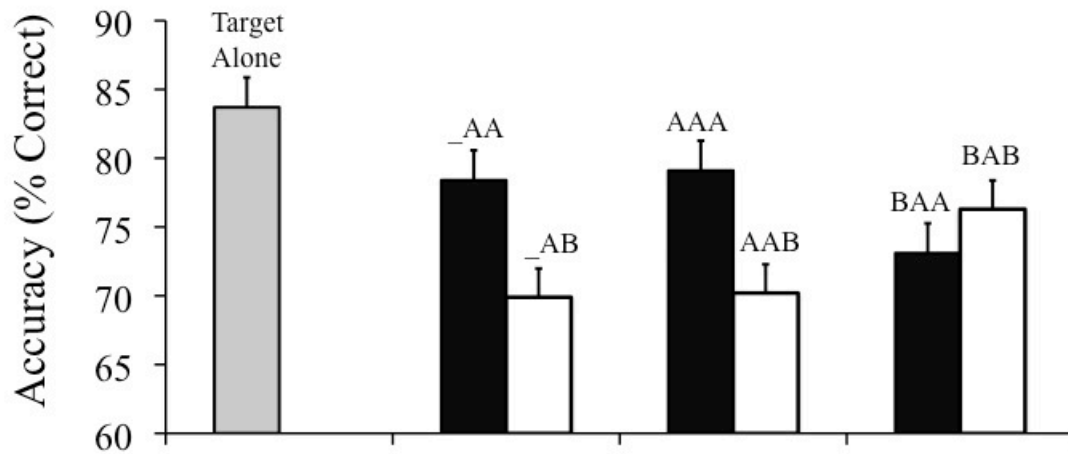


Figure 4-2: Results from Experiment 1.

Target identification accuracy plotted separately for each of the main trial types in Experiment 1. Consistent with prior studies, performance in all conditions involving distraction was significantly worse than performance in target alone trials, consistent with an overall attentional capture effect. Also as expected, performance in *_AB* trials was worse than performance in *_AA* trials, in line with a set-specific capture effect. Critically, when D1's color matched a different attentional set as D2's color, set-specific capture vanished as indicated by (a) no difference in performance between BAB and BAA trials and (b) better performance in BAB than in *_AB* trials. In contrast, when D1's color matched the same attentional set as D2's color, set-specific capture was still present as indicated by worse performance in AAB than in AAA trials. Error bars illustrate the standard error of the mean.

Also as predicted, set-specific capture arising from D2 was not reduced when D1's color matched the same attentional set as D2's color. Indeed, target identification accuracy was worse in AAB (70.7%) than in AAA (80.8%) trials [$t(21) = 4.08$, $p < 0.001$]. Moreover, target identification accuracy did not significantly differ in AAB and _AB trials [$t(21) = 0.17$, $p = 0.87$]. These findings indicate that D1 did not reduce set-specific capture arising from D2 when D1's color matched the same attentional set as D2's color.

We also investigated whether D1 reduced contingent attentional capture effects arising from D2 when D1, D2, and the target were all the same color, as in Folk et al.'s (2009) study. Surprisingly, we did not observe significantly higher target identification accuracy in AAA than in _AA trials [$t(21) = 0.53$, $p = 0.61$]. We reserve a discussion of this failure to replicate Folk et al.'s (2009) finding for the General Discussion.

Finally, whether D2 and the target were from the same or different halves of the alphabet did not influence the results. In particular, there was no main effect of response congruency, and response congruency did not interact with any other factors (all $p > 0.4$).

Discussion

In Experiment 1, two sets of findings confirmed our prediction that D1 would reduce set-specific capture arising from D2, but only when D1's color matched a different attentional set than D2's color. First, target identification accuracy (a) did not differ in BAB and BAA trials and (b) was higher in BAB than in _AB trials. These results indicate that D1 reduced set-specific capture arising from D2 when D1's color

matched a different attentional set than D2's color. Second, performance was (a) worse in AAB than in AAA trials and (b) not better in AAB than in _AB trials. These results indicate that D1 did not reduce set-specific capture arising from D2 when D1's color matched the same attentional set as D2's color. Taken together, these findings provide converging evidence that contingent attentional capture arising from a peripheral distractor can be reduced under certain conditions (Folk et al., 2009). Next, we consider two hypotheses about how D1 might reduce set-specific capture arising from D2 when D1's color matches a different attentional set than D2's color.

The *D1 capture hypothesis* posits that D1 reduces set-specific capture arising from D2 simply by preventing the attentional set corresponding to D2's color from entering the focus of attention. According to this account, when D1 is detected, the attentional set corresponding to its color enters the focus of attention and still occupies it when D2 appears two items later (233 ms after D1 onset). Thus, when D2 is presented, the attentional set corresponding to its color is unable to enter the focus of attention. When the processing of D1 is completed, the attentional set corresponding to its color leaves the focus of attention, and this occurs before the target appears four items later (466 ms after D1 onset). Therefore, the focus of attention is unoccupied when the target appears, leading to equivalent performance in BAB and BAA trials.

The D1 capture hypothesis also explains why performance is better in BAB than in _AB trials. In particular, since D1 is not presented in _AB trials, the attentional set corresponding to D2's color is able to enter the focus of attention, where it still resides when the target appears two items later. Because the attentional set corresponding to D2's color does not match the upcoming target's color, target identification is impaired.

In sum, the D1 capture hypothesis nicely explains our findings indicating that D1 reduces set-specific capture arising from D2 when the colors of D1 and D2 match different attentional sets.

The *D1 enhancement hypothesis* posits that D1 reduces set-specific capture arising from D2 by bringing the upcoming target's attentional set into the focus of attention. As in the D1 capture hypothesis, when D1 is detected, the attentional set corresponding to its color enters the focus of attention. Moreover, when D2 is presented two items (233 ms) later, its corresponding attentional set is unable to enter the already-occupied focus of attention. However, unlike the D1 capture hypothesis, the attentional set corresponding to D1's color still occupies the focus of attention when the target is presented four items (466 ms) later. Thus, in BAB trials, D1 reduces set-specific capture arising from D2 in two ways. First, it prevents the attentional set corresponding to D2's color from entering the focus of attention. Second, it leads the attentional set that specifies the upcoming target's color to enter the focus of attention.

Can the D1 enhancement hypothesis account for the effects we have observed? On the one hand, it nicely explains why target identification accuracy is higher in BAB than in _AB trials. Specifically, the attentional set corresponding to the target's color is already inside the focus of attention when the target appears in BAB (but not _AB) trials, thereby facilitating target identification. On the other hand, the D1 enhancement hypothesis appears to have difficulty explaining why target identification accuracy is not significantly higher in BAB than in BAA trials. However, the absence of this effect may not be inconsistent with the D1 enhancement hypothesis. In some trials, the processing of D1 may be completed before D2 appears two items later, meaning that the focus of

attention is not occupied when D2 appears. Thus, the attentional set corresponding to D2's color enters the focus of attention and is still there when the target appears two items later. The effect of D2 occupying the focus of attention when the target appears is to impair target identification in BAB trials while enhancing it in BAA trials, potentially leading to no overall difference in performance between these trial types. For this reason, it is unclear whether our findings in Experiment 1 support the D1 capture hypothesis or the D1 enhancement hypothesis. Thus, we conducted a second experiment.

Experiment 2

In Experiment 2, we sought to distinguish between the D1 capture and D1 enhancement hypotheses. The task was identical to that in Experiment 1, except that participants identified target letters appearing in any of *three* possible colors within the central RSVP stream. Using this task, we were able to include an additional trial type, BAC, in which D1, D2, and the target were all different target colors. We reasoned that even if the attentional set corresponding to D2's color occasionally entered the focus of attention, it would impair target identification equally in BAB and BAC trials. Thus, contrasting performance in these two trial types would allow us to determine if it mattered whether D1's color matched the target's color and, consequently, to distinguish between the D1 capture and D1 enhancement hypotheses. Specifically, the D1 capture hypothesis predicted equivalent performance in these trial types; in contrast, the D1 enhancement hypothesis predicted better performance in BAB trials than in BAC trials.

Methods

Participants

Forty-four University of Michigan students (25 female) participated in exchange for course credit. All participants (age range: 18-25) reported normal or corrected vision and no history of neurological injury or disease. Participants gave written informed consent before the experiment in accordance with the University of Michigan Behavioral Sciences Institutional Review Board.

Procedure and Design

The task was the same as that in Experiment 1 except that participants were told to identify letters in the central RSVP stream that appeared in any of three possible target colors (Figure 4-3 provides example trials for the main trial types). Consequently, Experiment 2 employed the same trial types as Experiment 1 with the exception of one new trial type: BAC (see Figure 4-1A). In this trial type, D1's color, D2's color, and the target's color (e.g., orange, green, and lavender) matched distinct attentional sets. The number of trials per condition differed slightly from that in Experiment 1 to accommodate the new trial type (see Table 4-1 for details).

