9-12-2014

Can Irrelevant Onsets Capture Attention? Searching for a Unified Model of Attention Capture

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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

Psychology

The University of New Mexico
Albuquerque, New Mexico

July 2014

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ABSTRACT

Can salient stimuli, such as abrupt onsets, capture attention? Some researchers consistently find that they do, regardless of the observer's current goals, whereas others consistently find the opposite. The present research begins with the observation that different theoretical camps consistently rely on different types of visual search: letter vs. color. In the present pre-cuing experiments, I directly compared these two approaches using identical stimulus displays, changing only the search dimension. The results were striking: letter search produced large cue validity effects, whereas color search produced negligible effects. Later experiments demonstrated a key role of search difficulty.   I tested several candidate theoretical explanations for this phenomenon. The results support a nonstrategic cost of capture account called the search time model. This dissertation helps to resolve a twenty-year debate about attention capture and has profound implications for developing a comprehensive model of attention capture.

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Chapter 1

Introduction

Attention capture researchers are sharply divided on whether abrupt onsets can capture visual attention. Stimulus-driven theorists propose that onsets can capture attention, whereas goal-driven theorists propose that onsets do not. Puzzlingly, both camps consistently produce opposite results despite using nearly identical methods. For two decades, this puzzle has inspired numerous attempts at reconciliation, none of which appear to have been widely successful. The present thesis indicates that this discrepancy results from a subtle – and thus far overlooked – difference in methodology: search difficulty.

In Chapter 1, I review the literature on attention capture by abrupt onsets. In Chapter 2, I test the hypothesis that search dimension (letter vs. color) is responsible for the discrepant results between theoretical camps. In Chapter 3, I test the hypothesis that search difficulty is a key variable underlying the impact of search dimension. In Chapter 4, I describe several theoretical accounts that can explain the search-difficulty-by-cue-validity interaction. In Chapter 5, I test whether the search-difficulty-by-cue-validity interaction stems from strategic adjustments, by seeing whether it requires foreknowledge of the upcoming search difficulty. In Chapter 6, I directly test the role of cued search item rejection in the search-difficulty-by-cue-validity interaction. In Chapter 7, I summarize the conclusions that can be drawn from this thesis.

Spatial Attention in Visual Processing

Our visual environments are complex and rich in detail. Our visual systems select only a small subset of this available information for deep, semantic processing (Broadbent, 1958; Lachter, Forster, & Ruthruff, 2004). This selection is accomplished by two mechanisms. The first, more obvious, mechanism is eye movement. We can adjust our gaze to aspects of a visual scene that seem most relevant to our goals, so that these aspects fall onto the fovea, a region of the retina densely packed with photoreceptors.

The other, more subtle, selection mechanism is *spatial attention*. Spatial attention, often called the "mind's eye," allows us to covertly shift our processing resources across a scene, even while the eyes are stationary (Eriksen & Hoffman, 1973; Posner, Nissen, & Ogden, 1978; Posner, 1980). Early studies of spatial attention relied on what is called a *cuing paradigm*. In one version of this paradigm, the participant indicates the identity of a target stimulus, which can appear in one of two locations. This target stimulus is preceded by a central cue, such as an arrow, pointing at a potential target location. This cue can either be valid (pointing to the target location), invalid (pointing to a different location than the target), or neutral (pointing to both locations or neither location). Importantly, in early cuing experiments, this cue is typically *predictive* of the target location – it was valid (e.g., 80%) more often than it was invalid (e.g., 20%). Thus, participants had incentive to voluntarily attend to these cues. Researchers found that participants identified the target more quickly when the cue was valid compared to when it was invalid. Because participants were fixated centrally on the display (as measured by an eye tracker), these results from the cuing paradigm were taken as clear evidence of selective attentional processes in vision.

