CHAPTER EIGHT

The Control of Visual Attention: Toward a Unified Account

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Abstract

Visual attention is deployed through visual scenes to find behaviorally relevant targets. This attentional deployment—or attentional control—can be based on either stimulus factors, such as the salience of an object or region, or goal relevance, such as the match between an object and the target being searched for. Decades of research have measured attentional control by examining attentional interruption by a completely

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irrelevant distracting object, which may or may not capture attention. Based on the results of attentional capture tasks, the literature has distilled two alternative views of attentional control and capture: one focused on stimulus-driven factors and the other based on goal-driven factors. In the current paper, we propose an alternative in which stimulus-driven control and goal-driven control are not mutually exclusive but instead related through task dynamics, specifically experience. Attentional control is initially stimulus-driven. However, as participants gain experience with all aspects of a task, attentional control rapidly becomes increasingly goal-driven. We present four experiments that examine this experience-dependent attentional tuning. We show that to resist capture and be highly selective based on target properties, attention must be configured to aspects of a task through experience.

1. INTRODUCTION

The study of attention has a long and rich history in cognitive psychology. William James (1890) provided a well-known characterization of attention, but other early writers also highlighted the nature of attention. For example, Seashore (1925) linked attention with the focusing of consciousness and, in doing so, anticipated many contemporary issues in the study of visual attention:

> *"We shall find that memory and the learning process in general are interpreted… in terms of the mechanism of attention; that to imagine is to train the focus of consciousness in search for something new, somewhat as the beams of the search-light go out over the sea and… spot a distant vessel…." (p. 119)*

Not only did Seashore highlight the selective role of attention and consciousness, but he also noted the function of attention to search for objects. Seashore (1925) likened this search to a spatial spotlight and viewed learning and memory as linked with attention. A generation later, such descriptive, almost folk psychological, accounts of attention became the topic of empirical study (e.g., Cherry, 1953).[1] Contemporary studies of attention maintain many similarities to Seashore's account of attention: Visual search is arguably the dominant task with which to study visual attention, and search usually happens across objects located in space, consistent with the idea of a spatial spotlight (e.g., Posner, Snyder, & Davidson, 1980). Although attention might be different from consciousness (Koch & Tsuchiya, 2007; Lamme,

[1] We should note that there were many important studies of attention during Seashore's time, including those reporting the Stroop effect (Stroop, 1935), task switching (Jersild, 1927), and the psychological refractory period (Telford, 1931).

2003), the tight coupling of attention awareness remains (Cohen, Cavanagh, Chun, & Nakayama, 2012).

In addition to being a common laboratory task, visual search is an everyday event. We search for traffic in our blind spot, for a face in a crowd, or for the ketchup in the refrigerator. Often, search is accompanied by eye and head movements but can also occur without eye movements. However, the apparent ease of directing attention to find an object is just that—apparent. The frequency and ease of attentional search begs the question of how attention knows where to go when we search for a desired object. This is the issue of *attentional control*.

1.1. Attentional Control

Most accounts of attentional control have proposed at least two means for directing attention: *stimulus-based factors*, also called bottom-up control, and *goal-driven factors*, also called top-down control. The distinction between these two control modes is illustrated in Fig. 8.1, where the viewer is instructed to search for a black tilted T. In the left panel, there is a single black item with homogenous distracters that are dissimilar from the target, which allows the target to pop out and attract attention to itself. Visual search in such displays is highly efficient, and as the number of distracter items increases, response time (RT) increases little, if at all. In the right panel, the distracters are heterogeneous and visually similar to the target; consequently, the target is more difficult to find. Search through such displays in which the target is similar to the distracters and the distracters are dissimilar from one another is particularly inefficient (e.g., Duncan & Humphreys, 1989), and RTs increase substantially as the number of distracters increase.

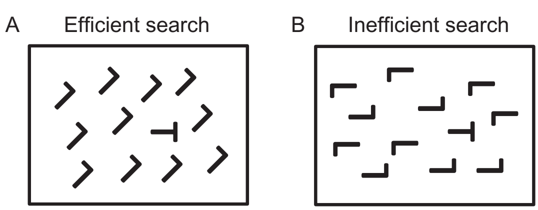

Figure 8.1 Sample visual search tasks. (A) An efficient visual search, in which the distracters are dissimilar from the target and homogenous. (B) An inefficient search, with distracters that are similar to the target and heterogeneous (i.e., dissimilar to one another).

1.1.1 Stimulus-Driven Attentional Capture

Typical visual search tasks, however, are not ideal for studying attentional control, because participants search for a known target. Knowing the target allows goal-driven factors to affect search, even efficient feature-based searches, which conflate stimulus-driven and goal-driven factors. Because of this challenge, many studies of attentional control have eliminated or minimized any goal-driven, top-down control with experimental manipulations that decouple a participant's goals (i.e., target properties) and salient stimuli that are irrelevant to those goals. The general logic of such tasks is to study the selectivity of attentional control; that is, when set to search for a specific target, can participants resist attending to an otherwise salient, conspicuous nontarget–distracter? Attentional capture results when goal-directed attention fails and participants attend to an irrelevant item.

Two widely used tasks for studying attentional control and capture appear in Fig. 8.2. In one such task, Yantis and colleagues asked if abruptly appearing objects have an attentional priority over static objects (see Yantis, 1998; Yantis & Johnson, 1990; Yantis & Jonides, 1984, 1990). Participants were instructed to search for two targets (e.g., the letters E and H) and report which appeared in a display that contained distracting letters. An initial display contained a set of placeholder objects (Fig. 8.2A, left panel), and features fell away from these placeholders to reveal letters (Fig. 8.2A, right panels). On some trials, the target appeared as a new object that abruptly appeared at a nonplaceholder location; on other trials, the target emerged from a placeholder, making it an old object. To discourage participants from preferentially attending to the abruptly appearing "onset" object, the target was no more likely to be the abruptly appearing object than it was to be a static, "offset" object. Nevertheless, participants showed a clear benefit when the target is an abrupt onset. RTs were faster overall for onset targets than for offset targets. Further, as the display size increased, RTs remained fast and increased little for onset targets but increased linearly for offset targets.

In another attentional capture task, Theeuwes asked if perceptually salient nontarget distracters could interfere with search for a known target (Theeuwes, 1991, 1992, 2010; also see Awh, Belopolsky, & Theeuwes, 2012; Hickey, McDonald, & Theeuwes, 2006; Van der Stigchel et al., 2009). In this irrelevant singleton task, participants search for a target based on its shape (e.g., a diamond) and report the orientation of a line within that shape (e.g., horizontal or vertical). In most versions of this task, the target shape appears among homogenous distracters, as shown in Fig. 8.2B. On half of the trials, the target and distracters are all the same color, but on the other

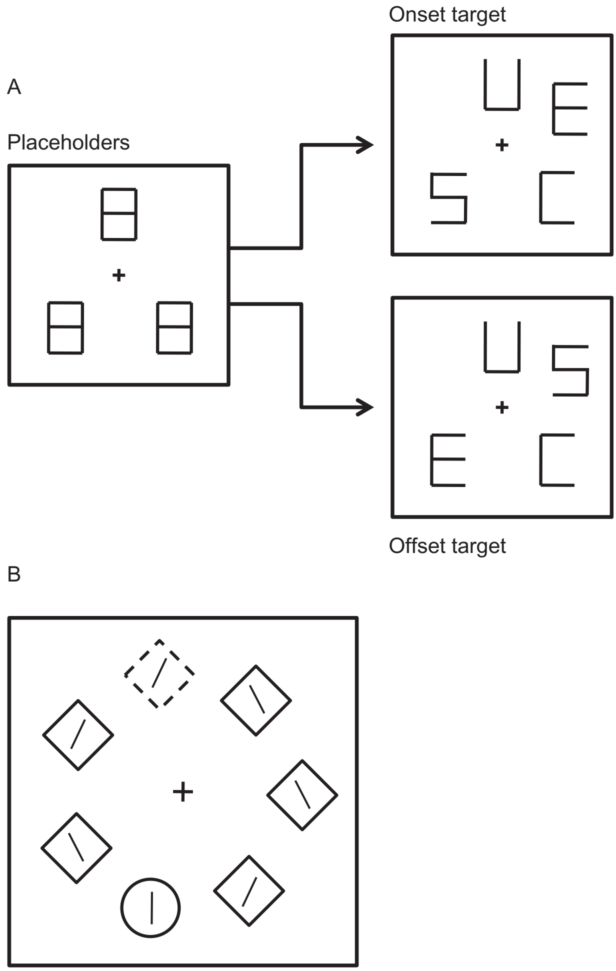

Figure 8.2 Sample capture tasks, based on those used in previous work (e.g., Theeuwes, 1991, 1992; Yantis & Jonides, 1984). (A) Capture by abruptly appearing objects. Following a placeholder display, features are removed to define offset letters. Simultaneously, a new object appears. In the upper panel, the target letter E is an onset; in the lower panel, the target letter E is an offset. (B) The irrelevant singleton task. Participants search for the novel shape (the circle) and report the orientation of the line within (horizontal or vertical). On critical trials, one of the distracter diamonds is a unique color (denoted by dashed lines in the figure). The presence of this irrelevant singleton distracter captures attention and slows response times.

half of trials, one of the distracters is a salient color singleton that pops out of the display. Although the singleton distracter is irrelevant and never contains the to-be-reported line, this distracter slows participants RTs.

The results from both onset capture and irrelevant singleton capture suggest that visual attention is controlled initially by stimulus properties (Itti &

Koch, 2001; Kawahara, 2010; Li, 2002; Theeuwes, 2010). Extending this view, many studies have searched for stimulus properties that capture attention against one's goals; in addition to abrupt onsets and salient color singletons, motion (Abrams & Christ, 2003; Franconeri & Simons, 2003) and animacy (Pratt, Radulescu, Guo, & Abrams, 2010) may capture attention in a stimulus-driven manner. In general, under the stimulus-driven view, visual attention is relatively unselective; a target, goal, or "set" appears to be insufficient in preventing attention from being captured by an irrelevant stimulus. Although the target is ultimately selected, the initial attentional selection is driven by stimulus salience.