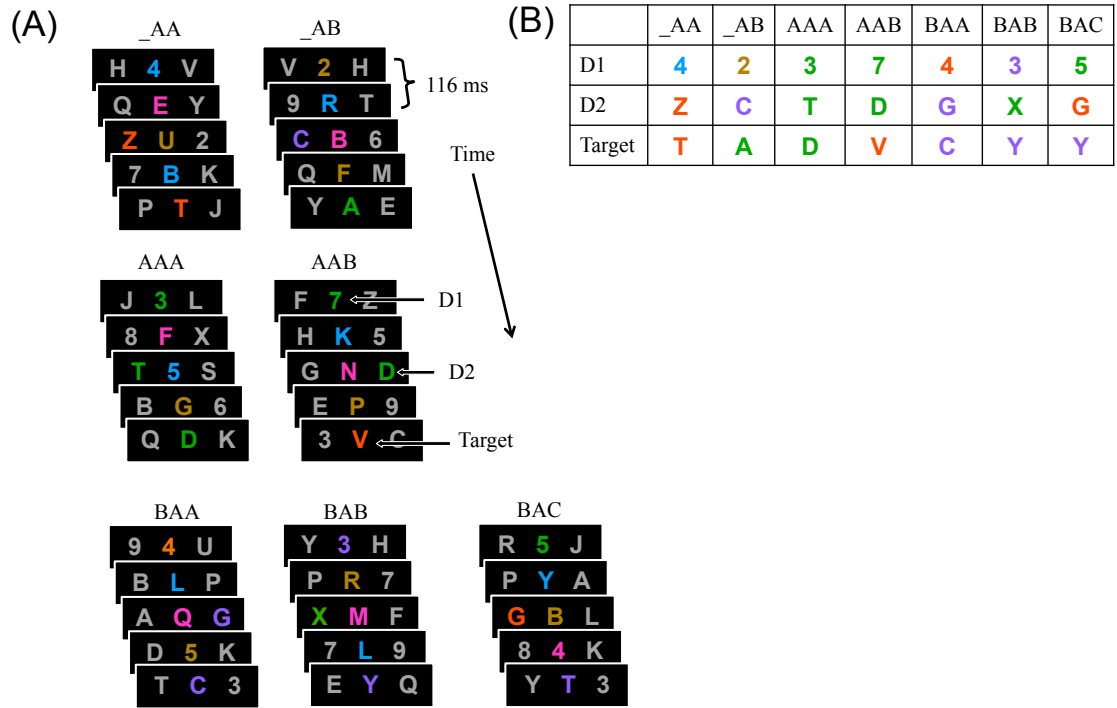


Figure 4-3: Stimuli in Experiment 2.

(A) Examples of the stimulus displays used in Experiment 2. Participants searched for target letters in a central RSVP stream that could appear in any of three possible colors (i.e., orange, green, and lavender) while ignoring occasional target-colored distractors that appeared in either of two peripheral RSVP streams. Using three target colors allowed us to include an additional trial type, BAC, in which the colors of D1, D2, and the target all matched different attentional sets. (B) A list of the trial types in Experiment 2, which includes an example stimulus sequence for each trial type.

Apparatus and Stimuli

The apparatus and stimuli in Experiment 2 were the same as those in Experiment 1 with one important exception: there were now three target colors (i.e., orange, green, and lavender: colors 1, 3, and 5 of the 6-color wheel shown in Figure 4-1C). Due to this change, the non-target color (i.e., D1's color in **_AA** and **_AB** trials) was chosen randomly from colors 2, 4, and 6 in the color wheel (i.e., tan, turquoise, and magenta). Although each of these colors was not equally discriminable from each of the target colors, the main contrast of interest (i.e., **BAB** versus **BAC**) did not involve trial types in

which a non-target color was presented. Thus, our choice was acceptable. Moreover, it allowed us to use a similar color scheme as in Experiment 1, thereby making the stimulus displays in Experiments 1 and 2 more comparable than would otherwise be the case.

Results

Mean accuracy was the dependent measure in all analyses. Before conducting the critical analyses, we excluded eleven participants (five female) whose performance indicated that they were unable to remember the target colors. In particular, these participants failed to correctly discriminate the target letter in more than 20% of target catch trials and/or produced false alarms in more than 20% of non-target catch trials.

The results of Experiment 2 replicated the main findings of Experiment 1 (Figure 4-4). First, performance was worse in $_AA$ trials (80.2%) than in target alone trials (82.7%), [$t(33) = 2.71, p < 0.01$], consistent with an attentional capture effect (Folk, et al., 2009; Charles L. Folk, et al., 2002; Folk, et al., 2008; Moore & Weissman, in press; John T. Serences, et al., 2005). Second, performance was worse in $_AB$ (74.0%) than in $_AA$ (80.2%) trials [$t(33) = 3.78, p < 0.001$], in line with a set-specific capture effect (Moore & Weissman, in press). Third, set-specific capture was reduced when D1's color matched a different attentional set than D2's color as indicated by statistically equivalent performance in BAB (77.8%) and BAA (76.4%) trials [$t(33) = 1.15, p = 0.26$] as well as better performance in BAB (77.8%) than in $_AB$ trials (73.6%) [$t(33) = 2.10, p < 0.043$]. Fourth, set-specific capture was not reduced when D1's color matched the same attentional set as D2's color as indicated by statistically equivalent performance in AAB

(73.7%) and $_AB$ (73.6%) trials [$t(33) = 0.26, p = 0.80$]. In sum, Experiment 2 replicated the main findings of Experiment 1.

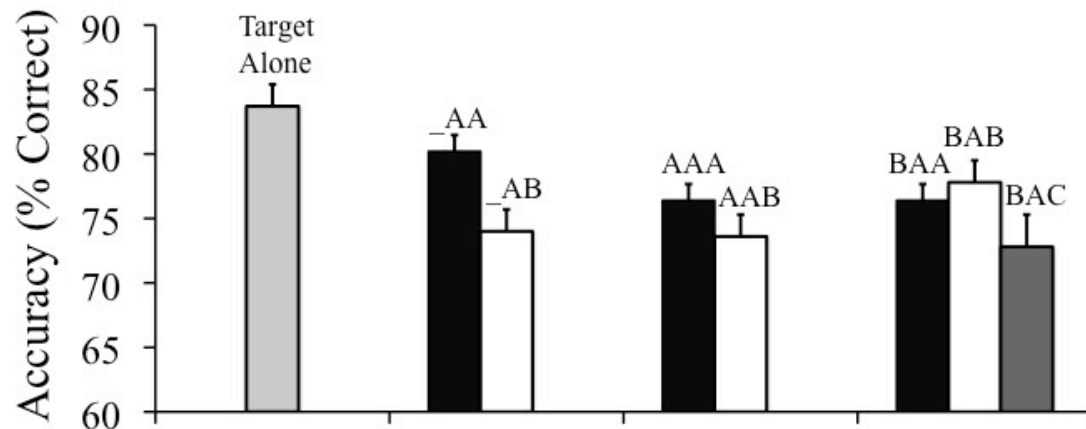


Figure 4-4: Results from Experiment 2.

Target identification accuracy plotted separately for each of the main trial types in Experiment 2. Experiment 2 replicated the three main findings of Experiment 1. First, there was an overall attentional capture effect as performance in all conditions involving distraction was worse than that in target alone trials. Second, there was a set-specific contingent attentional capture effect because performance in $_AB$ trials was worse than performance in $_AA$ trials. Third, set-specific capture was reduced when D1's color matched a different attentional set than D2's color. Specifically, performance in BAB trials did not differ from performance in BAA trials and was better than in $_AB$ trials. Critically, in line with the D1 enhancement hypothesis, performance was better in BAB than in BAC trials. Error bars illustrate the standard error of the mean.

As we mentioned in the discussion of Experiment 1, the findings above do not allow us to distinguish between the D1 capture and D1 enhancement hypotheses. Therefore, we arbitrated between these hypotheses by comparing performance in BAB and BAC trials. As uniquely predicted by the D1 enhancement hypothesis, target identification accuracy was significantly higher in BAB (77.8%) than in BAC trials (72.8%) [$t(33) = 3.46, p < 0.002$]. Also in line with the D1 enhancement hypothesis, set-specific capture was observed in BAC trials; specifically, performance was significantly

worse in BAC trials (72.8%) than in BAA trials (76.4%) [$t(33) = 2.39, p < 0.023$]. Thus, our findings in Experiment 2 support the D1 enhancement hypothesis.

As in Experiment 1, we also investigated whether focusing spatial attention on an upcoming target's location reduces contingent attentional capture (Folk, et al., 2009). However, once again, no such effect was observed. Quite the opposite, performance was significantly worse in AAA than in _AA trials, [$t(33) = 2.16, p < 0.038$]. We reserve a discussion of this result for the General Discussion.

Finally, whether D2 and the target were from the same or different parts of the alphabet did not influence the results. There was no main effect of response congruency, and response congruency did not interact with any other factors (all $p > 0.3$).

Discussion

In Experiment 2, we distinguished between the D1 capture and D1 enhancement hypotheses. The D1 capture hypothesis predicted equivalent performance in BAB and BAC trials. In contrast, the D1 enhancement hypothesis predicted better performance in BAB than in BAC trials. Critically, our findings supported the D1 enhancement hypothesis. Thus, it would appear that D1 reduced set-specific capture by bringing the upcoming target's attentional set into the focus of attention.

General Discussion

In everyday life, visual search is often guided by multiple attentional sets for color. For example, in the produce section at the grocery store, one may simultaneously search for apples and bananas by maintaining the colors red and yellow in distinct

attentional sets. Using a laboratory analog of this task in which participants searched for target letters appearing in either of two possible colors (e.g., orange and green), we recently reported a novel contingent attentional capture effect (Moore & Weissman, in press). Specifically, approximately 100-300 milliseconds after a target-colored (e.g., orange) peripheral distractor was presented, it was more difficult to identify a target if its color (e.g., green) matched a different attentional set (e.g., identify green letters) than if its color (e.g., orange) matched the same attentional set (e.g., identify orange letters). Low-level factors (e.g., perceptual priming) could not account for this set-specific capture effect. Thus, we suggested that detecting a target-colored item leads the corresponding attentional set to briefly enter a limited-capacity focus of attention in working memory, which temporarily impairs the ability to attend and identify a subsequent item whose color matches a different attentional set.