Spatial attention is often likened to a spotlight that moves across a visual image, facilitating the perception of objects that it covers. It can be moved independently of eye movement (Horowitz, Fine, Fencsik, Yurgenson, & Wolfe, 2007). In fact, some evidence even suggests that shifts of spatial attention guide subsequent eye movement (Hoffman & Subramaniam, 1995). Spatial attention is imperative for performing a wide variety of daily activities. Tasks like searching for a friend in a crowd and even reading words on this page would be nearly impossible without spatial attention (Wolfe, 2007). Patients suffering from hemispatial neglect, a neuropsychological condition primarily affecting spatial attention, suffer severe impairments in day-to-day functioning. These patients completely ignore stimuli in the contralesional visual field, leading to persistent errors, such as finishing only half of their dinner plate, forgetting to groom one side of their body, or colliding into objects on the neglected side (Vallar, 1998).

Involuntary Attention Capture

There is a key distinction between *voluntary (endogenous)* and *involuntary (exogenous)* shifts of spatial attention. Many early cuing studies of visual attention (as those discussed in the previous section) demonstrated that people can execute voluntary (endogenous) shifts of spatial attention (e.g., Posner, 1980). For example, you might voluntarily monitor an unsavory stranger on a busy street, while trying to avoid eye contact. These willful, deliberate shifts of spatial attention are relatively slow (200-400 ms; Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009).

Some shifts of spatial attention, however, happen against the will of the viewer. For example, while driving, a flashing police beacon might "capture" your attention, even though you are busy trying to search for a restaurant. These *involuntary* (*exogenous*)

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shifts of attention happen rapidly (35-100 ms; Horowitz et al., 2009) and have the potential to draw our attention toward or away from important visual information.

From annoying internet pop-up advertisements to a lost penny gleaming in the sun, our visual systems are constantly bombarded with salient stimuli. Understanding involuntary attentional capture would have an enormous impact on our daily lives, especially in situations, where a person must be visually warned of some imminent danger. For example, capture research could inform civil engineers on how to warn drivers of upcoming road hazards. It could help aircraft designers make more effective cockpit displays, warning pilots of component failures or other in-flight risks. It could even help software designers visually warn users of an important message (e.g., on a smart phone). The applications of attention capture research are nearly endless.

Involuntary Capture by Abrupt Onsets: Stimulus-Driven or Goal-Driven?

Attention capture researchers generally align with one of two very different theoretical positions: *stimulus-driven* and *goal-driven*. Stimulus-driven theories claim that salient features automatically guide spatial attention, regardless of our goals (Theeuwes, 2010; Yantis, 1993). For example, a shopper searching for a red box of cereal would be distracted by a neon green soda display. Thus, these theories predict persistent and uncontrollable distraction. Several salient features have been proposed to capture attention, but perhaps the most widely agreed upon are abrupt onsets: objects appearing suddenly in a visual scene (Franconeri & Simons, 2003; Yantis & Jonides, 1984).

In a seminal study of onset capture, Yantis and Jonides (1984) used what is now called the *irrelevant feature paradigm* (Figure 1a). Participants searched an array of

either 2 or 4 letters and reported whether a target letter was present or absent. Before the

search array appeared, 1 or 3 premasks appeared. Thus, when the target was present, it

(a) Irrelevant Feature Paradigm (Yantis & Jonides, 1984)