1.1.2 Goal-Driven Attentional Control

Although the foregoing results appear straightforward in suggesting stimulus-driven attentional control, there are numerous results that support goal-driven control that also explain apparent stimulus-driven capture. An initial account of goal-driven control came from Folk and colleagues, who argued that attentional capture is contingent upon a participant's goals (Folk, Remington, & Johnston, 1992; also see Egeth, Leonard, & Leber, 2010; Folk, Leber, & Egeth, 2002; Leber & Egeth, 2006a, 2006b). Under this account, salient items will capture attention only when they match properties of the target—that is, only when the salient item can be interpreted within the current task goals or configuration.

Folk et al.'s (1992) initial support for contingent capture came from a cuing task, depicted in Fig. 8.3. Participants were set to search for different types of targets, either a singleton target, in which the target was the uniquely colored item in a search array, or an onset target, in which the target appeared alone but appeared suddenly. Prior to the target's appearance, a task-irrelevant spatial cue appeared. This cue was either a color singleton or an abrupt onset, and the cue type was crossed with the target type. Finally, the cue could appear in a location later occupied by the target (valid cue) or a location later not occupied by the target (invalid cue); the cue did not predict the upcoming target's location.

Results from this contingent capture task show that the cue only captures attention when it matches the target type. For example, when the target is a unique color singleton, participants are faster to identify validly cued targets than invalidly cued targets, but only with singleton cues; no cuing effect is observed for onset cues. The converse pattern appears for onset targets: cuing effects are present for onset cues, but not for singleton cues. Because singleton and onset cues are highly salient, both should capture attention if

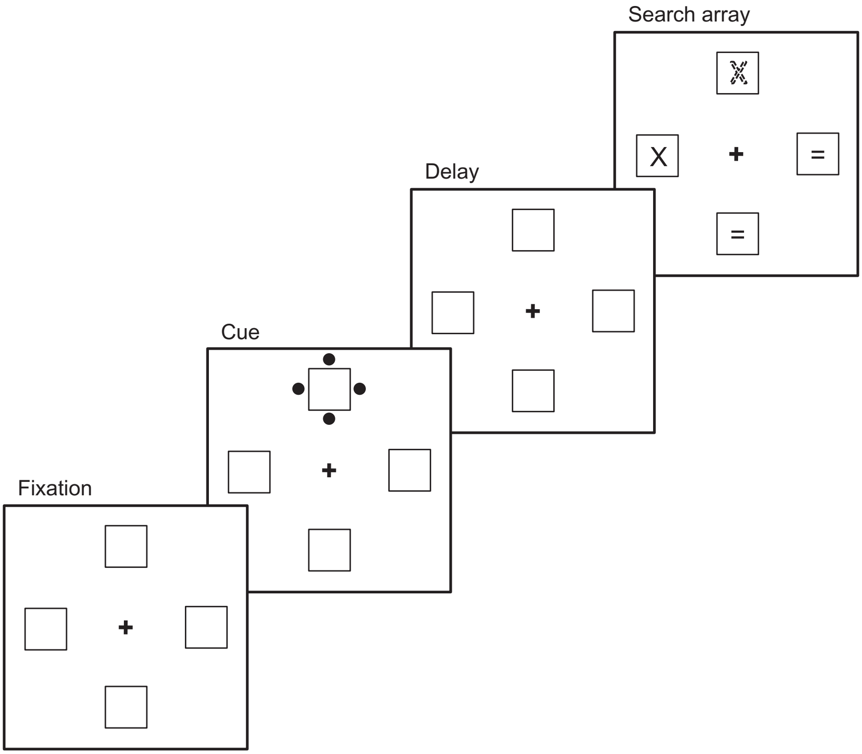

Figure 8.3 The cuing procedure used to measure contingent attentional capture. Items in the cue display can either match or mismatch features of the target. In the example depicted, the target is a unique color singleton (depicted by dashed lines), but the cue is an abruptly onset cue, which mismatches the target type (color singleton). The cue captures attention only when it matches the target (e.g., when the cue is a singleton and the target is a singleton). *Based on the task introduced by Folk et al. (1992).*

attentional control is initially stimulus-driven. The finding that capture is contingent on target properties—that is, a participant's goals—suggests that attentional control is based on current behavioral goals (also see Folk et al., 2002).

A related line of research has demonstrated that salient stimuli do not always capture attention; instead, the type of attentional search can influence capture. Bacon and Egeth (1994) demonstrated that search for a specific feature, such as a circle among heterogeneous distracters (squares, diamonds, and triangles), could prevent capture by an irrelevant singleton. When a singleton distracter appeared on half of the trials, participants were no slower than when this distracter was absent. Based on this finding, many have argued that attentional capture by an irrelevant color singleton (e.g., Theeuwes, 1992) does not reflect stimulus-driven capture. Instead, in the irrelevant singleton task, participants use goal-driven attentional control to search for a singleton, because the target is a shape singleton (e.g., circle among diamonds); because the irrelevant color singleton is, nevertheless, a singleton, it matches the goal-driven control setting and attracts attention. Thus, as with Folk et al.'s (1992) findings, capture is mediated by a participant's goals and the demands of the task. When Bacon and Egeth's (1994) participants were required to search for a specific feature (e.g., the circle), they could not rely on a singleton search control setting but instead needed to use "feature search mode." Because the irrelevant color singleton does not match target properties under feature search mode, the singleton distracter does not capture attention (also see Leber & Egeth, 2006a; Leber, Kawahara, & Gabari, 2009; Vatterott & Vecera, 2012). A related account can provide a goal-driven explanation of how abruptly appearing objects capture attention (Gibson & Kelsey, 1998).

1.1.3 20 Years of Attentional Capture

Since the initial demonstrations of both stimulus-driven and goal-driven capture, there has been a running debate over these two control modes, with advocates of each control mode attempting to explain results supporting the alternate mode. For example, Theeuwes (1994) responded to Folk et al.'s (1992) results by demonstrating that visual search displays containing two salient stimuli—a color singleton and an abruptly appearing object—did not show contingent capture effects. Instead, salient distracters captured attention and slowed responses irrespective of the top-down attentional set. However, in Theeuwes (1994) task, participants searched for a singleton target, either a color singleton or an abrupt onset, and participants could have relied on search for any unique item. Because both the color singleton and the abrupt onset were unique in their color and onset status, respectively, a goal-driven setting for uniqueness could explain the results (much as a singleton search mode explained previous capture findings).

Conversely, Folk and Remington (1998; also see Folk, Remington, & Wu, 2009) explained the results from the irrelevant singleton task as arising from a filtering cost (see Kahneman, Treisman, & Burkell, 1983), not from the capture of spatial attention to the distracter location. Under this account, RTs are slowed when a salient distracter is present because the distracter must be filtered before spatial attention is directed toward the target. Because filtering occurs before attention is deployed to the target, responses are slowed to displays requiring filtering (i.e., those containing salient distracters). Some results, however, appear at odds with a general filtering cost: If the singleton distracter is either compatible or incompatible with the response to the target, participants are faster to respond to the target when the distracter is compatible than when it is incompatible (Theeuwes, 1994; Theeuwes & Burger, 1998). For such response compatibility effects to emerge, the distracter would need to be attended and recognized, suggesting that attention had been captured by the distracter. These response compatibility effects also occur for feature searches (e.g., an E or R target among other heterogeneous letter distracters; Theeuwes & Burger, 1998), which rules out the use of a singleton search mode. Distinguishing filtering costs from attentional capture has remained elusive. Response compatibility effects are an indirect measure of attention to the distracter, which opens the door to alternative accounts of these findings (see Folk & Remington, 1998; Folk et al., 2009). Other studies have used a secondary probe detection task to assess the location of attention. After the appearance of a search display in the irrelevant singleton task, Kim and Cave (1999) presented an abruptly appearing secondary target that participants were instructed to detect with a key press. Target detection was fast when it occurred at the distracter location shortly after the appearance of the search display, suggesting attention was captured and visited the distracter's location. Using a similar logic, electrophysiological measures have the potential to covertly measure if attention has been deployed to a salient but irrelevant distracter. Some evidence indicates that irrelevant singletons capture attention (Hickey et al., 2006), arguing against a general filtering cost. Results from both the target detection task and the electrophysiological studies, however, can be explained by appealing to a goal-driven singleton search mode (see Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, & Johnston, 2010).

Another line of contention in the control debate involves an explanation of contingent capture results. To argue for stimulus-driven attentional control requires an explanation of why target identity (i.e., goals or set) appears to influence capture by distracters that match properties of the target. One proposal is that when the target and distracter share matching properties (e.g., both are color singletons), attention is slower to disengage from the distracter location than when the target and distracter do not share properties. This "rapid disengagement" account argues that distracters initially capture attention in a stimulus-driven manner and that target–distracter contingencies affect disengagement, not attentional capture and control (see Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000). Rapid disengagement predicts that attentional capture should be observed at very short cue to target intervals in the contingent capture task, irrespective of whether distracters match or mismatch target properties. There is strong evidence against this prediction, however. Chen and Mordkoff (2007) demonstrated the standard contingent capture results with very brief (35 ms) cue–target onsets. For rapid disengagement to be a viable account of the contingent capture results, attention would need to be captured by a distracter, determine that the distracter did not share target properties, and then disengage from the distracter in less than 35 ms. This brief duration is an unrealistic estimate of the time to capture and then disengage attention (see Logan, 2005; Moore, Egeth, Berglan, & Luck, 1996; Theeuwes, Godijn, & Pratt, 2004).