In the present study, we further tested our hypothesis by investigating whether it is possible to reduce set-specific capture. We reasoned that presenting a target-colored (e.g., orange) central distractor (D1) would lead the corresponding attentional set (e.g., identify orange letters) to enter the focus of attention. Therefore, if a different-target-colored (e.g., green) peripheral distractor (D2) was presented 233 ms afterward, the attentional set corresponding to its color (e.g., identify green letters) would be unable to enter the already-occupied focus of attention. The result, we predicted, would be a reduction of set-specific capture arising from D2.

In Experiment 1, we both replicated our prior findings of set-specific capture and observed initial support for our hypothesis. First, target identification accuracy was lower when D2's color and the subsequent target's color matched different attentional

sets than when they matched the same attentional set, consistent with set-specific capture (Moore & Weissman, in press). Second, this effect was reduced by presenting D1 before presenting D2, but only when D1's color matched a different attentional set than D2's color. Thus, the results of Experiment 1 supported our hypothesis.

In Experiment 2, we distinguished between two competing hypotheses about how D1 reduces set-specific capture arising from D2. The D1 capture hypothesis posits that D1 prevents the attentional set corresponding to D2's color from entering the focus of attention. In contrast, the D1 enhancement hypothesis posits that D1 prevents the attentional set corresponding to D2's color from entering the focus of attention *and* brings the upcoming target's attentional set into the focus of attention. Consistent with the D1 enhancement hypothesis, set-specific capture was reduced in BAB trials, in which D1's color and the target's color matched the same attentional set, but not in BAC trials, in which D1's color and the target's color matched different attentional sets. Bringing the upcoming target's attentional set into the focus of attention was thus crucial for reducing set-specific capture arising from D2.

Although the present findings support the D1 enhancement hypothesis, whether a particular experiment provides support for the D1 enhancement or the D1 capture hypothesis should depend on the amount of time separating D1 from the target. In particular, our hypothesis posits that the attentional set corresponding to D1's color remains in the focus of attention only as long as D1 is attended. Evidence to support the D1 enhancement hypothesis should therefore be obtained only when D1 is presented just before the target, such that the attentional set corresponding to D1's color still occupies the focus of attention when the target appears. In contrast, evidence to support the D1

capture hypothesis might be observed when more time separates D1 from the target. Finally, even when a constant amount of time separates D1 and D2 (e.g., 233 ms in the present study), D1 capture and D1 enhancement might occur in different trials if there is variability across trials in the amount of time spent attending to D1. Thus, additional studies investigating the temporal parameters that give rise to D1 enhancement and D1 capture will likely be needed to fully appreciate the conditions under which set-specific capture can be reduced.

Future studies investigating the time course of set-specific capture may also shed light on why the present results differ so markedly from prior findings indicating that attentional sets can be strategically primed across trials (Belopolsky, et al., 2010). In seeming contradiction to the present results, these findings indicate that target identification in trial n is *worse* if a target shares a feature with a distractor in trial $n-1$ than if it does not (Lleras, et al., 2009; Olivers & Humphreys, 2003). However, this discrepancy is likely more apparent than real because set-specific capture and inter-trial priming of attentional sets have strikingly different time courses. Specifically, while set-specific capture lasts for only a few hundred milliseconds, inter-trial priming of attentional sets emerges only after a second or more has passed. Thus, we would argue that set-specific capture reflects a short-lived enhancement of the attentional set corresponding to a distractor's color, which serves to increase attention to a possible target (Dux & Marois, 2009); in contrast, inter-trial priming of attentional sets may reflect a strategic modulation of attentional control settings that is influenced by whether attending to a particular target color was beneficial in the prior trial (Folk & Remington, 2008). In sum, although we have found that set-specific capture influences performance

in ways that differ markedly from inter-trial priming of attentional sets, this result likely stems from the different temporal intervals over which the two phenomena operate.

We have argued that the present findings fit nicely with a limited-capacity focus of attention that maintains just a single item, but other explanations are possible. For example, our findings could also arise from an unequal allocation of limited resources among multiple attentional sets, consistent with models in which attention is allocated to multiple representations in a graded fashion (McLeod, 1977; Vergauwe, Barrouillet, & Camos, 2009). More precisely, an attentional set might receive the most resources when a stimulus matching its color appears first, fewer resources when a stimulus matching its color appears second, and so on. In such a scenario, detecting D1's color (e.g., orange) would lead the corresponding attentional set to receive the lion's share of resources, but would not fully prevent the attentional set corresponding to D2's color (e.g., green) from receiving some resources as well. Still, D1 would greatly reduce the resources allocated to D2. Thus, this "divided resource" account might also explain our finding that D1 reduced set-specific capture arising from D2.

To distinguish between *focus of attention* and *divided resource* accounts of our findings, one could use a variant of our task in which participants identify D1, D2, and the target at the end of each trial³. In this task, one could compare target identification accuracy in BAB and BAC trials given that both D1 and D2 were successfully identified. Selecting trials in which D1 and D2 were identified would be crucial since, according to the focus of attention account, simply detecting a target-colored item does not guarantee

³ Such a task would require a discrete trial format as opposed to the continuous paradigm that we used in the current study.

that the corresponding attentional set enters the focus of attention (i.e., it will not enter if the focus of attention is already occupied).

Critically, when D1 and D2 are both identified, the focus of attention and divided resource accounts make distinct predictions about relative performance in BAB and BAC trials. According to the focus of attention account, target identification accuracy in these conditions should not differ. Indeed, after D2 is identified, only the attentional set corresponding to its color (i.e., “A”) should occupy the focus of attention. Thus, the ability to identify a target whose color (i.e., “B” or “C”) matches a different attentional set should be uniformly poor. In contrast, the divided resource account predicts higher target identification accuracy in BAB than in BAC trials. This account posits that resources have been divided between the attentional sets corresponding to D1’s color (“B”) and D2’s color (“A”). Thus, a target should be identified more accurately if its color (“B”) matches one of these attentional sets than if its color (“C”) does not match either of these attentional sets. Future studies aimed at differentiating between these accounts will likely further our understanding of set-specific capture.

Studies that distinguish trials in which D2 is identified from those in which D2 is not identified might also be useful for determining whether task set inhibition influences the size of set-specific capture effects. Evidence for task set inhibition often comes from task switching studies, in which participants respond more slowly and less accurately when the task they are cued to perform in one trial mismatches (versus matches) the task they performed in the previous trial (Monsell, 2003; Rubenstein, Meyer, & Evans, 2001; Wylie & Allport, 2000). Critically, this effect is exacerbated when participants are required to switch to a task that was recently performed, suggesting that switching away

from a task involves inhibiting the associated task set (Mayr & Keele, 2000). In the present study, we observed better performance in BAB than in BAC trials, suggesting that switching attention from D1 to D2 did not lead task set inhibition to be applied to D1. However, the application of task set inhibition to D1 may only have been necessary when the attentional set corresponding to D2's color actually entered the focus of attention, which probably occurred infrequently in BAB and BAC trials. Thus, isolating trials in which D2 is identified, and therefore enters the focus of attention, could be helpful for revealing whether task set inhibition influences the magnitude of set-specific capture effects.

The present results fit conceptually with prior findings indicating that contingent attentional capture arising from a target-colored peripheral distractor can be reduced (Folk, et al., 2009), but they do not replicate those findings. Specifically, we did not observe better performance in AAA trials than in _AA trials. Our failure to replicate this effect may stem from any of several differences between our experimental design and that of Folk et al. (2009). These include requiring participants to maintain multiple attentional sets as compared to just one and embedding peripheral distractors in RSVP streams instead of presenting them in isolation. A critical difference, however, may involve the nature of the target-colored central distractor, which was a digit in our experiments as compared to a square that outlined the central RSVP stream in Folk et al.'s (2009) study. Because D1 was a digit in our study, it resembled a letter and probably consumed limited resources that were needed to identify the upcoming target letter. In contrast, the square that outlined the central RSVP stream in Folk et al.'s study did not resemble a letter and probably did not consume resources that were needed to

identify the upcoming target letter. In sum, differences between the paradigms used to investigate contingent attentional capture effects may explain why the present results did not replicate Folk and colleagues' finding that performance was better in AAA than in _AA trials.

As we suggested earlier, the present findings may have important implications for everyday activities in which target selection is guided by multiple attentional sets. For example, while driving on a winding highway, a driver may be searching for both a yellow warning sign indicating an upcoming curve in the road and a restaurant billboard that is printed in the same color as the warning sign (e.g., yellow, Waffle House) or in a different color (e.g., blue, International House of Pancakes). The existence of set-specific capture suggests that the driver would be more likely to miss the yellow warning sign when it is immediately preceded by a target-colored billboard appearing in a different (versus the same) color. However, the present findings suggest that such effects could be reduced by placing a salient yellow object on the side of the road shortly before the billboard appears, thereby bringing the color of the upcoming warning sign into the focus of attention. Because almost 80% of car accidents are preceded by a moment of driver inattention (Ranney, 2008), failing to minimize set-specific contingent attentional capture in real-world situations may lead to dire outcomes.

In conclusion, we have shown that set-specific capture can be reduced by bringing an upcoming target's attentional set into a limited-capacity focus of attention. This finding fits with other data indicating that contingent attentional capture can be reduced (Folk et al., 2009). It also has important implications for everyday activities in which multiple attentional sets guide the selection of relevant stimuli. Future studies

investigating whether and how reducing set-specific capture arising from a target-colored distractor depends on (a) the relative times at which target and distractor stimuli are presented, (b) conscious perception of the target-colored distractor, and (c) task set inhibition may reveal important new information about how to minimize distraction in both laboratory and real-world situations.