Shallower search slopes for onset targets than offset targets indicates attention capture.
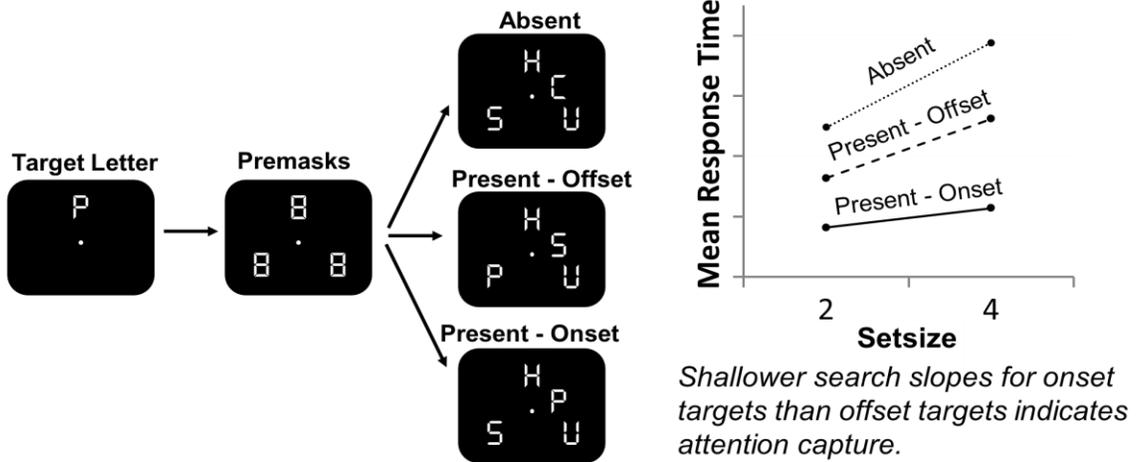
(b) Precuing Paradigm (Folk, Remington, & Johnston, 1992)

Absent validity effects from onset cues indicates no attention capture when searching for color
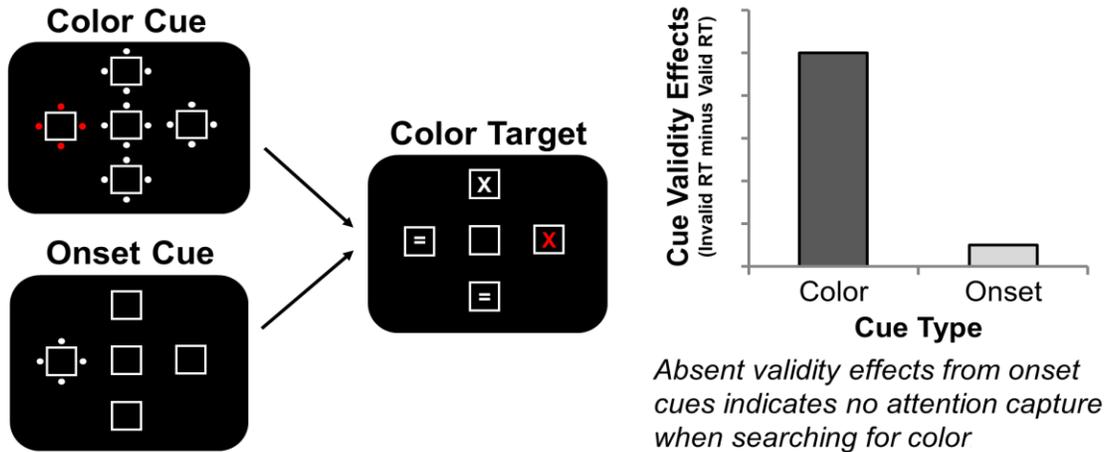
Figure 1. A comparison of the irrelevant feature paradigm and the pre-cuing paradigm. Both are frequently used to study attention capture by irrelevant abrupt onsets, yet consistently produce the opposite results. Whereas the irrelevant feature paradigm shows evidence of capture by irrelevant onsets based search slopes, the precuing paradigm consistently shows no capture by irrelevant onsets based on the cue validity effect.

could appear in an old location (offset) or a new location (onset). The key finding was

that *search slopes* (setsize-by-reaction-time functions) were shallow for onset targets, but steep for offset targets. The authors concluded that onset targets automatically captured attention, eliminating the need for visual search. Subsequently, several researchers, typically utilizing this irrelevant feature paradigm, have also argued that irrelevant onsets capture spatial attention (Franconeri, Hollingworth, & Simons, 2005; Franconeri, Simons, & Junge, 2004; Franconeri & Simons, 2003; Hollingworth, Simons, & Franconeri, 2010; Jonides & Yantis, 1988).