Another challenge for the goal-driven view, particularly the absence of attentional capture in feature search mode, has focused on the breadth or scope of attention. One potential reason that a salient distracter might fail to capture attention during a feature search (i.e., search for a circle among heterogeneous shapes) is that attention needs to be relatively narrow to perform this demanding search. This constriction of attention effectively excludes the distracter, preventing capture (see Theeuwes, 2004). Some evidence for this view comes from Belopolsky and colleagues (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007): When attention was broadened widely across a display, a salient color singleton captured attention and influenced RTs; however, in the same displays, when attention was narrowed to a tighter focus, the color singleton did not influence responses.

Despite the evidence that the scope of attention can influence capture by a salient color singleton, not all results are compatible with an "attentional scope" view. If attentional control and capture could be explained by the scope of attention, then capture should only be observed when attention is set broadly and visual search occurs efficiently, possibly in parallel, across the display (Theeuwes, 2004). Such efficient search would predict flat search slopes; that is, visual search times would not increase as the number of objects in the display increased. Conversely, attentional capture should be absent under inefficient searches, in which attention is set narrowly and in which visual search times increase as the number of objects in a display increases. Leber and Egeth (2006b) tested these predictions of the attentional scope view. Participants performed a feature search task, searching for a circle among heterogeneous shape distracters. This search was very efficient, as the number of distracters had a negligible effect on visual search. Despite this efficient search, the participants were unaffected by a color singleton distracter, suggesting that the breadth or scope of attention was not the primary determinant of capture.

Finally, our recent work suggests that stimulus-driven capture is modulated strongly by perceptual load or complexity. Typical perceptual load tasks rely on the flanker effect to examine the role of display complexity (i.e., perceptual load) on attentional selectivity (e.g., Lavie, 1995). Participants search an array for a target letter; outside this task-relevant region a flanking, distracter letter appears, and this distracter is compatible, incompatible, or neutral with respect to the target. The flanker effect refers to faster RTs when the flanking letter is compatible or neutral than when it is incompatible with the target (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1973). However, this flanker effect only appears under low perceptual load, when the target appears alone or pops out from the distracters (e.g., Lavie, 1995; Lavie & Cox, 1997). Under high perceptual load, when the target appears among several visually similar distracters, attentional resources are taxed and no attention is left to spill over to the flanker letter; consequently, no flanker effect appears under high perceptual load (also see Roper, Cosman, & Vecera, 2013, for a detailed study of the stimulus factors that contribute to perceptual load).

If salient visual stimuli captured attention in a completely stimulus-driven manner, then the perceptual load of a display should have little effect on attentional capture, provided that the capturing stimulus was sufficiently salient. However, we have found that abruptly appearing flankers (Cosman & Vecera, 2009) and flankers that move or loom (Cosman & Vecera, 2010a, 2010b) do not produce a flanker effect under high perceptual load. These same salient flankers do elicit a flanker effect under low perceptual load. Given that most real-world scenes are high perceptual load and contain many objects that can be both visually and semantically related to any particular target, our findings limit the functional range of salience-driven attentional capture.

In summary, attention can be deployed based on both stimulus factors and goals, and both the scope of attention and perceptual load can impact visual search and attentional control. But, the evidence remains equivocal regarding which control modes—stimulus-driven or goal-driven—are the default of the attentional system. In the succeeding text, we outline an alternative to the modal, dichotomous view of attentional control and capture that highlights how other factors, such as experience and learning, result in varying degrees of attentional tuning. The extent of this attentional tuning determines the extent to which attentional control is stimulus-driven or goal-driven.

1.2. Experience-Based Attentional Tuning

1.2.1 Relevant Background

Our framework is not alone in suggesting a role for experience in guiding attention. For example, contextual cuing of attention results from the repeated presentation of search arrays and appears as faster search times through repeated displays than novel displays (Chun, 2000; Chun & Jiang, 1998). The decrease in search times with experience arises because of the repeated visual context, primarily provided not only by the local relationship between distracters and the target (Brady & Chun, 2007; Jiang & Wagner, 2004; Olson & Chun, 2002) but also by surrounding scene context (Brooks, Rasmussen, & Hollingworth, 2010). Our framework is not reducible to contextual cuing, however, because we investigate the role of experience on capture by task-irrelevant distracters, a topic that has not been the focus of contextual cuing studies. Further, in our previous work (Vatterott & Vecera, 2012) and the experiments in the succeeding text, we show that experience with nonspatial context—namely, the color of a task-irrelevant distracter—can affect the degree of attentional capture.

Experience also affects attention through priming, as in priming of pop-out (Maljkovic & Nakayama, 1994, 1996, 2000; see Kristjánsson & Campana, 2010, for a review). In priming of pop-out, participants report the shape of a color singleton target (e.g., a red shape among green shapes), but the color of this singleton target varies from trial to trial. On some trials, the target and distracters are the same color as on the previous trial, and on other trials, the target and distracters swap colors compared to the previous trial (e.g., the red target/green distracters on trial $n-1$ become a green target and red distracters on trial n). Priming of pop-out is defined as faster RTs when the target–distracter colors repeat compared to when they switch. Priming of pop-out appears to be due to altering the gains or relative weights of visual features (Lee, Mozer, & Vecera, 2009; Wolfe, Butcher, Lee, & Hyle, 2003). Many other attentional phenomena show trial-by-trial modulations similar to priming of pop-out (see Fecteau & Munoz, 2003).

Recent work from Leber and colleagues (Leber & Egeth, 2006a; Leber et al., 2009) is more closely aligned with our account in demonstrating that experience with a particular type of search mode configures attention and has long-lasting effects on attentional capture. Leber and Egeth (2006a) assigned participants to one of two search tasks in a rapid, serial visual presentation (RSVP) task. During a training phase, participants in the singleton search task reported the identity of a varying color target that appeared among homogenously colored distracters (e.g., all gray); participants in the feature search task reported the identity of a specifically colored target (e.g., red) that appeared among heterogeneously colored distracters (e.g., purple, blue, yellow, and orange). During training, participants performing the singleton search task were captured by an irrelevant color singleton distracter. In contrast, capture was attenuated for those participants performing the feature search task; these participants were only captured by distracters that matched the target color, as in contingent capture (Folk et al., 1992, 2002).

Following training, participants were transferred to "option trials," in which participants reported the identity of a specifically colored target (e.g., red) among homogenous distracters (gray). These option trials could be performed as either a singleton search task (search for the uniquely colored target) or a feature search task (search for the red target). Critically, Leber and Egeth (2006a) found that participants used their experience in the training trials to perform the option trials. Participants who had performed the singleton search task continued to search for a singleton target and showed large capture effects. Participants who had performed the feature search task searched for a specific color value and continued to show attenuated capture, again only being captured by distracters that matched the target color. Participants will continue to use the trained search mode for up to a week after the initial experience (Leber et al., 2009).

Our framework focuses on different aspects of attention than Leber's demonstration of a role of experience on attentional capture and control settings. Specifically, Leber focuses on priming a search mode and the continued use of this mode; our focus is on how a search mode—governed by stimulus- or goal-based control—emerges from experience in the first place. We predict that participants in the feature search task required experience to perform a selective feature search for a specific target color. Indeed, using a feature search task (Bacon & Egeth, 1994), we have demonstrated that participants are captured initially by an irrelevant color singleton distracter (Vatterott & Vecera, 2012). Only when participants have experience learning to reject specific distracters is this capture eliminated. This learned distracter rejection is highly specific: if the distracter color changes during the experiment, participants are again captured by the distracter and must relearn distracter rejection. Other recent results demonstrate a similar finding in which experience with a distracter during training is critical to learn distracter rejection (experiments 1 and 2, Zehetleitner, Goschy, & Müller, 2012).

As noted earlier, a main feature of our account is that attentional capture and control should become more goal-directed with increased experience. Note, however, that this does not imply that control will become completely goal-directed and abolish capture by a highly salient distracter. Some task environments might increase the overall salience of a distracter and make it impossible to overcome completely. For example, displays with low perceptual load or those with singleton targets and distracters might resist complete goal-driven control.

As reviewed earlier, some of our recent work provides initial support for experience-based tuning by demonstrating capture by a color singleton distracter in the initial phases of a feature search task (Vatterott & Vecera, 2012). Other results in the literature demonstrate a role for experience on capture and control. For example, Warner et al. (1990) examined participants' ability to direct attention opposite of an abruptly appearing peripheral cue. This cue was counterpredictive—it indicated that a target was likely to appear opposite of the cued region. Only with extensive practice on the order of a few thousand trials could participants direct attention to the likely, uncued target location. These results could have been due to increased goal-directed control to the likely target position or a rapid disengagement from the peripherally cued region. Similarly, Kim and Cave (1999) found that relatively extensive practice affected attentional capture. Their participants briefly attended the location of a color singleton distracter (~60 ms after display onset) but were then likely to reorient toward the target. However, this initial allocation to the singleton distracter was most pronounced in the first session of 768 trials; following sessions showed little, if any capture by the singleton (but see Theeuwes, 1992).

Finally, we should note that our account does not imply that increased experience allows control to become completely goal-directed and to abolish capture. Other properties of the task environment will likely affect the degree of attentional tuning. For example, displays with low perceptual load or those with singleton targets and distracters might resist complete goal-driven control. Indeed, we have demonstrated that attentional capture by a salient, abruptly appearing distracter depends on both perceptual load and experience. When participants are engaged in a demanding, high-perceptual-load search, an abruptly appearing distracter does not capture attention, although the same distracter readily captures attention under low perceptual load (Cosman & Vecera, 2009; also see Cosman & Vecera, 2010a). However, participants' ability to resist capture when engaging in a demanding search task depends on experience. If the onset distracter appears less frequently, capture is not eliminated under high perceptual load (Cosman & Vecera, 2010b). As a distracter appears less frequently, we hypothesize that participants have less experience rejecting or disengaging from this distracter, allowing the distracter to remain more potent for a longer period of time. Other findings are consistent with this result. For example, capture by an abruptly appearing distracter can be reduced if attention is directed elsewhere (Yantis & Jonides, 1990) but only when the distracter appears frequently. Infrequent distracters continue to capture attention (Neo & Chua, 2006; also see Sayim et al., 2010). Similar findings arise for color singleton distracters, which capture attention more strongly when they are infrequent than when they are frequent (Geyer et al., 2008; Horstmann, 2005; Müller et al., 2009).