Chapter 5

Set-specific capture reflects a limited-capacity focus of attention

Abstract

We recently found that contingent attentional capture effects are larger when a distractor and target match different concurrently-maintained attentional sets than when they match the same attentional set, a phenomenon we call set-specific capture (Moore & Weissman, in press). In a rapid serial visual presentation (RSVP) search for green and orange target letters, target identification was more impaired when a green distractor preceded an orange target by 100-300 ms than when it preceded a green target. We explained this result by positing that distractor detection leads to an immediate enhancement of the corresponding attentional set. In the current study, we examined whether this enhancement is all-or-none as suggested by a limited-capacity focus of attention model, or graded as suggested by a shared resources model. Using an RSVP task in which participants searched for letters appearing in any of three possible colors and identified up to three targets on a single trial, we found evidence to support the all-or-none focus of attention model.

Introduction

Selective attention allows us to avoid overloading limited processing resources by facilitating the perception of information while inhibiting distraction. To accomplish this, attentional settings define targets related to our current goals based on perceptual or conceptual attributes such as color, location, size, or category (Adamo, et al., 2008; Ariga & Yokosawa, 2008; Folk, et al., 1992; Olivers, 2008). These attentional sets then bias sensory systems to boost signals of incoming stimuli that share features with targets (Corbetta & Shulman, 2002). Together, the components of this attentional network help to preserve limited processing resources for goal-related stimuli.

Visual search and contingent attentional capture studies provide evidence that attentional sets are flexible, susceptible to priming, and adaptive to optimize behavior. For example, in studies of the distractor-previewing effect, participants are faster to respond to a color singleton target when the distractors on the current trial are the same color as those on the previous trial (Ariga & Kawahara, 2004; Lleras, et al., 2009). An interpretation is that when a feature (e.g. red) is associated with the concept “distractor,” we tune our attentional sets to be biased against this feature, thus facilitating target identification when the target has a different feature (e.g. blue). Contingent attentional capture studies also provide evidence that attentional sets are susceptible to inter-trial priming (Belopolsky, et al., 2010; Olivers & Humphreys, 2003). For example, using a search task in which targets and uninformative pre-cues could both be colored either red or green, Folk & Remington found that cueing effects were much larger when the cue on the current trial was the same color as the target on the previous trial than when it was the same color as the distractor on the previous trial (Folk & Remington,

2008). In other words, features that were common with recent targets became enhanced, and features that were common with recent distractors became suppressed. These findings indicate that we use task information to constantly update and refine our attentional sets in order to best achieve our goals.

Using a contingent attentional capture paradigm, we recently demonstrated that attentional sets can be changed more rapidly, and in a less controlled or beneficial fashion (Moore & Weissman, in press). More specifically, we determined that when attention is captured by a stimulus sharing features with a current attentional set, the corresponding set is temporarily enhanced. In our study, participants searched a heterogeneously-colored RSVP stream for occasional targets that appeared in either of two colors (e.g. orange and green). As in other contingent attentional capture studies (Folk, et al., 2002; Folk, et al., 2008; Serences, et al., 2005), a peripheral distractor impaired performance more when it was target colored (e.g. orange) than when it had a different color (e.g. purple.) Critically, at short stimulus onset asynchronies (SOAs) of 116-233 ms, this effect was two to three times larger when the peripheral distractor (e.g. orange) was a different target color than the subsequent target (e.g. green), as compared to when the target and distractor were the same color (e.g. both orange). We identified this phenomenon as set-specific capture, and demonstrated in follow-up experiments that the effect is not due to bottom-up perceptual priming, but rather enhancement of the attentional set corresponding to the relevant feature. Critically, and contrary to the studies reviewed above, our results show attention is briefly increased towards a feature possessed by a current distractor. In set-specific capture, any stimulus matching an

attentional set, target or distractor, can cause a brief enhancement of the corresponding set.

What mechanism best describes the attentional set adjustment observed in set-specific capture? One possibility is that the mechanism involves balancing resources across currently maintained attentional sets, as would be suggested by a *graded enhancement* model. This account may be likened to limited-resource models of attention that posit a shared resource for concurrently maintained items or task rules (McLeod, 1977; Vergauwe, et al., 2009). According to this graded model, the detection of an item matching one of the current attentional sets leads to a temporary change in the distribution of resources allocated to each set. Other modulations of attentional set such those mentioned above (Ariga & Kawahara, 2004; Belopolsky, et al., 2010; Folk & Remington, 2008; Lleras, et al., 2009; Olivers & Humphreys, 2003) likely rely on a graded enhancement model. For example, items that are defined by a previous (but not current) attentional set still capture attention, and this effect dissipates gradually rather than abruptly (Leber & Egeth, 2006; Thompson, et al., 2007). Thus, one would expect in these experiments that the balance of strength of attentional sets was also changing slowly over the course of multiple trials.

Another possibility, which we raised in our previous investigations, is that set-specific capture involves an all-or-none adjustment of attentional set (Moore & Weissman, in press, submitted), as would be suggested by a *focus of attention* model. This model is based on a current model of working memory that posits a focus of attention limited to a single item (Jonides, et al., 2008; McElree, 2001; Oberauer, 2002, 2003), and suggests that the act of attending to a target-colored item (e.g. an orange

distractor) leads the corresponding attentional set (e.g. identify orange letters) to enter the focus of attention (Moore & Weissman, in press). According to this model, during active search (i.e. before a target-colored item has been detected), attentional sets reside outside the focus of attention, either in the region of direct access in working memory (Oberauer, 2002, 2003) or in long term memory⁴, and from here, they boost the signals of target-colored stimuli in order to facilitate target detection. Only once a target-colored item has been detected does the corresponding attentional set enter the focus of attention. Entry into the focus is required for deeper processing, including identification. Critically, only one attentional set can be present in the focus of attention at a time. Thus, if a stimulus matching a different attentional set appears while another set is in the focus of attention, the stimulus may be detected, but it will not be attended or identified.

Support for this model comes from a variety of sources, including studies of working memory (Berti, 2008; Garavan, 1998), task switching (Monsell, 2003), and the attentional blink (Juola, et al., 2004). For example, when maintaining in working memory the number of items that have been presented of different types of stimuli (e.g. circles and triangles), participants are faster to update a particular counter (e.g. the number of circles) just after the same counter has been updated, as opposed to when another counter has been most recently updated, suggesting that only a single counter can occupy the focus of attention at a time (Garavan, 1998). This difference cannot be explained by perceptual priming; when the instruction is to update a single counter for all

⁴ There is a debate on whether attentional sets are maintained in working memory (Olivers & Meeter, 2008) or in a more durable, capacity-unlimited state such as long term memory (Leber & Egeth, 2006; Thompson, et al., 2007). The focus of attention model does not contribute to this debate.

items, whether the previously presented stimulus matches the current one does not affect response time (Bao, et al., 2007).

Because both the *graded enhancement* and *focus of attention* models are consistent with our previous findings, we designed the current study to distinguish between these models of set-specific capture. Participants searched an RSVP stream for targets matching any of three different concurrently maintained attentional sets (orange, green, and lavender colored letters.) Every RSVP trial contained up to three targets, each of which could be any of the target colors. We examined accuracy for the third target (T3) depending on whether it was the same color as either of the previous two targets, under the conditions that a) T1 and T2 were different target colors, and b) both T1 and T2 were correctly reported.

Under these conditions, the two models made different predictions. The focus of attention model predicted T3 performance would not differ depending on whether T3 was the same color as T1. For example, when T1 was orange and T2 was green, participants would be equally likely to identify an orange T3 as a lavender T3. The graded enhancement model, on the other hand, predicted that T1's color would have a lingering influence on T3 performance. Thus, T3 performance would be better when it was the same color as T1 than when all targets were different colors, because T1's corresponding attentional set would still be partially enhanced at the time of T3 identification. In the example in which T1 was orange and T2 was green, the graded enhancement model predicted participants to be more likely to identify T3 when it was orange than when it was lavender.

Method

Participants

Forty-two University of Michigan students from 18 to 25 years of age participated in exchange for course credit. All participants reported normal or corrected vision and no history of neurological injury or disease. Each consented in accordance with the University of Michigan Behavioral Sciences Institutional Review Board.

Apparatus and Stimuli

Colored letter stimuli were displayed on a 19" Viewsonic CRT monitor with a 60 Hz refresh rate, controlled by a Dell PC running Windows XP. Presentation software (Neurobehavioral Systems, Inc.) displayed stimuli and collected responses. Participants viewed the screen from 80 cm using a chin rest.

On each trial, fifteen letters ($2.07^\circ \times 1.88^\circ$ in size) appeared successively in a rapid serial visual presentation (RSVP) display in the center of the screen, with a black background. Letters included all from the alphabet except for I, O, and W. No letter repeated within a trial.

We colored the letters according to the "light" color scheme of Moore & Weissman (Moore & Weissman, in press). These colors were chosen for their near-uniform salience (luminance and saturation) as well as equal perceptual distance from each other. Participants were instructed to search for three target colors, which were orange, lavender, and green. Other colors in the display were magenta, tan, and turquoise (see Figure 5-1 for a color wheel and R,G,B values). Because there were no more than three targets on a single trial but there were fifteen letters, these non-target colors repeated often over the course of a trial. They were randomly assigned to the non-target

letters in the display with the contingency that no two letters in a row would have the same color.