Not all researchers, however, agree that irrelevant onsets capture attention. Unlike stimulus-driven theories, goal-driven theories claim that only stimuli that match what you are looking for capture attention. For example, if a shopper is searching for a red cereal box, other red items (e.g., a chili pepper) will capture attention, but non-red items (e.g., a yellow caution sign) will not. Thus, goal-driven theories predict that viewers can block distraction by salient-but-irrelevant items, but will fail to notice important, unexpected events (e.g., a waving gorilla; Simons & Chabris, 1999).

Folk, Remington, and Johnston (1992) explored how a viewer's goals modulate attention capture using a *precuing paradigm* (Figure 1b). Participants searched for a target and reported its identity ("X" or "="). This search display was preceded by a salient cue, which could be either red or an abrupt onset. The cue location was chosen at random and was thus nonpredictive of the upcoming target location (it appeared at the target location on $1/n^{th}$ of trials, where *n* is the set size). If this cue captures attention, participants should respond more slowly when it is invalid (at a nontarget location) than valid (at target location), called a *cue validity effect*.

Interestingly, cue validity effects were found only for cues that matched the target-finding feature. For example, when the target was red, red cues produced validity effects but white onset cues did not. They argued that any stimulus that mismatches the viewer's attentional set will be unable to capture attention, no matter how salient. Subsequently, many studies have supported this goal-driven account of onset capture, typically also relying on the precuing paradigm (Burnham, 2007; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Folk & Remington, 1998; Lien, Gemperle, & Ruthruff, 2010; Lien, Ruthruff, Goodin, & Remington, 2008; Lien, Ruthruff, & Johnston, 2010; Noesen, Lien, & Ruthruff, 2014).

How can these two theoretical camps consistently produce *opposing* results, and reach opposing conclusions, despite using similar methods? For example, Folk et al. (1992) argue that irrelevant abrupt onsets cannot capture attention, "…abrupt [onsets] (i.e., dynamic discontinuities) do not involuntarily summon spatial attention…We have also shown that, contrary to the conclusions of previous research (e.g., Jonides & Yantis, 1988), conditions exist in which properties other than abrupt [onsets] (i.e., static discontinuities) do involuntarily summon attention. Thus, we have shown that the occurrence of involuntary attention shifts is systematically contingent on the relationship between the stimulus properties of the cue and the properties required to locate the target." (p. 1041). On the other hand, Yantis (1993), in response to Folk et al. (1992), concludes from a literature review that irrelevant onsets can capture attention, "The evidence suggests, then, that [abrupt onsets] alone can capture attention in the absence of a deliberate attentional set for that attribute…the evidence reported by Folk et al. does not

unconditionally corroborate the contingent-capture…[hypothesis] as stated in their article." (p. 680)

This debate, which began over 20 years ago, continues today. For example, Hollingworth, Franconeri, and Simons (2010) argue that "…salient stimuli can recruit attention independently of, or even in opposition to, an observer's goals…Under the transient hypothesis…attention is drawn by the abrupt sensory transients created when an object undergoes a salient change." (p. 1298). However, Lien, Ruthruff, Goodin, and Remington (2008) conclude that onsets cannot capture attention, "…the present data support the extreme hypothesis that attentional capture by an object depends purely on the observer's intentions, not the abruptness of the onset" (p. 528). These strikingly disparate conclusions reveal the isolation of stimulus-driven and goal-driven camps.

Previous Reconciliations

Researchers have suggested several possible reconciliations for the discrepant results, including the attentional window account (Theeuwes, 1991, 1992), rapid disengagement (Theeuwes & Burger, 1998; Theeuwes, 2010), displaywide attentional sets (Burnham, 2007; Gibson & Kelsey, 1998), and stimulus rarity (Neo & Chua, 2006). However, none have achieved a consensus. Next, I will briefly review these arguments and why they do not adequately explain the discrepant results with abrupt onsets.