1.2.2 Characteristics of Experience-Based Tuning

In our proposed framework, *experience-based attentional tuning*, we hypothesize that stimulus-driven control and goal-driven control lie on a continuum of processing. Such a continuum is a common theme in several accounts of visual search (e.g., Cave & Wolfe, 1990; Müller, Heller, & Ziegler, 1995; Navalpakkam & Itti, 2005; Wolfe, 1994, 2007) in which bottom-up, stimulus factors and top-down, goal factors simultaneously influence a master map of locations that guides search. Instead of focusing on a particular search mode, such as feature search or singleton search, our framework, depicted in Fig. 8.4, focuses instead on the relative contributions of stimulus factors and goal factors on attentional control. Most important, we highlight the role of experience and learning as a critical factor in determining the relative contributions of stimulus-driven control and goal-driven control. Specifically, as the amount of experience with a task increases, we predict greater goal-driven control; conversely, with relatively little experience, we predict greater stimulus-driven control.

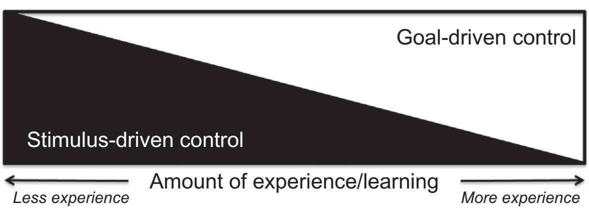

Figure 8.4 Our framework, in which goal-driven attentional control emerges with increased experience with a task. With relatively little experience, attentional control tends to be more stimulus-driven.

Also critical to our account is the distinction between goal-driven control by working memory representations and longer-term representations. Much work in visual search has highlighted the importance of a "target template" to guide attention in top-down, goal-driven manner (e.g., Bundesen, 1990; Desimone & Duncan, 1995). In contrast, in our view, experience with a task and all of its elements—stimuli, context, and regularities—is learned and has an influence over attentional control with repeated experience. Our account is influenced by approaches to skill learning and automaticity, and we draw parallels between skill learning and attentional control by longer-term representations. Many theories of skill learning and automaticity propose that automaticity emerges after sufficient experience with a task and its context (e.g., Logan, 1988, 2002; Norman & Shallice, 1986; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Expert performance also emerges with experience. Expertise often involves different representations or extraction of different information, as when chess grandmasters extract "chunks" of visual information based on the functional properties of individual pieces (Chase & Simon, 1973) or speeded recognition of a board configuration (Gobet & Simon, 1996). Logan's instance theory (Logan, 1988, 2002) provides a clear example of how experience affects automaticity. Instance theory proposes that experience with a task allows for an accumulation of longer-term episodic memories (instances) of previous encounters with the task. With additional experience, task performance is more likely to be based by the speeded retrieval of an instance from memory than by the use of an algorithm to compute the task's solution, which is slower overall. The transition from algorithm use to memory retrieval can emerge relatively rapidly by following a power law of learning (Logan, 1988; Newell & Rosenbloom, 1981). Indeed, there is evidence that attentional control is initially based on visual working memory but quickly transitions to longer-term visual representations (e.g., Carlisle, Arita, Pardo, & Woodman, 2011).

To map our framework to skill learning assumes that stimulus-driven control be the default mode by which attention operates in the absence of experience (see Kawahara, 2010, for relevant evidence). Stimulus-driven control would be akin to algorithmic processing in instance theory. With experience, however, attentional control becomes increasingly goal-driven (memory-based processing in instance theory). We would quickly add, however, that although stimulus-driven control might be a default mode, it is likely that this default mode is used relatively little in attentional guidance through real-world scenes. In such scenes, previous experience would allow previous "instances" of control to guide attention in a goal-driven manner, and the context provided by a scene might be sufficient to reinstantiate goal-driven control settings, as we will discuss later. To that end, we speculate that although stimulus-driven control might be the default mode of attention, goal-driven control is the more frequently used mode.

Task and scene context might act as a retrieval cue that allows an attentional control setting to be extracted from memory to guide online behavior (Logan, 1988, 2002), allowing for relatively high-level attentional control with minimal cognitive effort. In familiar everyday scenes, the semantic context and visual co-occurrences provided by the scene might allow for attentional control to be driven by past goals and experiences, reducing stimulus-driven control. Recent evidence supports our supposition that scene context can guide attentional control. Task-irrelevant scene context can alter the allocation of visual search in contextual cuing (Brooks et al., 2010). More directly, we have recently demonstrated that task-irrelevant context can be associated with specific attentional control settings (Cosman & Vecera, 2013a, 2013b). Participants searched for a target in either singleton search mode (e.g., circle target among diamonds) or feature search mode (e.g., circle target among triangles, diamonds, and squares). Unbeknownst to participants, each of these search displays was surrounded by a different context; for example, singleton displays might be surrounded by forest scenes and feature displays might be surrounded by city scenes. When participants were transferred to option trials that allowed either singleton or feature search mode to be used (Leber & Egeth, 2006a), the surrounding context determined attentional control. When a search array was surrounded by the context associated with singleton search, a salient color distracter captured attention and slowed responses. In contrast, when the same search array was surrounded by the context associated with feature search, capture was absent. In short, context determined the degree of attentional control.

Context might be intimately tied up with attentional control settings as a consequence of relational memory systems in medial temporal lobe areas that bind scene elements to form episodic memory representations (e.g., Davachi, 2006; Eichenbaum, 2004; Hannula, Tranel, & Cohen, 2006; O'Reilly & Rudy, 2001). Consistent with this, we have recently demonstrated that patients with medial temporal lobe (MTL) damage can learn goal-driven attentional control but fail to transfer this setting to a new task setting (Cosman & Vecera, 2013a, 2013b). MTL patients can quickly learn to reject a color singleton distracter while performing feature search, but the same distracter captures attention when the patients are transferred to option trials that can be performed with either singleton or feature search. Learning feature search is intact, but these learned settings do not persist to new displays because of a change in context.

1.3. Experiments: Experience-Based Contingent Attentional Capture

Both our account and our experimental approach focus on using tasks typically thought to tap goal-driven control and showing that this control emerges over time. In contrast, much of the previous work described earlier either investigates cases of stimulus-driven control that is altered with practice or trial-by-trial experience or does not look at the specificity of control by examining capture.

In the experiments that follow, we examine the rapid, experience-dependent emergence of goal-directed attentional control settings in a contingent capture task. Specifically, as reviewed earlier, the contingent capture task demonstrates that only target-relevant information captures attention. For example, when searching for a color singleton target, a color singleton distracter, but not an onset distracter, captures attention. To track the emergence of contingent, goal-driven control settings, we conducted a replication of the typical Folk et al. (1992) cuing task. Instead of examining aggregate data only, we tracked participants' performance over time by epoching the data in bins of 24 trials to examine how task experience affects the ability to overcome capture. This fine-grained analysis amounts to a microgenetic approach to analyzing attentional control (see Siegler & Chen, 1998; Siegler & Crowley, 1991), in which we can examine attentional control as it develops during the course of an experiment.

Figure 8.3 depicts the order of events in a typical trial. In our version of the task, participants performed a singleton search, reporting the identity of the color singleton that appeared among white nontargets. Prior to the presentation of the search array, a task-irrelevant white abrupt onset cue (experiment 1a) or distracter (experiment 1b) appeared briefly at one of the four locations. Goal-directed attention should be configured to search for the color singleton, which should allow participants to effectively ignore the onset cue (Folk et al., 1992).

2. LEARNING ATTENTIONAL CONTROL SETTINGS: EXPERIMENTS 1A AND 1B

In experiment 1a, the onset cue appeared at any of the four possible locations with equal probability; on 75% of trials, it cued one of the three nontarget locations (i.e., it was an "invalid" cue), and on 25% of trials, it cued the target location (a "valid" cue). In experiment 1b, the white onset was always a distracter that *never* appeared at the target location; this distracter appeared on half of the trials and was absent on the other half of the trials (similar to the logic used in the additional singleton paradigm of Theeuwes, 1992). In both experiments, as part of the instructions, participants were always explicitly told to ignore the white onset and focus on finding the red target, because attending to the onset would hurt their performance. Experiment 1b is important to argue that distracter rejection resulting from contingent control settings emerges with experience even when the onset is never predictive. It is possible that the presence of a few valid trials in experiment 1a could encourage participants to strategically attend the cue, especially early in the task.

If participants' task and target goals are sufficient to overcome capture from the onset of the task as would be predicted by most accounts of goal-driven control, we would expect to see no effect of task experience on control. Participants would show no capture by the onset cue/distracter. In contrast, if participants need experience with a task to effectively configure attention to task-relevant properties, we would expect capture early in the task, with a reduction in capture as a contingent control setting for the singleton target emerged with experience. In short, we would predict a steep learning curve in which participants would quickly learn to attenuate processing of the onset item.

2.1. Method

Participants were 30 University of Iowa undergraduates (15 in experiment 1a and 15 in experiment 1b) who participated for course credit. All had normal or corrected to normal vision and were not color blind.

Stimuli were presented on a 15″ CRT monitor powered by a Macintosh minicomputer, using MATLAB and the Psychtoolbox (Brainard, 1997). Participants sat approximately 65 cm from the screen and viewed displays resembling those in Fig. 8.3. The fixation display consisted of four placeholder boxes measuring 1.4×1.4 and positioned on the corners of an imaginary diamond centered around fixation. The distance from fixation to the center of each placeholder box was 5.2°. The placeholder boxes were light gray (RGB 160, 160, 160) on a black background. Cues (experiment 1a) and distracters (experiment 1b) consisted of four white dots (radius 0.21°) centered on the edges of one placeholder box and were always presented as abrupt onsets, with each dot positioned 0.46° peripheral to the side of the placeholder box. On each trial, a single target was presented in red (RGB 255, 0, 0) within one of the placeholder boxes, and the target was equally likely to be an "X" or "=" symbol, drawn in 56-point Helvetica bold font. White "X" or "=" nontarget search items were presented in each of the three remaining placeholder boxes, with nontarget item identities being determined randomly on each trial.