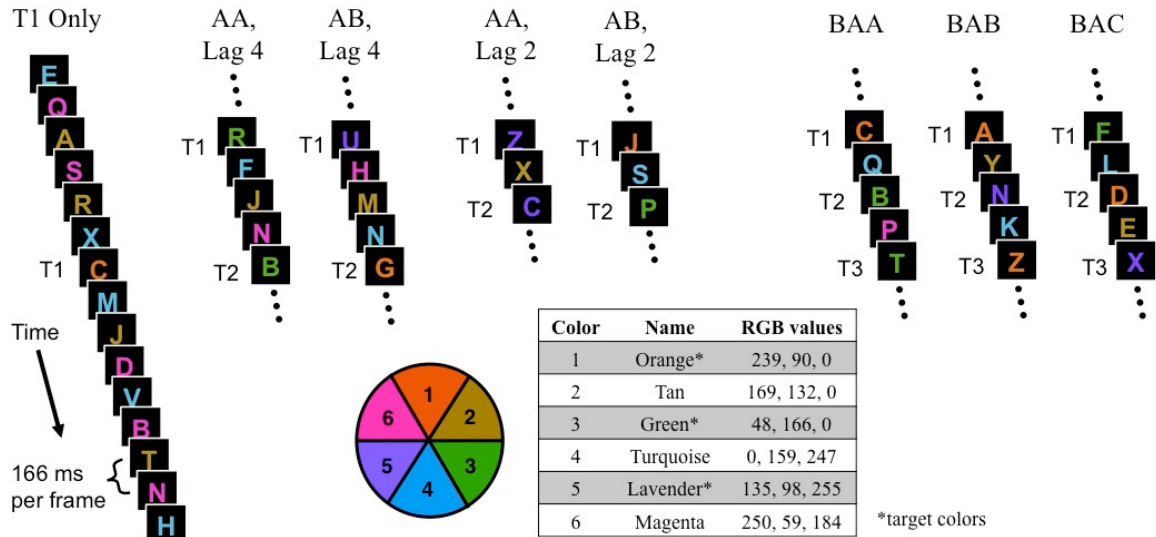


Figure 5-1: Experimental task and stimuli.

On each trial, participants viewed an RSVP stream containing 15 colored letters and one to three targets, which were colored orange, green, or lavender. Other items in the display were tan, magenta, and turquoise (see color wheel and table for R,G,B values). Items in the stream appeared for 150 ms followed by a blank space lasting 16 ms. In the figure, the T1 Only trial type represents a full trial. The other trial types depict example targets and intervening non-target stimuli as they would appear in the middle of an RSVP trial. The first target (T1) appeared anywhere from the fourth to eighth item in the stream. AA and AB trials contained two targets (T1 & T2) that were the same (AA) or different (AB) colors, and were separated by one (lag 2) or three (lag 4) intervening items. BAA, BAB, and BAC trials contained three targets (T1, T2 & T3), each of which was separated by one intervening item. The trial types were named according to the colors of T1, T2, and T3—in BAA, the colors of T2 and T3 matched but were different from T1; in BAB, the colors of T1 and T3 matched but were different from T2; and in BAC, each target was a different color.

Procedure

The participants' task was to identify letters in the 15-item stream that matched any of three target colors, and they were told trials could contain one, two, or three targets. Letters appeared for 150 ms followed by a 16 ms blank space between stimuli. The first target appeared anywhere from the fourth to the eighth position in the RSVP stream (assigned randomly).

At the end of the RSVP display on each trial, a prompt appeared asking for the identity of the first target. Participants were instructed to type the exact letter of that target. Immediately, the prompt would then ask for the second target, and after receiving a response, the third target. The next RSVP trial started 500 ms after participants made the third response. Participants were instructed to press the space bar to advance through the prompts if they saw fewer than three targets on a trial. We reasoned that the uncertainty regarding the number of targets on a trial would lead to fewer false alarm guesses.

Design

There were eight trial types (Figure 5-1). In T1 Only trials (n = 168), a single target appeared. The remaining seven trial types were labeled using a combination of “A,” “B,” and “C” to represent variable names for the three target colors. For the two trial types with two targets, AA trials (n = 84) were those in which the first (T1) and second targets (T2) were the same color (e.g. both were lavender), and AB trials (n = 84) were those in which T1 and T2 were different colors (e.g. T1 was orange, and T2 was green.) In half of AA and half of AB trials, T1 and T2 were separated by one intervening non-target item (Lag 2 condition). In the other half, T1 and T2 were separated by three intervening non-target items (Lag 4 condition).

The five trial types with three targets were AAA, AAB, BAA, BAB, and BAC. For these trial types, each target was always separated by one intervening non-target item. AAA and AAB trials (not pictured in Figure 5-1) were not critical for distinguishing between the focus of attention and graded enhancement hypotheses, but

we included them anyway in smaller numbers ($n = 24$ each) so that participants would not develop expectations about the color of the third target (T3) based on the colors of T1 and T2. Including a small number of these trial types also allowed us to maintain an equal number of trials (168) containing one, two, and three targets. However, because there were fewer AAA and AAB trials in the experiment, we lacked sufficient power to analyze their results, and thus will not report them.

There were 42 trials in each of the BAA, BAB, and BAC trial types. In these trials, T1 and T2 were always different target colors. T3 matched T2 (BAA), matched T1 (BAB), or was different from both T1 and T2 (BAC).

Data Analysis

We used accuracy as the dependent measure in all analyses. Accuracy was based on percentage of hits to a target in a trial type out of the total number of trials of that type in the experiment. Some analyses (e.g., T3 accuracy) were contingent upon correctly or incorrectly identifying other targets in the same trial (e.g. T1 and/or T2). Thus, at times there were uneven numbers of trials per trial type across participants, because participants had different accuracies on other targets within a trial. For all analyses, we included only those participants with at least four trials in each condition. Moreover, though our tests were all within-subject comparisons, we used the conservative Welch t-test, as this statistic does not require the groups to have equal variance. Note that this t-test calculates the degrees of freedom based on the estimated variance in each group, and so the degrees of freedom will be different across analyses.

First we identified our comparisons of interest, and eliminated participants with fewer than four trials in each critical trial type. We considered critical types to be the following: T2 accuracy given T1 correct in AA and AB trials (at both lags); T2 accuracy given T1 incorrect in AA and AB trials (at both lags); T3 accuracy given both T1 and T2 correct in BAA, BAB, and BAC trials; and T3 accuracy given T1 correct but T2 incorrect in BAA, BAB, and BAC trials. In total, we eliminated seven participants and were left with thirty-five. These participants were eliminated for having too few errors in trial types requiring T1 or T2 to be incorrect, or too many errors in trial types requiring both T1 and T2 to be reported correctly.

Results

We first examined trials with two targets in order to determine whether we replicated our previous finding of set-specific capture (Moore & Weissman, in press). Consistent with set-specific capture, in trials with correct responses to T1, T2 accuracy was better in AA than AB trials at both lag 2 [AA = 91.2%, AB = 53.4%, $t(59) = 7.07$, $p < 0.0001$] and lag 4 [AA = 86.0%, AB = 68.4%, $t(48) = 4.78$, $p < 0.0001$] (Figure 5-2, left). Also consistent with our previous findings, the set-specific effect was larger at lag 2 than at lag 4 [$F(1,35) = 14.8$, $p < 0.0001$].

We next examined trials in which T1 was missed to determine whether, consistent with both models, set-specific capture would be present only when T1 was identified. Consistent with their predictions, in trials with missing or incorrect responses to T1, T2 accuracy was the same in AA and AB trials for both lags [for lag 2: AA = 83.1%, AB =

86.3%, $t(56) = 0.745$, $p = 0.459$; for lag 4: AA = 80.8%, AB = 78.2%, $t(59) = 0.691$, $p = 0.492$] (Figure 5-2, right).

Trials with Two Targets

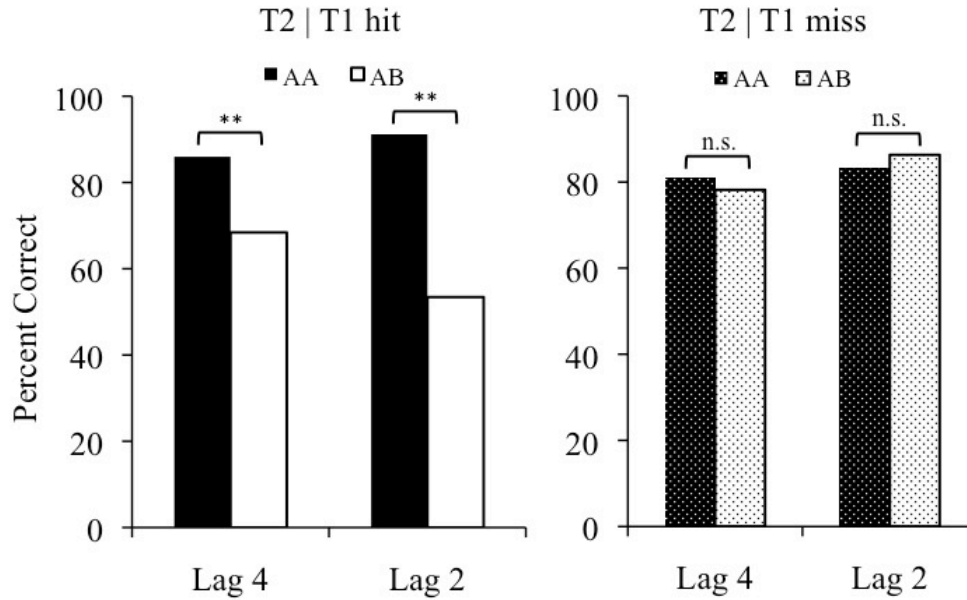


Figure 5-2: T2 performance on trials with two targets.