Attentional Window Account

According to Theeuwes (1991), participants are more likely to be captured by onsets when spatial attention is spread diffusely across the visual scene (see also Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). In other words, when the attentional "window" is diffuse (i.e., covers the entire search display), spatial attention will "zoom

in" on the most salient stimulus within the window. When the attentional window is focused (i.e., the salient item falls outside of the window), however, spatial attention can exert top-down control to avoid the salient item. In other words, this account predicts that a salient stimulus will capture attention if and only if it falls within the attentional window. Thus, abrupt onsets can capture attention if the attentional window is spread diffusely across the entire search display.

There are several reasons to doubt this account. First, parallel search – involving a wide attentional window that includes the entire display – is not <u>sufficient</u> to produce capture. Many researchers find no evidence of stimulus-driven capture with seemingly parallel (or "easy") visual search (e.g., Folk et al., 1992; Gaspelin, Ruthruff, Jung, Cosman, & Vecera, 2012). For example, Gaspelin et al. (2012) had participants search displays for a letter target and ignore an irrelevant flanker. On some trials, search was very efficient (an E vs. H target amongst a homogenous set of O distractors). Compatibility effects were not enhanced by making the flanker a color singleton, suggesting that color singletons do not always capture attention, even with a "diffuse" attentional window. Second, a diffuse attentional window is not <u>necessary</u> to produce capture. Abrupt onsets often capture attention under difficult "serial" visual search. For example, Gaspelin, Ruthruff, Lien, and Jung (2012) had participants perform a precuing paradigm where they searched for an orange target letter and reported its identity (T vs. L). In the serial search condition, the distractor letters were close in color space to the orange target (e.g., yellow and red). In the parallel search condition, the distractor letters were far in color space from the target color (e.g., blue and green). In two separate experiments, validity effects were larger under serial search than parallel search (for other

evidence of capture by abrupt onsets under seemingly serial search, see Franconeri et al., 2005, 2004; Franconeri & Simons, 2003; Hollingworth et al., 2010; Jonides & Yantis, 1988; Lamy & Egeth, 2003; Yantis & Jonides, 1984).

Also, the attentional window account relies heavily on evidence from the additional singleton paradigm, which has certain undesirable properties (Theeuwes, 1992, 1994, 2004, 2010). Some evidence suggests that the primary measure of capture in this paradigm (present-absent costs) does not necessarily reflect actual attentional capture. For example, Folk and Remington (1998) have convincingly argued that the present-absent costs in this paradigm reflect a slowing of the decision about where to move attention (called *filtering costs;* Kahneman, Treisman, & Burkell, 1983; Treisman, Kahneman, & Burkell, 1983). Participants searched for a target of a specific color and identified it (X vs. =). Precues could either be a relevant color singleton (matched the target color) or an irrelevant color singleton (mismatched the target color). Even though irrelevant color singletons did not produce cue validity effects, they did increase overall reaction time compared to cue absent trials. The authors concluded that although irrelevant color singletons did not capture attention (as evidenced by cue validity effects), they did slow the decision about where to move spatial attention (for other evidence of filtering costs, see Becker, 2007).

Even if we assume that capture effects in the additional singleton paradigm reflect true capture, other evidence suggests the capture effects observed in the additional singleton paradigm may not be truly stimulus-driven. Bacon and Egeth (1994) have argued that, when the target is made highly salient, participants may search for any singleton (called *singleton detection mode*). When participants searched displays for a

circle target amongst a set of homogenous diamonds (i.e., when the target was a shape

singleton), an irrelevant color singleton slowed overall search when it was present

(similar to Theeuwes, 1994). However, when the target was a circle amongst a

heterogeneous set of triangles and diamonds (i.e., when the target was not a shape

singleton), the color singleton distractor no longer slowed overall reaction time. These

authors argued that color singletons can only capture attention when participants have an

attentional set attuned broadly for any type of feature singleton (for further evidence of

singleton detection mode, see Egeth, Leonard, & Leber, 2010; Lamy & Egeth, 2003;

Lamy & Tsal, 1999; Leber & Egeth, 2006; Pashler, 1988)

To review, much empirical evidence troubles the attentional window account.