In experiment 1a, our instructions stressed that the cue would not predict the target location. On each trial, a fixation display was presented for 1000 ms, followed by a single nonpredictive, white onset cue for 50 ms, and then by a 100 ms interstimulus interval (ISI) in which only the fixation display was presented, producing a cue–target SOA of 150 ms. Directly following this, a search array was presented for 50 ms, and the red target could be either a "X" or "=" symbol, chosen pseudorandomly on each trial. The duration from the time of cue onset to the time of target onset was 200 ms, a duration short enough to preclude eye movements to the cue or target locations. The fixation display was then presented until participants made a response using either the "Z" or the "M" keys, with target-response mappings counterbalanced across participants. Participants were told to perform the task as quickly and accurately as possible. Participants completed 8 blocks of 24 trials, for a total of 192 trials, with no distinct "practice" block. The first trial of the experiment was the participants' first exposure to the stimulus displays.

In experiment 1b, our general procedure was identical to that in experiment 1a, with the following exceptions: Participants were informed that the white onset was a distracter that would appear on only half of the trials and would never appear at the target location. Again, the instructions stressed that participants should ignore the white onset if it appeared. The timing of events was identical to that in experiment 1a, except that on distracter-absent trials, the fixation display was presented for 50 ms longer to keep the timing between fixation onset and target onset constant across conditions and experiments. Participants were told to perform the task as quickly and accurately as possible and completed 8 blocks of 24 trials, for a total of 192 trials.

2.2. Results

For both experiments 1a and 1b, incorrect trials and outlier trials with reaction times (RTs) greater than 3 SDs above individual means were excluded from further analysis. This outlier trimming resulted in a removal of less than 3% of the total RT data. Participants' overall mean correct reaction time data appear in Figs. 8.6 (experiment 1a) and 8.7 (experiment 1b).

Experiment 1a represented a straight replication of Folk et al. (1992) and demonstrated that the current stimuli and design generate a normal contingent capture effect when analyzed in the typical manner, (i.e., when the first block of 24 trials is treated as an unanalyzed "practice" block and the remaining data are aggregated). Specifically, planned comparisons between validity conditions (valid vs. invalid) were conducted on the aggregate RT and error rate data. This comparison revealed no significant cuing effects for the onset cues in RTs, $t(14) = 1.1$, $p = 0.28$, or error rate, $t(14) < 1$, *n.s.*, indicating that an attentional set for a color target attenuated onset capture in this experiment, just as in Folk et al. (1992) and subsequent work (Folk & Remington, 1998; Folk et al., 1994).

To examine the role of experience on the emergence of contingent capture effects, we analyzed data from all trials and epoched these data in bins of 24 trials (the length of a block), resulting in 8 bins of 24 trials. Epoched data for each validity condition are shown in Fig. 8.5. We performed a two-factor ANOVA with epoch (1–8) and cue validity (valid vs. invalid) as

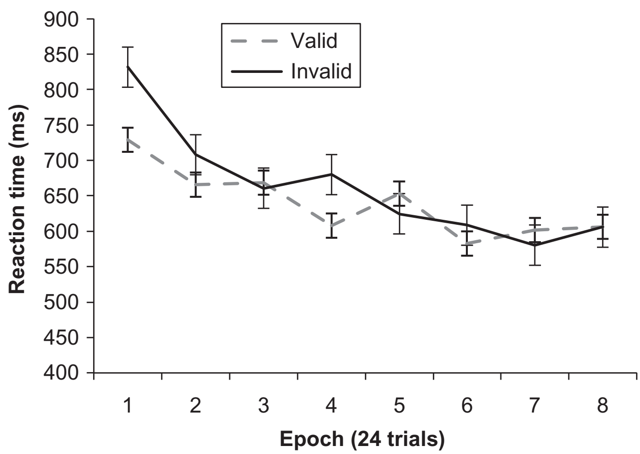

Figure 8.5 Response time results from experiment 1a. Error bars on this and all following plots represent 95% within-subjects confidence intervals (see Cousineau, 2005; Loftus & Masson, 1994; Morey, 2008).

factors on both RT and error rate data. For RTs, we found significant main effects of epoch, $F(7,98) = 7.69$, $p < 0.001$, $\eta^2 = 0.35$, and validity, $F(1,14) = 9.92$, $p < 0.01$, $\eta^2 = 0.42$. Importantly, we found a significant interaction between epoch and validity, $F(7,98) = 2.29$, $p = 0.03$, $\eta^2 = 0.15$, indicating that when participants are set for color, capture by onset cues varies as a function of epoch (i.e., task experience). In order to further elaborate on this interaction, we performed planned comparisons between valid and invalid trials in each epoch. These comparisons revealed a significant effect of cue validity during the first epoch, $t(14) = 3.22$, $p < 0.01$, but effect in the subsequent epochs, $t_s < 1.74$, $p_s > 0.11$. Thus, despite a set to search for a color singleton target, onset cues captured attention early in the task. Error rates were generally low (less than 10%), and these data showed neither main effects nor interactions, indicating that the cues did not have an effect on error rates and indicating that there were no speed–accuracy trade-offs in the current data.

We conducted identical analyses on the data from experiment 1b, and the epoched data appear in Fig. 8.6. Planned comparisons between distracter-present and distracter-absent conditions on the aggregate RT and error rate data revealed no significant interference effects from the task-irrelevant onset distracters in RTs, $t(14) = 2.0$, $p = 0.07$, or error rate, $t(14) < 1.28$, $p = 0.22$, paralleling the results from experiment 1a. We computed a two-factor ANOVA with epoch (1–8) and distracter presence (present vs. absent) as factors on both RT and error rate data from experiment

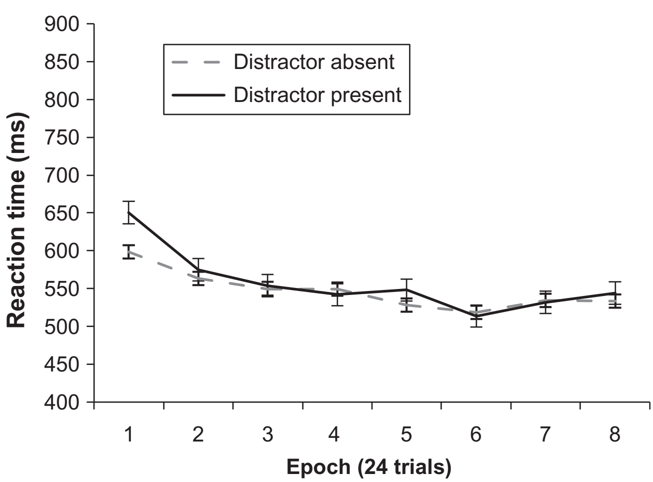

Figure 8.6 Response time results from experiment 1b.

1b. For RTs, we found a significant main effect of epoch, $F(7,98) = 8.98$, $p < 0.001$, $\eta^2 = 0.40$, and a marginal effect of distracter presence, $F(1,14) = 4.2$, $p < 0.06$, $\eta^2 = 0.23$. As in experiment 1a, we observed a significant interaction between epoch and distracter presence, $F(7,98) = 2.53$, $p = 0.02$, $\eta^2 = 0.16$, demonstrating that when participants are set for a color singleton target, capture by onset distracters varied as a function of task experience. Planned comparisons between the distracter-present and the distracter-absent conditions for each epoch revealed a significant effect of the onset distracter during the first epoch, $t(14) = 4.12$, $p < 0.01$, but not in any of the subsequent epochs, $t_s < 1.50$, $p_s > 0.16$. Onset distracters retained the ability to capture attention and produce capture effects early, but not later, in the task. Error rates were low (6% or less) and showed neither main effects nor interactions, ruling out any speed–accuracy trade-offs.

2.3. Discussion

The results of experiment 1 are clear and indicate that despite an explicit set for color and an intention to ignore the white abrupt onset cues/distracters, these onsets retained the ability to capture attention early in a task when participants had little experience with the specific stimulus attributes they are instructed to either search for or ignore. However, this initial capture effect dissipates rapidly, with goal-directed control becoming effective at attenuating capture following 24 trials or less of exposure to the task. These results suggest that giving participants precise, explicit information regarding the defining dimensions of both the search target and the distracter is insufficient to instantiate goal-driven attentional control settings. Even when participants know with 100% certainty that the onset will never signal the target location (as in experiment 1b), they are still susceptible to capture early in the task. We propose that participants rely on experience with specific instances of the stimuli and task to tune the attention system to exert effective goal-directed control over capture.

Although experience appears necessary to configure attention to a high level of precision, the specific nature of this experience is not available in experiment 1. Early in the task, in addition to having little experience with specific target–distracter attributes, participants also have little experience carrying out the search task itself. Lack of experience with the search task might place a greater "executive" demand on participants in the early trials because participants attempt to maintain the task instructions, including the target identity, in working memory during the first few trials of the experiment. If working memory is also involved in distracter inhibition as has been shown in a number of related lines of work (de Fockert, Rees, Frith, & Lavie, 2001, 2004; Lavie & de Fockert, 2005), then distracter interference might occur early in the task because of the greater working memory load.

Another source of the experience observed in experiment 1 is more specific to the mechanisms that drive the typical goal-driven, contingent control effect observed in this task. Most accounts of goal-driven control, including contingent capture, propose that target properties establish attentional control settings that filter for incoming sensory information, allowing capture only by information that matches this target template (Folk & Remington, 2006; Folk et al., 1992; Müller, Reimann, & Krummenacher, 2003). Under this view, the initial stimulus-driven control observed in experiment 1 would be a by-product of a weak target template. Only when target properties were effectively practiced could a contingent attentional control setting guide attention to target-relevant properties and prevent capture by distracters that do not match these target properties.