Accuracy is reported as the percent of correct responses. The left panel displays T2 performance when T1 was also correctly reported. Black bars correspond to the AA trial type, and white bars to the AB trial type. Replicating our prior findings of set-specific capture, performance was better in AA than in AB trials at both Lags 2 and 4. The double asterisk indicates a p -value less than 0.0005. The right panel displays T2 performance when T1 was missed or reported incorrectly. Black bars again represent AA trials and white bars AB trials. T2 performance was unaffected by T1's color when T1 was missed.

We also found evidence for set-specific capture in trials with three targets, by measuring T3 accuracy when T1 and T2 were both correctly reported on BAA, BAB, and BAC trials. Performance was better in BAA trials (66.6%) than on either of BAB trials (24.6%) [$t(67) = 6.78$, $p < 0.0001$] or BAC trials (23.6%) [$t(69) = 6.83$, $p < 0.0001$]. Thus, when all three targets were identified, T3 identification was facilitated when T2 and T3 matched the same attentional set.

In order to differentiate between the focus of attention and graded enhancement models, we compared T3 performance in BAB versus BAC trials under the same conditions (T1 and T2 reported correctly). Consistent with the focus of attention model, performance was equivalent on BAB and BAC trials [$t(67) = 0.046$, $p = 0.963$], suggesting that once T2 was correctly identified, T1 was no longer enhanced and therefore had no lingering influence on T3 performance (Figure 5-3, left).

Trials with Three Targets

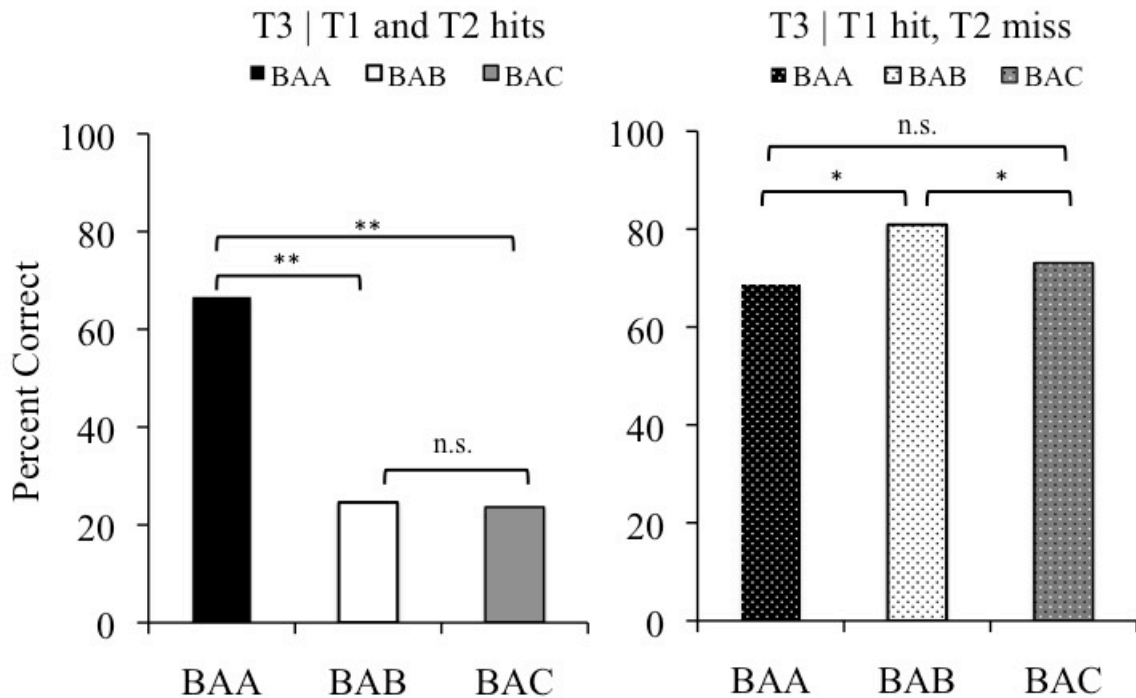


Figure 5-3: T3 performance, contingent on T1 and T2 report.

The left panel displays T3 performance when both T1 and T2 were correctly reported in BAA, BAB, and BAC trials. Performance was better when T3's color was the same as T2's (BAA), than when it was not (BAB and BAC). Critically and in support of the focus of attention model, BAB and BAC performance did not differ. The right panel displays T3 performance in the same trial types when T1 was correctly reported, but T2 was missed. Now, BAB performance was better than BAA and BAC, and there was no difference between BAB and BAC. This result indicates that when T2 was missed, T1's color influenced T3 identification, whereas T2's color did not. A double asterisk indicates $p < 0.0005$, and a single asterisk indicates $p < 0.05$.

It is possible that the result above was caused by a graded enhancement mechanism in which both T1's and T2's corresponding attentional sets were simultaneously enhanced, but T1's enhancement had simply worn off by the time T3 was presented. To investigate this possibility, we performed an analysis on the same trial types when T1 was reported correctly but T2 was missed. For this graded enhancement explanation to hold, we would not expect to find evidence of T1 enhancement. To the contrary, performance was better in BAB trials (80.9%) than in either BAC (73.1%) [$t(65) = 2.30, p < 0.025$] or BAA (68.4%) trials [$t(54) = 2.72, p < 0.008$]. This result suggests that T1's corresponding attentional set remained enhanced when T2 was missed. Together, these findings support the focus of attention model and argue against the graded enhancement model.

Also of note, there was no difference in performance between BAC and BAA trials [$t(61) = 0.949, p = 0.346$], suggesting that T2's attentional set was not enhanced when T2 was missed. See Figure 5-2, right.

We repeated all analyses using conventional paired sample t-tests and replicated every result.

Discussion

We replicated our previous findings of set-specific capture in a new paradigm requiring the report of multiple targets, while also finding support for the focus of attention model. Consistent with our prior findings of set-specific capture, participants were more accurate at reporting the second of two targets (T2) when the previously identified target (T1) was the same color as T2 (AA trial type) than when it was a

different color (AB trial type). This effect disappeared when T1 was not identified, indicating that T1's corresponding set had not been enhanced, and therefore that T2 identification was not impaired. These results are similar to those found in our previous contingent capture experiment, in which target identification was more impaired when a preceding target-colored distractor was a different target color than when it was the same color as the target (Moore & Weissman, in press).

In support of the *focus of attention* model of set-specific capture, we found that only the attentional set corresponding to the most recently-identified target influenced future target identification. More specifically, when T1's color and T2's color matched different attentional sets and both were reported accurately, T3 performance was better when it was the same color as T2 (BAA trials) than when it was different (BAB and BAC trials). Critically, whether T3 was the same or a different color as T1 (BAB or BAC trials) did not affect T3 performance. In other words, when both T1 and T2 were reported accurately, T1's corresponding attentional set was no longer enhanced at the time of T3 detection. This result is uniquely predicted by the focus of attention model, because this model states that only one set can be in the focus of attention at a time. Thus, it predicts no lingering enhancement of a previously-enhanced set, as long as a different one was attended to more recently.

One might argue that the graded enhancement model could still explain the above result if, by the time of T3 presentation, the enhancement of T1's corresponding attentional set has worn-off. According to this argument, at an earlier time point than the presentation of T3, T1 and T2's attentional sets would both be simultaneously partially enhanced, but our task was not sensitive (i.e. fast) enough to detect this moment of shared

enhancement. This explanation is highly unlikely, though, when considering T3 performance in the face of T2 misses. When T1 was correctly reported but T2 was not, T1's corresponding attentional set remained enhanced: T3 performance was better in BAB than in either BAA or BAC trials. The most parsimonious account for this pattern of findings is provided by the focus of attention model—in order for a target to be processed deeply enough to be identified, its corresponding attentional set must enter the focus of attention. Because the focus is limited to a single item, only the attentional set corresponding to the most-recently identified target is enhanced. Sure enough, when T1 was reported correctly and T2 was missed, performance on T3 mirrored that of trials with two targets (see Figure 5-3, right, and Figure 5-2, left). BAB performance was similar to AA performance at lag 4, and both BAA and BAC performance were similar to AB performance at lag 4.

We have argued that T1's corresponding attentional set exerts no influence on T3 performance when T1 and T2 are correctly identified. Nonetheless, one might wonder why T3 performance in the BAA trial type appears to be lower than T2 performance in the AA trial type when all previous targets have been correctly identified. If only T2's corresponding attentional set influences T3 performance, then it should not matter that T1 and T3 match different attentional sets in BAA. However, T3 accuracy in this condition was lower than T2 accuracy in AA. We argue that T1's corresponding attentional set does not influence T3 performance, but rather the difference between BAA and AA trials reflects an additional cost for trial types with three targets. Precisely, on BAA, BAB, and BAC trials, participants must maintain three specific responses in working memory through the duration of the trial. AA performance, on the other hand, requires

maintaining just two responses. A better link to make is the one mentioned in the previous paragraph comparing trials with two targets to those with three targets in which T2 is missed (i.e. Figure 5-3, right). In both cases, just two responses must be maintained during the trial. As mentioned previously, these scores were similar.