A final possibility, consistent with our experience-dependent tuning account, is that participants must learn specific instances about the cue or distracter to avoid being captured by it (also see Vatterott & Vecera, 2012). Attention must be configured to specific instances to not only seek (i.e., the target) but also avoid or reject. Experience with the overall search task will provide experience-dependent tuning to target properties, but not to distracter properties.

To examine the specific type of experience that allows participants to tune attention to reject the cues and distracters, we gave participants practice with the search task prior to the introduction of task-irrelevant cues (experiment 2a) or distracters (experiment 2b), similar to how Vatterott and Vecera (2012) provided exposure to a feature search task before introducing color singleton distracters. In the current experiments, if capture was observed early in experiment 1 because executive resources were occupied with instructional rehearsal or because of a weak target representation early in the task, we would expect that the introduction of the cue/distracter would have little effect on performance: Practice with the search task should allow participants sufficient practice to overcome both issues prior to the introduction of the distracter. In contrast, if participants must learn something specific about the cue/distracter to avoid capture and to develop goal-driven control settings, we would expect to see an effect similar to that observed in experiment 1. Specifically, the cue/distracter should capture attention immediately following its introduction, but this effect should be rapidly attenuated with experience.

3. INTRODUCTION OF A DISTRACTER AFTER TASK LEARNING: EXPERIMENTS 2A AND 2B

3.1. Method

Participants were 30 University of Iowa undergraduates (15 in experiment 2a and 15 in experiment 2b) who participated for course credit. All had normal or corrected to normal vision and were not color blind.

The stimuli and procedure were identical to those used in experiments 1a and 1b, with the exception that participants performed a set of "tuning" trials in which no cue/distracter appeared. In experiment 1b, participants completed 8 blocks of 24 trials (192 total trials) without a cue, and in experiment 2a, they completed 6 blocks of 24 trials in experiment 2b (144 total trials) without a distracter. After the introduction of the cue or distracter, participants completed another 8 blocks of 24 trials (192 total trials) in experiment 2a and 6 blocks of 24 trials (144 total trials) in experiment 2b. Participants were given identical instructions to those used in experiment 1 and were informed of the presence of task-irrelevant onsets from the outset of the experiment.

3.2. Results

For both experiments 2a and 2b, incorrect trials and outlier trials with RTs greater than 3 SDs above individual means were excluded from further analysis; this trimming removed approximately 2% of the total data. Participants' overall mean correct reaction time (RT) data appear in Figs. 8.7 (experiment 2b) and 8.8 (experiment 2b). For both experiments, error rates were identical or paralleled the RT results ruling out a speed–accuracy trade-off, and there were no significant results from the error data. Error rates were generally higher in the attentional tuning trials (7% on average) than on the trials containing the cue/distracter (approximately 4% on average). Given our interest in the effect of the cue/distracter, we analyze only the data from the posttuning blocks in which the cue/distracter was present.

For experiment 2a, we performed a two-factor ANOVA with epoch (epochs 9–16) and cue validity (valid vs. invalid) as factors on the RT data. There were significant main effects of epoch, $F(7,98)=5.28$, $p<0.001$, $\eta^2=0.28$, and validity, $F(1,14)=18.1$, $p<0.01$, $\eta^2=0.56$. In this case, the two-way interaction between epoch and validity was not significant, $F(7,98)<1$, *n.s.*, likely reflecting the more gradual decrease in capture in this experiment. However, given the specific question being addressed in

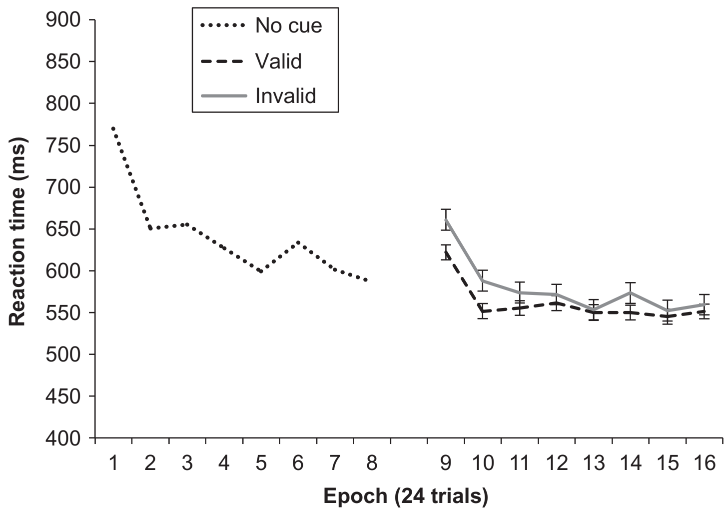

Figure 8.7 Response time results from experiment 2a.

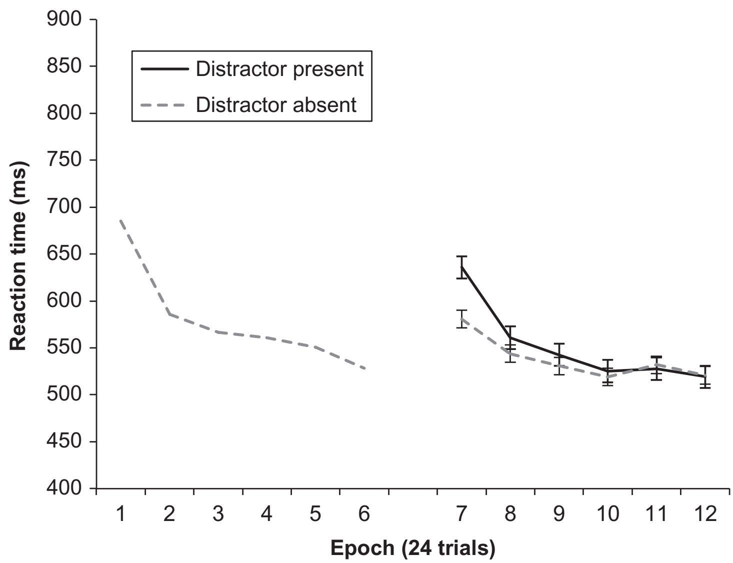

Figure 8.8 Response time results from experiment 2b.

this experiment, we conducted planned comparisons that were performed for valid versus invalid RTs in each epoch. As in the previous experiments, these comparisons revealed a significant effect of cue validity during the first epoch, $t(14) = 2.37$, $p = 0.03$, but none of the subsequent epochs, $t_s < 1.69$, $p_s > 0.12$, consistent with the effects observed in experiment 1a.

For experiment 2b, we also performed a two-factor ANOVA with epoch (7–12) and distracter presence (present vs. absent) as factors on the RT data. We found significant main effects of epoch, $F(5,70)=10.8$, $p<0.001$, $\eta^2=0.44$, and distracter presence, $F(1,14)=10.8$, $p<0.001$, $\eta^2=0.53$. Importantly, we also found a significant interaction between epoch and distracter presence, $F(5,70)=2.3$, $p=0.05$, $\eta^2=0.14$, demonstrating that even after 192 trials of practice with a task in which participants are set to search for color, capture by onset distracters varies as a function of epoch (i.e., task experience). Planned comparisons again revealed a significant effect of the onset distracter during the first epoch, $t(14)=3.12$, $p<0.01$, but not in the subsequent epochs, $t_s<1.44$, $p_s>0.17$. Despite a set for a specific color, onset cues retain the ability to capture attention and produce capture effects early in the task.

3.3. Discussion

In experiment 2, introduction of a distracter again caused capture even after nearly 200 trials of practice with the search task itself. This finding is consistent with the notion that participants need experience with specific attributes of the distracter before they can reject it, even in the face of experience with the goal-relevant attributes of the task (e.g., the target, locations, and timing parameters) in the absence of distracters. Taken with the results of experiment 1, the current results suggest that participants represent information regarding both the target of search and to-be-ignored distracters in order to implement the form of goal-directed control over capture observed in this task, with this information being acquired through experience. This is inconsistent with accounts of feature-based, goal-directed control that emphasize a solitary role for the active maintenance of target information in the filtering of task-irrelevant information (e.g., McNab & Klingberg, 2008; Vogel, McCollough, & Machizawa, 2005), instead arguing that such control arises on the basis of experience with multiple task attributes (as in Carlisle et al., 2011; Vatterott & Vecera, 2012).

Having established a general role for experience on attentional control, we next turn to the types of information that contribute to the experience-dependent control we have observed. In experiments 1 and 2, it is possible that participants simply learn to ignore visual onset transients and that as exposure to task-irrelevant transients increases, there is a habituation of the orienting response normally elicited by these onsets (e.g., Cosman & Vecera, 2010b;

Neo & Chua, 2006). Under this view, consistent exposure to an onset distracter should cause it to lose its ability to capture attention regardless of changes to, other aspects of it, such as its surface features or form.

Alternatively, participants might learn specific information regarding the identity of the transient distracter itself, developing a specific representation of the to-be-ignored stimulus such that salient transients that do not match the specific identity of the ignored stimulus retain the ability to capture attention. Such a mechanism could be considered adaptive, since transient events often signal significant changes in the environment, and blanket attenuation could lead an organism to ignore these changes even when they are important. To distinguish these possibilities, in experiment 3, we employed a design similar to that used in experiment 2, but once participants ceased to show capture effects to the onset transient, we introduced a change in the surface feature associated with the distracter (in this case color, also see Vatterott & Vecera, 2012).

The two possibilities outlined earlier make differing predictions regarding how changing the surface features associated with the distracter will affect capture; if the effects observed in experiments 1 and 2 reflect general habituation to the presence of a distracting transient, we would expect that changing the color of the distracter should not affect capture, since the distracter will maintain its status as a transient. In contrast, if participants are tuning attention to specific attributes of the distracter, we would expect color change to lead to an increase in capture for a brief period of time following the change. In this case, participants would need to "relearn" the distracter-defining feature in order to effectively overcome capture by it. Based on our previous work, we anticipate that changes to the distracter will cause goal-driven control parameters to be reset and will require new parameters to be learned for the new distracter.

4. THE EFFECT OF INTRODUCING NEW DISTRACTERS: EXPERIMENT 3

4.1. Method

The stimuli and timing parameters were nearly identical to those used in experiment 2a. The cues appeared in four possible cue colors: white (255, 255, 255), red (255, 0, 0), blue (0, 0, 255), or green (0, 255, 0). For a given participant, the target was a single color for the entire experiment (either red, blue, or green), counterbalanced across participants, and this color determined the participant's "attentional set" for the search task.

Importantly, the cue never matched the participant's set target color and thus should not produce a capture effect in this task. This design resulted in three possible cue colors, with the order in which each cue color was presented being counterbalanced across participants (e.g., the target was red, and the cue color for epochs 6–10 = green, for epochs 11–15 = white, and for 16–20 = green).

Fifteen participants first performed a block of 120 trials of the search task in which no cue was presented to replicate the basic findings from experiment 2a when examining the transition from no cue to cue trials in epoch 6. Following this initial block, on each trial, the search array was preceded by a cue that either validly (25% of trials) or invalidly (75% of trials) predicted the target location as in the previous experiments. Critically, to test the specificity of learning for cue properties, the color of the cue switched every 120 trials, such that the cue appeared for the first time on trial 121 (the first trial of epoch 6), and switched colors on trials 241 (the first trial of epoch 11) and 361(the first trial of epoch 16). Thus, participants performed 480 trials total, completing 5 blocks of 24 trials for each cue color. Participants were informed during the instructions at the beginning of the task that the cue could appear in any of three possible colors and that the cues were task-irrelevant and should be ignored because they would hurt performance.

4.2. Results

We again excluded incorrect trials and RTs greater than 3 SDs above individual means that were excluded from further analysis, and this trimming eliminated approximately 4% of the total RT data. As in experiment 2b, we only analyzed trials in which a cue was present (epochs 6–20) because of our interest in the effect of the cue's color change on attentional capture. As before, we epoched the data in bins of 24 trials, resulting in 15 bins of 24 trials each. Epoched data for each validity condition for each of the cue-present blocks of the experiment are shown in Fig. 8.9.

We computed a three-factor ANOVA on both RTs and error rate data, with cue color, epoch, and validity as factors. This analysis revealed a main effect of epoch, $F(4,56) = 3.1$, $p = 0.02$, $\eta^2 = 0.18$, with RTs generally decreasing across epochs, and a main effect of validity, $F(1,14) = 7.5$, $p = 0.02$, $\eta^2 = 0.35$, with RTs on valid trials being faster than those on invalid trials. There was no main effect of cue color, $F(2,28) = 3.0$, $p < 0.07$. We found an interaction between epoch and validity was significant, $F(4,56) =$

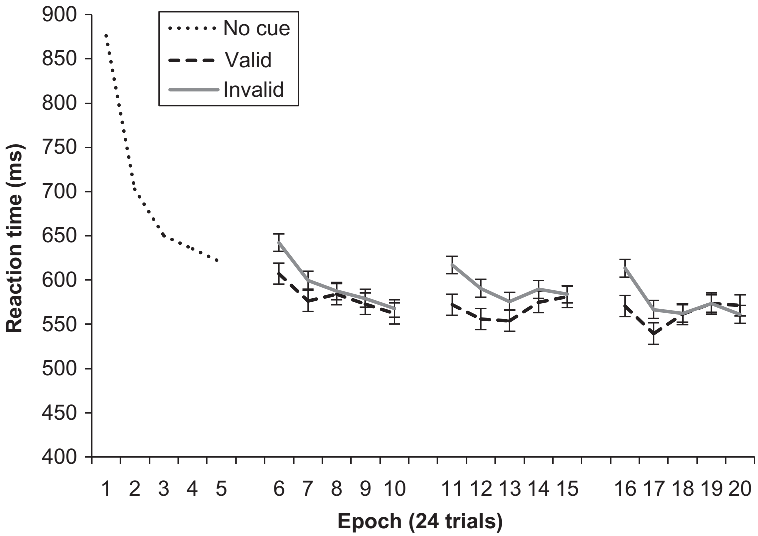

Figure 8.9 Response time results for experiment 3.

2.8, $p = 0.05$, $\eta^2 = 0.15$, indicating that the cue's ability to capture attention depended critically on the amount of experience a participant had with the cue. Critically, there was no three-way interaction between cue color, epoch, and validity, $F < 1$, *n.s.*, indicating that the epoch-by-validity interaction did not vary with the color of the cue.

To probe the nature of the epoch-by-validity interaction, we conducted planned comparisons on the magnitude of the cuing effect within each epoch. When the cue was first introduced, it produced a significant capture effect during the first 24-trial epoch (epoch 6), $t(14) = 2.3$, $p = 0.04$, but not during any subsequent epochs prior to the cue color change. This replicates the findings of experiment 2a and provides further evidence that participants needed experience with the cue before they were able to effectively ignore it. We also conducted planned comparisons for cuing effects during the first epoch following a color change (epochs 11 and 16), and we found significant cuing effects in both epochs 11, $t(14) = 2.7$, $p = 0.02$, and 16, $t(14) = 2.3$, $p = 0.04$. Thus, the cue captured attention and produced cuing effects during the first epoch that was introduced (epoch 6) or following a color change (epochs 11 and 16), suggesting that participants need both experience with the distracter and experience with its associated features (in this case, color) in order to effectively ignore it.

For the error rate data, there was a trend toward a significant main effect of validity, $F(4,56) = 2.8$, $p = 0.06$, but no other main effects or interactions approached significance $F_s < 1.5$, $p_s > 0.17$.

4.3. Discussion

The results of experiment 3 demonstrated that changing the surface feature associated with a distracter leads to an increase in capture effects in the epoch directly following the change. These findings suggest that participants code information about the defining features of a distracter (i.e., color) and use these features to configure optimal attentional control. Although the cue mismatches the target's properties, the cue initially captures attention, as in the previous experiments. Once participants have sufficient experience with a cue (around 50 trials) to allow for optimal goal-driven attentional control, the cue no longer attracts attention. When distracter features change, as in the color changes in the current experiment, the current attentional control settings no longer match the distracter, and the new cue captures attention until sufficient experience allows a new set of goal-driven control parameters to emerge. The current results parallel those from Vatterott and Vecera (2012) that we have discussed earlier. One important contribution of the current experiment is that the cue was more readily segregated from the target than the distracters in our previous work. Despite the temporal separation of the cue and search array in experiment 3, participants nevertheless required experience with cues to effectively reject them.

One lingering question from the current results, however, is whether they represent an increase in capture in response to a novel distracter color or to a *change* in the distracter-defining color. For example, it is possible that any time a distracter changes color, it may be more likely to capture attention even if the participant has had extensive practice with a distracter of that particular color in the past. In contrast, it is possible that participants overcome capture by using specific knowledge about distracter-defining features—that is, specific instances or episodes of the cue. On this latter account, increased capture only occurs when the distracter changes to a *novel* color that participants have not previously encountered.

Our final experiment aims to disambiguate these possibilities. In experiment 4, we included a condition in which the cue's color reverts to a color that participants experienced previously. If any change in feature information disrupts attentional control, then we would expect larger capture in an epoch following any color change. However, if participants are tuning attentional control to specific distracter features, we would expect that changing a distracter to a novel color would lead to increased capture effects in the epoch following the change, but that changing it to a previously experienced color would do little to affect capture. This latter result would argue for a strong, feature-specific mechanism of goal-directed control, whereby participants use specific information regarding the association between distracting information and its defining features to overcome capture.

5. ARE PREVIOUS CONTROL SETTINGS RETAINED OR LOST? EXPERIMENT 4

5.1. Method

This experiment was identical to experiment 3, with the following exceptions. We included a condition in which the color of the distracter reverted to a color participants already had extensive experience ignoring. For the "novel color change" condition, the order in which each cue color was introduced was counterbalanced across participants. In the "familiar color change" condition, the cue reverted to the color in which it was originally introduced, and this change is always occurring during epoch 16. For example, for a given participant, the target color was always red, and the cue was absent for epochs 1–5; the cue color for epochs 6–10 was green; for epochs 11–15, it switched to white; for epochs 16–20, it *switched back* to green; and for epochs 21–25, it switched to blue. This design allowed us to dissociate the effects of *any* change in distracter color from those of changes to *specific* colors. In particular, if any color change leads to an increase in capture, we would expect increased capture (i.e., a large cuing effect) in the epoch directly following the change in distracter color. On the other hand, if participants tune to specific distracter features, we would expect large cuing effects in the epoch following the change only for cue colors that participants had not previously been exposed to.

Fifteen participants first performed a block of 120 trials of the search task in which no cue was presented. Following this block, and for the rest of the trials in the experiment (epochs 6–25), on each trial, the search array was preceded by a cue that either validly (25% of trials) or invalidly (75% of trials) predicted the target location as in the previous experiments.

Participants performed 600 trials total, completing 5 blocks of 24 trials for each cue condition. Participants were informed during the instructions at the beginning of the task that (1) the cue could appear in any color and (2) the cues were task-irrelevant and should be ignored because they would hurt performance. Thus, as in the previous experiments, any effect of the cue should occur in the face of a strong intention to ignore it.