The evidence in favor of the focus of attention model over the graded enhancement model provides further support that set-specific capture is a different phenomenon than inter-trial priming of attentional set. In these studies, attentional sets change over long time-scales, such as across a block of trials (Leber & Egeth, 2006; Thompson, et al., 2007) or from one trial to the next (Belopolsky, et al., 2010; Lleras, et al., 2009; Olivers & Humphreys, 2003). Typically, participants make beneficial adjustments to attentional sets, by boosting the signal of features shared with recent targets (Olivers & Humphreys, 2003), suppressing the signal of features shared with recent distractors (Ariga & Kawahara, 2004; Lleras, et al., 2009), or both (Folk & Remington, 2008). In set-specific capture, on the other hand, both distractor and target detection lead to rapid enhancement of the corresponding attentional set (Moore & Weissman, in press, submitted). To further differentiate the root of these phenomena, we presently showed that set-specific capture is best explained by a limited-capacity focus of attention model, in contrast to inter-trial priming results that are better explained by a graded enhancement model.

Our study also provides evidence that set-specific capture is not likely to be related to task-set inhibition. Evidence for task set inhibition comes from task switching studies in which participants respond more slowly and less accurately when the task they are cued to perform in one trial is different from (versus the same as) the task they

performed in the previous trial (Mayr & Keele, 2000; Monsell, 2003; Rubenstein, et al., 2001; Wylie & Allport, 2000). Critically, this effect is exacerbated when participants are required to switch to a task that was recently performed, suggesting that switching away from a task involves inhibiting the associated task set (Mayr & Keele, 2000). In the present study, we observed equivalent T3 performance in BAB and BAC trials when T1 and T2 were both correctly reported, signifying that switching attention from T1 to T2 did not cause task set inhibition to be applied to T1. Thus, set-specific capture is unlikely related to task set inhibition.

In contrast to findings demonstrating that subliminally presented stimuli can capture spatial attention, our results suggest that attentional set enhancement during set-specific capture only occurs when a stimulus has been consciously perceived. Wyble and colleagues found that participants were more likely to report the second of two targets in a rapidly changing display when the first and second targets were in the same location than when the targets appeared in different locations, even when the first target was not reported (Wyble, Bowman, & Potter, 2009). Therefore, an unconsciously-perceived target was capable of drawing spatial attention. However, in the present study, we demonstrated that attentional set enhancement requires identification of the item matching the set. For example, we observed set-specific capture in trials with two targets (AA > AB), but only when T1 was identified correctly. Likewise, when T1 was reported correctly and T2 was missed, T3 performance was the same on BAA and BAC trials. In both cases, the attentional set corresponding to a missed target was never enhanced. These results point out a key difference between set-specific and spatial capture, which future studies should further explore.

In sum, we replicated set-specific capture in an RSVP paradigm with multiple targets on a single trial, and we provided evidence for the focus of attention model of set-specific capture. Specifically, consistent with set-specific capture, accuracy to the second of two targets was better when it was the same color as the first target than when it was a different color, and this difference was present only when the first target was correctly identified. In support of the focus of attention model over the graded enhancement model, performance on T3 following correct identification of T1 and T2 did not depend on whether T3's color matched T1's color, and this result could not be explained by a rapid recovery from graded enhancement of T1. These results suggest that only a single attentional set can be enhanced at a time. Future studies will be required to clarify other components of this model, such as how multiple attentional sets are maintained (i.e. in long-term or short-term memory) during active search, and whether multiple sets can enter the focus of attention if the sets are temporarily bound into a single set (Bao, et al., 2007).

Chapter 6

General Discussion

The current studies demonstrated that external irrelevant stimuli can cause an involuntarily direction of attention to a goal in working memory. In Chapter 2, we showed that irrelevant instructions bearing resemblance to relevant instructions caused participants to prepare the wrong task. Chapters 3 & 4 demonstrated that an irrelevant item resembling a target caused participants to enhance the search set related to that target. In Chapter 5, we provided evidence that this enhancement took place in a limited-capacity focus of attention within working memory. Collectively, these studies provide a novel link between attention and memory systems, and they help to clarify how our ability to multitask is limited.

The focus of attention model of goal enhancement

Based on findings from Chapters 3-5, we proposed a focus of attention model to explain how attention is directed to goals (i.e., attentional sets) in working memory. According to this model, multiple attentional sets can simultaneously be maintained in memory without costs (as compared to maintaining a single set), and they serve to boost signals coming from stimuli that share target features. However, the model states that only a single attentional set can be present at a time in a privileged state within working memory called the “focus of attention.” The detection of a stimulus matching an attentional set (e.g., a target or a target-like distractor) causes the corresponding attentional set to enter the focus of attention, an action that is required in order for the

stimulus to be processed deeply enough to be identified.

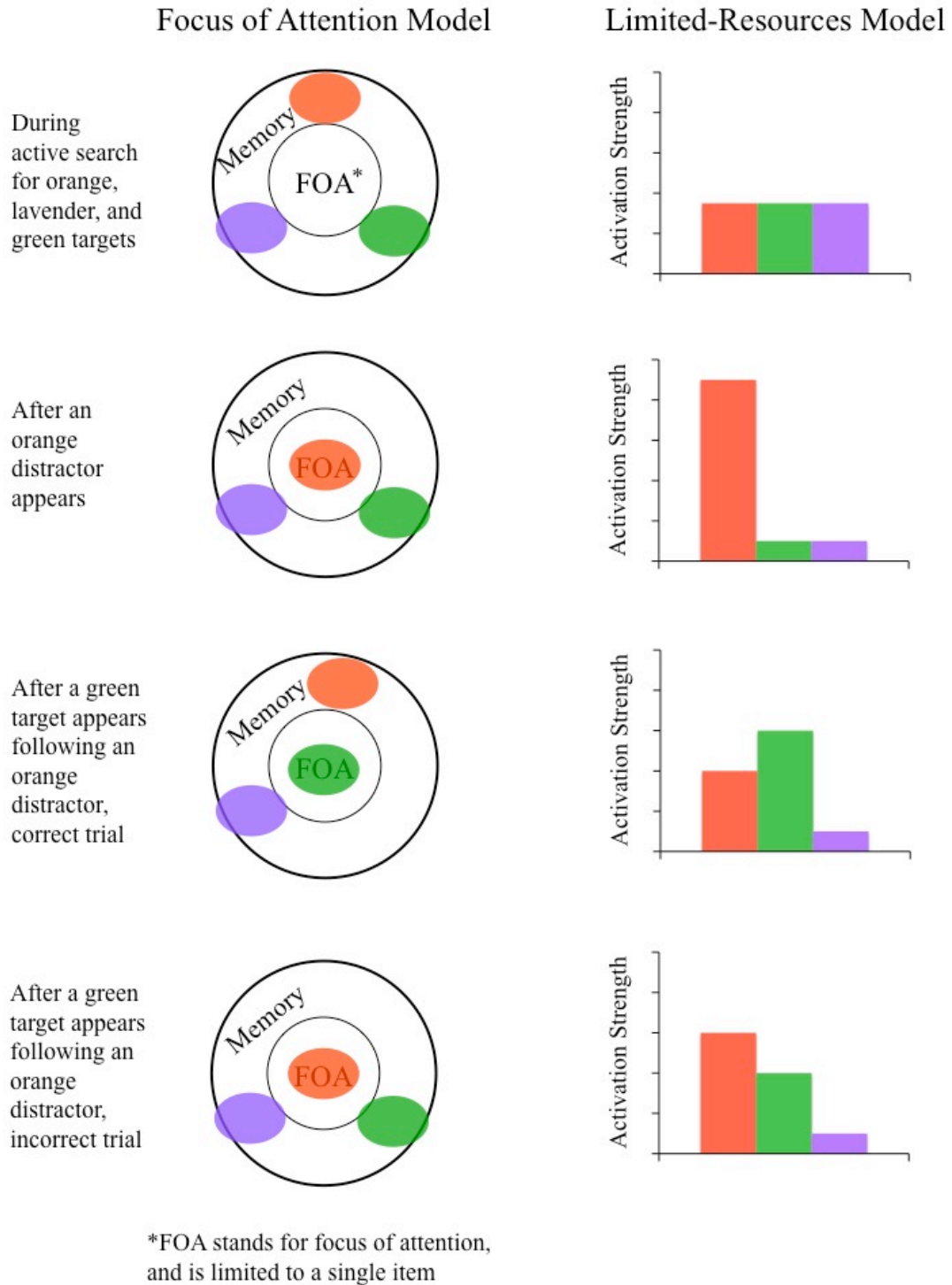


Figure 6-1: Depictions of attentional set enhancement in the focus of attention and limited resource models

The focus of attention model is all-or-none, in contrast to a graded limited-resources model (Figure 6-1). According to the focus of attention model, an attentional set is either enhanced in the focus or not. A limited-resource model, on other hand, contends that attentional set enhancement can be shared across different sets, in a graded fashion. This model is akin to shared resource models of attention for multiple tasks or items (MacLeod & Dunbar, 1988; McLeod, 1977). The data from Chapter 5 argue against a graded model of attentional set enhancement, finding that only the attentional set corresponding to the most recently identified target in a series of targets exhibits evidence of being enhanced.

The focus of attention model is based on a structure in working memory containing a single item that is more privileged (i.e., activated) than any other information in memory (Jonides, et al., 2008; McElree, 2001; Oberauer, 2002, 2003). Models of working memory that include a focus of attention do not all agree on the rest of the structure or capacity of working memory. For example, McElree posits that working memory is limited to the focus of attention, and the rest of memory can be considered long-term-memory, in various states of activation (McElree, 2001). Consistent with a large body of evidence that working memory capacity is about four items (Cowan, 2000), Oberauer's model contends that working memory contains both the privileged focus of attention and a region of direct access with a capacity of three additional items. The remainder of memory is long-term (Oberauer, 2002, 2003) (Figure 6-2). Finally, in a recent review, Jonides and colleagues attempt to reconcile these views by stating that working memory is limited to a single item, but that often multiple items

can be bound into a single representation (Jonides, et al., 2008).