5.2. Results and Discussion

Again, incorrect trials and outlier trials with RTs greater than 3 SDs above individual means were excluded from further analysis; this trimming resulted in the removal of approximately 3% of the total data. We collapsed across cue color and analyzed only data from the epoch following a color change using a two-factor ANOVA with cue color (novel vs. familiar) and cue validity (valid vs. invalid) as factors. The mean RTs appear in Fig. 8.10. The ANOVA revealed a significant main effect of cue color, $F(1,14)=3.1$, $p=0.03$, $\eta^2=0.28$, but not cue validity, $F(1,14)=1.3$, $p=0.26$. Importantly, we found an interaction between cue color and cue validity, $F(1,14)=6.4$, $p=0.02$, $\eta^2=0.31$. Specifically, a significant cuing effect was observed in the epoch following a novel color change, $t(14)=3.1$, $p<0.01$, but not in the epoch following a familiar color change, $t<1$, *n.s.*

When the cue color reverts to a previously viewed color in the familiar condition, no cuing (i.e., no capture) is evident. This lack of a cuing effect for the familiar color suggests that color specificity, not general novelty, is learned during attentional tuning. This suggests that participants represent distracters in a highly specific manner, coding information about their defining surface features, in this case color.

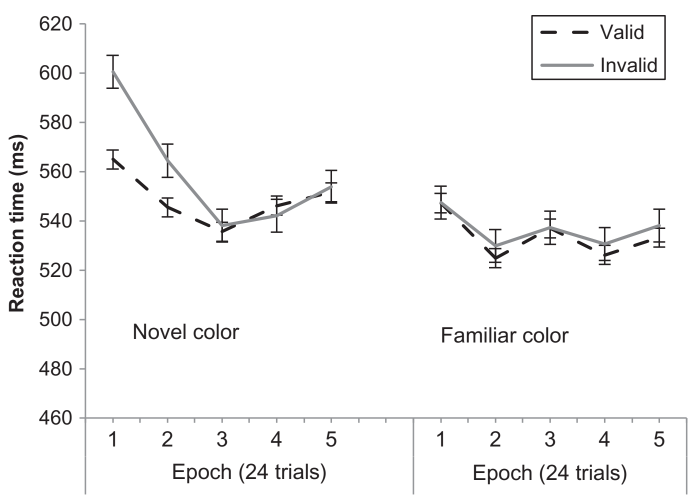

Figure 8.10 Response time results from experiment 4.

However, one could argue that these results instead indicate serial position effects in the amount of capture over time. Because the familiar color change always occurred following 360 trials of experience, it may simply be that color changes introduced following more extensive practice are less likely to affect capture. In order to rule out this possibility, we conducted a planned comparison on RTs from the epoch following the final color change, which in this case occurred 120 trials *after the* familiar color change (epoch 21). A significant cuing effect was observed following this change, $t(14)=2.3$, $p=0.04$, indicating that amount of practice has little effect on the ability of novel color changes to induce capture. Instead, experience with the color determines the presence or absence of a cuing effect. Taken together, these results indicate that the learned representations used to influence attentional capture in this task are highly feature-specific, with capture effects being sensitive to changes in surface features only when a participant has had no prior experience with the particular feature.

6. SUMMARY AND CONCLUSIONS

Attentional control, typically assayed via capture by a task-irrelevant stimulus, has been viewed as being either stimulus-driven or goal-driven, with ongoing, active debate between these theoretical alternatives. In an attempt to cut across this debate, we have proposed that attentional control is determined by experience with a task and its associated stimuli. With little experience, attentional control is more likely stimulus-driven, but as experience accrues, control shifts to becoming more goal-directed. Our account, *experience-based attentional tuning*, views stimulus-driven control and goal-driven control as lying on a continuum, instead of viewing them as dichotomous processing modes. The results of four experiments generally support experience-based attentional tuning by showing that contingent attentional capture—the hallmark measure of goal-driven attentional control—emerges with experience, with attention being driven by stimulus factors early in the task- and goal-driven guidance emerging later.

We would hasten to add that experience will not be the only factor that determines one's placement on the attentional control continuum depicted in Fig. 8.4. Although experience will move control from stimulus-driven to goal-driven, other factors might restrict the influence of experience, preventing control from becoming completely goal-driven. Perceptual load, or display complexity, is one such factor. As we discussed earlier, a task-irrelevant distracter will continue to draw attention in simple, uncluttered displays of low perceptual load, suggesting that attentional control never becomes fully goal-driven and able to exclude the irrelevant information. We would predict that experience nevertheless plays a role and that the distracter would draw more attention early in the task than later in the task. But, because of the low perceptual load of the displays, some degree of attention might mandatorily spill over to the distracter (as proposed by load theory; see Lavie, 1995), thereby limiting the emergence of full goal-driven control.

Both the current results and our previous findings (Vatterott & Vecera, 2012) appear consistent with the phenomenon of novel pop-out. Novel stimuli, such as an upside-down letter among upright letters, appear to have an attentional priority in visual search (Reicher, Snyder, & Richards, 1976). In later work, novel (i.e., unrepeated) words in four-word arrays produced greater localization accuracy than familiar (repeated) words (Johnston, Hawley, Plewe, Elliott, & DeWitt, 1990), suggesting that the novel word received an attentional priority. Although novel stimuli appear to be more likely to be attended in some situations, the connection between novel pop-out and our experience-dependent attentional tuning account is unclear. First, novel pop-out can be explained without appealing to attentional capture (Christie & Klein, 1996). Second, novel pop-out might reflect violations of expectancy (e.g., Horstmann, 2005), and such violations could be closely tied to trial-by-trial modulations of attentional control settings (e.g., Wolfe et al., 2003). Under our account, we would argue that individual trials provide attentional episodes or instances; this experience configures attention to optimize behavior and produces the fastest, most accurate responses possible. The attentional episodes reflect expectancies about the current task environment, and violations of the episodes produce nonoptimal behavior. In our experiments, this nonoptimality appears as attentional capture, but in other task environments, nonoptimality could have a different footprint (e.g., a large cost for changing a target's color; e.g., Maljkovic & Nakayama, 1994). We hypothesize that our results are produced by violations of attentional episodes and the expectancies that emerge from them, not novelty per se.

Our attentional tuning framework for attentional control finds broad support from recent electrophysiological studies of attention. One recent set of event-related potential (ERP) findings demonstrates that attention actively suppresses task-irrelevant distracters (Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2013). The distracter positivity, or Pd, component (see Hickey, Di Lollo, & McDonald, 2006, 2009) appears to reflect this suppression, with the Pd appearing as a more positive voltage contralateral than ipsilateral to a salient distracter. Irrelevant distracters appear to generate an "attend-to-me" signal that is then suppressed: these distracters do not appear to draw attention to themselves, as indexed by the N2pc component, although they do generate a Pd component, suggesting that they have been detected and suppressed (Sawaki & Luck, 2010, 2011). We hypothesize that the signal suppression reflected by the Pd component results from experience rejecting the distracter. Our account predicts that the distracter would initially capture attention, producing an N2pc; with experience, the distracter could be suppressed, causing the N2pc to disappear and the Pd to appear over the first several encounters with a distracter.

A second set of recent ERP findings indicates that attentional guidance by working memory is relatively short-lived and replaced with guidance by longer-term memories (Carlisle et al., 2011). When holding a target template in visual short-term memory, this target template generates a CDA component, thought to index the contents of visual memory (Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006; Klaver, Talsma, Wijers, Heinze, & Mulder, 1999; Vogel & Machizawa, 2004). When participants search for the same target over several trials, the CDA was reduced, suggesting a reduction in the role of visual short-term memory for maintaining the target template (Carlisle et al., 2011). As the CDA effect disappeared, another component, the P170, became more negative as a target was repeated (Woodman, Carlisle, & Reinhart, 2013). The P170 appears to reflect perceptual priming (Voss, Schendan, & Paller, 2010). Modulation of the P170 by target repetition might index the long-term memory representation of a target (Woodman et al., 2013), with more negative P170s corresponding to "old" (familiar) targets and more positive P170s elicited by "new" (novel) targets. The P170 component is particularly promising for our account as an index of the emergence of longer-term memories based on experience. If the P170 indeed reflects the contents or strength of long-term visual memory, then this component could be used to track not only target representations (Woodman et al., 2013) but also distracter representations (e.g., Vatterott & Vecera, 2012) and contextual influences on attentional control (Cosman & Vecera, 2013a, 2013b). We hasten to add, however, that substantially more work is needed to understand the P170. Other findings in this same latency range from similar electrode sites, which report differing results. Voss et al. (2010) reported that old items elicited early components that were more negative than those elicited by new items; however, Tsivilis, Otten, and Rugg (2001) found that *new* items elicited early components that were more negative than those elicited by a variety of old items. A more systematic study of the P170 will be critical to understanding how this component might relate to attentional control based on long-term memories acquired through experience.

One final point for discussion centers on the mechanisms that produce the learned distracter rejection that we have observed in the current experiments. Critically, a participant's intentions—that is, their explicit goal to search for a specific target—are insufficient to produce goal-driven control. Instead, as we have shown, goal-driven control emerges from trial-by-trial experience with distracter rejection. If trial-by-trial distracter rejection bears resemblance to other intertrial effects such as priming of pop-out, then distracter rejection might be the result of changing gains on target and distracter feature weights (e.g., Wolfe et al., 2003; also see Lee et al., 2009). Under such a view, later processes involving working memory or executive control might not be necessary for tuning optimal attentional control parameters. However, attentional control and capture are affected by later processes such as working memory and executive control. Visual search is disproportionately slowed when performing a secondary task that involves memory manipulation than one that involves memory maintenance (Han & Kim, 2004). Color singleton targets capture attention more strongly under a working memory load (Boot, Brockmole, & Simons, 2005). Perhaps, most relevant, irrelevant color singleton distracters are more likely to capture attention and slow responses when participants are under a working memory load compared to no load (e.g., de Fockert et al., 2001; Lavie & de Fockert, 2005, 2006). This latter finding suggests that working memory and executive processes might play a role in configuring attentional control. Whether these later processes affect the tuning itself or another process (e.g., the initial capture or attentional disengagement once captured) will require direct investigation.

As we noted at the outset, attention is a cognitive operation that we use extensively every day. Although attentional search appears effortless, deploying attention—that is, attentional control—has eluded complete understanding. By focusing on the role of experience and incremental, trial-by-trial learning on shaping optimal attentional control, we hope our framework can supersede accounts that are often thought to be mutually exclusive but might instead be complimentary modes of attentional control.

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