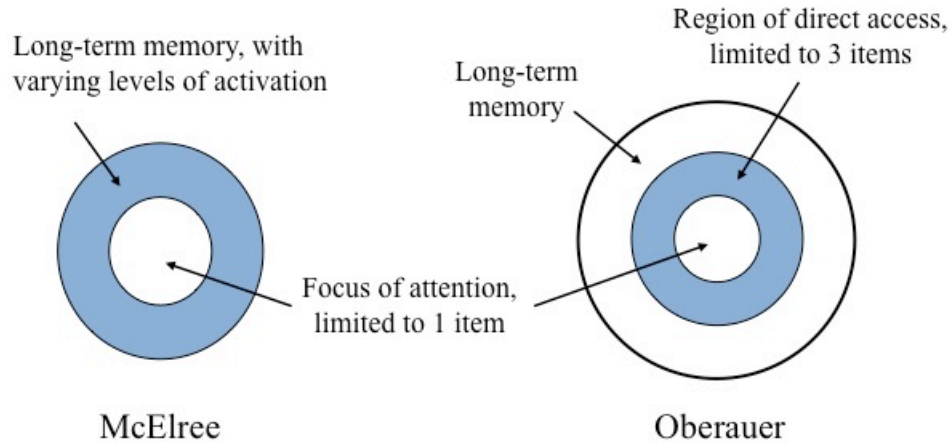


Figure 6-2: Models of working memory positing a focus of attention limited to a single item

Given disagreement in the literature, our focus of attention model does not make a claim regarding where attentional sets are maintained (i.e., in long-term or short-term memory) as they guide behavior prior to the detection of a potentially relevant stimulus. As stated above, memory models disagree as to whether there is even a working memory structure outside of the focus of attention. In the attention literature, some believe that attentional sets are maintained in working memory (Olivers & Meeter, 2008), but others contend that attentional sets reside in a more permanent state, such as long-term memory (Folk & Remington, 2008; Leber, et al., 2009). Thus, it is possible that attentional sets reside either in a region of direct access in working memory, or in long-term memory. In fact, attentional sets may occupy different structures in memory depending on the experimental paradigm (e.g., a new attentional set may be defined on a trial-by-trial basis,

or the same set may be maintained throughout the experiment) (Lien, Ruthruff, & Johnston, 2010).

Critically, our model asserts that no attentional set enters the focus of attention until a potentially relevant item has been detected. An alternate view would state that attentional sets must be in the focus of attention to guide search. Therefore, when multiple sets guide behavior, they would cycle in and out of the focus of attention during active search, taking turns in the privileged state. According to this view, the probability that a particular attentional set occupies the focus at any given moment should decrease as the number of concurrently maintained attentional sets increases. Therefore, traditional contingent attentional capture effects should be *reduced* the more attentional sets guide behavior, because an item would capture attention only if its corresponding attentional set is currently in the focus. Moreover, the cycling view would predict overall target identification performance to be worse as more sets are maintained in memory. To the contrary, we found that contingent capture effects were the same when one or two attentional sets guided behavior, as was identification performance when targets appeared without any distractors (Chapter 3, Experiment 1). Though we did not compare across set size in Chapter 4 (Experiments 1 and 2 were performed between subjects), a glance at the data suggests that target identification did not differ whether two or three attentional sets were maintained (in both experiments, Target Alone accuracy was 83.7%). For these reasons, our focus of attention model states that attentional sets remain outside of the focus of attention during active search, and enter only once a potentially relevant item has been detected.

Neural mechanisms of orienting to goals in wm

Chapter 2 provides neural evidence as to how attention is oriented to a current goal in memory. We showed that the orienting of attention to a goal in memory is likely facilitated by the same attentional network regions that are responsible for directing attention to goal-relevant stimuli (Corbetta, Kincade, & Shulman, 2002; Corbetta & Shulman, 2002; Hopfinger, et al., 2000). We found several frontal and parietal regions that were more active when relevant and irrelevant cues were incongruent than when the cues were congruent; thus these regions probably reflected the shift of attention to a goal in memory. As participants prepared a task, this shift of attention occurred whether the cues were congruent or incongruent. However, when the cues were incongruent, participants sometimes prepared the wrong task first, as evidenced by our data from the sensory regions. Consequently, correct performance required a second shift of attention to the other goal. Research investigating the neural mechanisms of episodic memory retrieval also suggests that the same regions are responsible for orienting to both environmental stimuli and memories (Cabeza, 2008; Ciaramelli, Grady, Levine, Ween, & Moscovitch, 2010; Ciaramelli, Grady, & Moscovitch, 2008).

Our behavioral studies on contingent attentional capture (Chapters 3-5) provide evidence that once attention has been allocated to a goal, that goal enters the focus of attention in memory; but our studies do not indicate a potential neural correlate of the focus. Recent work from a verbal working memory task shows that the neural correlate of the focus of attention might be the inferior temporal (IT) cortex (Nee & Jonides, 2008). In addition to representing the most recently rehearsed item, the IT cortex is more functionally connected to frontal-parietal network regions than are other memory regions that represent other remembered stimuli in the task. Given that the IT has been

implicated in visual perception, we might expect this region to provide the neural correlate of the focus of attention in our contingent capture tasks in which participants search for colored letters.

Future directions

Though our studies answer several questions about multitasking and the relationship between attention and memory, they also raise questions to be answered with future investigations. One question is whether attentional sets are maintained in working memory or in long-term memory. Solving this problem could inform both the debate regarding the relationship between working memory and attention in visual search (Downing, 2000; Downing & Dodds, 2004; Olivers, 2008; Olivers, 2009; Olivers & Meeter, 2008; Woodman & Luck, 2007) and the debate about the structure of memory (Cowan, 2000; Jonides, et al., 2008; McElree, 2001; Oberauer, 2002, 2003; Oberauer & Bialkova, 2009).

One way to examine how attentional sets are maintained when not in the focus would be to test participants' capacity to maintain multiple sets. We know that three sets can concurrently guide behavior with no noticeable cost in performance, but can four or five sets guide behavior? Though not everyone agrees (Jonides, et al., 2008; McElree, 2001), numerous studies suggest that working memory capacity is about four items (Awh, Barton, & Vogel, 2007; Todd & Marois, 2004; Xu & Chun, 2006); (see Cowan, 2000) for an extensive review). Thus, if working memory imposes a limit to the number of sets that can be concurrently maintained, completing a search task when five or more attentional sets define targets should be far more difficult (if even possible) than

completing a search task when one or two attentional sets define targets. If participants can complete these searches equally well, suggesting no obvious limit to the number of attentional sets that can be concurrently maintained, then the attentional sets are likely stored in long-term memory.

Though a seemingly simple study to conduct, this proposed experiment raises methodological challenges. For example, as the number of attentional sets increases, the percentage of stimuli in the environment sharing features with an attentional set will also increase, as long as the search environment does not change. For example, if you were to search a crowd of people for four different friends at once, more people in the crowd would capture attention because they share characteristics with at least one of your friends than if you were searching for only one friend. In our investigations, we found that the search environment for isoluminant, equally salient colors is too small to require participants to maintain more than three attentional sets at a time. In other words, when participants must search for more than three colors, the colors are too perceptually similar to distinguish targets from other items in the display. An appropriate experiment testing the limit of maintaining multiple sets would require a different (i.e., broader) stimulus dimension than color, as well as careful controlling of the search environment.

Another question of interest is whether the focus of attention can enhance more than one attentional set at a time, by binding sets together to form a single representation. Experiment 2 of Chapter 3 suggests this is possible, because set-specific capture vanishes when targets are defined as any colored letter in the central RSVP stream. Thus, participants combine all colors into a single attentional set to complete this task. In working memory studies, binding also allows multiple items to enter the focus of

attention. For example, Bao and colleagues gave participants a task to update a number and the spatial location of a dot in a grid. At the start of the trial, participants saw a number and a location. Participants then viewed about 20 images of arrows (up, down, left and right) that provided instructions for updating the grid location, intermixed randomly with plus signs that signaled participants to increment the number. They were to press a button after each stimulus display as soon as they had updated the appropriate counter. Participants who maintained separate counters observed a reaction time cost when switching from one counter to the next as compared to updating the same counter twice in a row. However, participants who adopted a strategy in which they incremented a digit located inside of a spatial grid (thereby binding the counters) did not experience a cost when switching between counters (Bao, et al., 2007). Thus, an important question is whether certain strategies can encourage the binding of attentional sets in visual search, thereby potentially eliminating set-specific capture costs.

A third important problem to explore is learning the neural correlate of the focus of attention. To find its location using our current behavioral paradigms, one could use fMRI to compare activity under conditions in which only a single attentional set enters the focus of attention (e.g., “AA” or “AAA” trials in Chapter 5) with conditions in which multiple attentional sets enter the focus of attention (e.g., “AB” or “BAC” trials in Chapter 5). This contrast would likely result in the region(s) supporting the switch into the focus of attention. As mentioned previously, evidence exists that the focus of attention is in the IT cortex (Nee & Jonides, 2008). However, it is possible that the focus of attention is instantiated differently for different kinds of stimuli. For example, for attentional sets related to listening (e.g. see Chapter 2), the focus of attention might be

part of the auditory cortex. Regardless, a good test of our model would be to measure whether our manipulation coheres with the existing literature on the neural correlates of the focus of attention.

These studies and others will help us further understand the link between attention and memory, and how these systems act together when multiple goals drive behavior.

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