The theory relies heavily on support from studies using color singletons in the additional

singleton paradigm. The theory frequently makes incorrect predictions for results in

other paradigms (e.g., the precuing paradigm) and other salient stimuli (e.g., abrupt

onsets). Moreover, it is unclear whether the capture effects observed in the additional

singleton paradigm (1) reflect actual movements of spatial attention (not filtering costs),

and (2) are not a result of some broadened goal (i.e., singleton detection mode).

Rapid Disengagement

According to this rapid disengagement account, spatial attention is always

captured by salient stimuli, but rapidly disengages when the salient item does not match

the attentional set (Theeuwes, 2010). Thus, according to this account, abrupt onsets do

capture spatial attention in the precuing paradigm used by goal-driven theorists.

However, the 150-ms SOA between the cue and search display, gives participants time to

quickly disengage from the irrelevant onset cues. The 0-ms SOA of the onset and search

display in the stimulus-driven irrelevant feature paradigm does not provide ample time for such disengagement.

There is, however, reason to doubt the rapid disengagement hypothesis (at least as posed by Theeuwes, 2010; see our Cue Location Rejection account in Chapter 4 for a feasible adaption). First, the disengagement account predicts that shortening the SOA between the search display and cue frame will prevent attention from disengaging from irrelevant onset cues. The inability to disengage from cues before the search display will thus revive validity effects from irrelevant abrupt onsets. Chen and Mordkoff (2007) did exactly this. Participants performed a precuing paradigm similar to Folk et al. (1992). In one condition, participants searched for a red target letter and reported its identity (X or =). This display was preceded by a cue display that was either a red cue or an abrupt onset (see Figure 1B). Critically, the SOA between the cue display and search display was 35 ms (instead of the previous 150 ms). Importantly, color cues showed validity effects while onsets cues did not. This study alone seems to rule out rapid disengagement, because participants would not have an opportunity to disengage from the onset cue before the search display appeared (involuntary shifts take 35-100 ms; Horowitz et al., 2009).

Second, rapid disengagement predicts enhanced processing of salient-but-irrelevant cues, even in the absence of validity effects. Folk and Remington (2006) had participants perform a precuing paradigm where they searched for a target letter of a specific color (green or red) and identified it (e.g., "X" vs. "="). Cues could either be a relevant color singleton (matched the target color) or an irrelevant color singleton (mismatched the target color). Critically, each cue had a foil (i.e., a potential target

identity) that could match (compatible) or mismatch (incompatible) the presented target identity. If spatial attention is captured by a cue, a compatibility effect should be present (even if spatial attention rapidly disengages from the cue). Thus, a disengagement account predicts compatibility effects for irrelevant cues, even in the absence of cue validity effects. Contingent capture theory, however, predicts compatibility effects only for relevant cues. Irrelevant cues should produce neither validity effects nor compatibility effects. Consistent with contingent capture theory, the authors found large compatibility effects for relevant color cues (28 ms) but no compatibility effects for irrelevant color cues (-1 ms). These findings again cast doubt on the rapid disengagement account.

In summary, several findings refute Theeuwes' rapid disengagement account of capture by onsets (for a direct debate of this account, see Theeuwes, 2010 vs. Folk & Remington, 2010). Thus, the disengagement account also seems inadequate to explain the opposing effects produced by the irrelevant feature paradigm and precuing paradigm.

<div align="center">**Displaywide Orienting Hypothesis**</div>

According to displaywide orienting accounts, all the evidence of onset capture is actually goal-driven capture. The attentional set, instead of reflecting features used to find the target, may reflect features used to find the search display. Gibson and Kelsey (1998) had participants perform a precuing task. Participants searched displays of red letters for a target letter (H vs U), which were preceded by an onset or red cue. Interestingly, both onset and red cues produced validity effects. They argued that participants established an attentional set for red onsetting items; although neither feature

could help the participants distinguish the target from distractors, they could help participants determine the beginning of the search display.

Additionally, Burnham (2007) performed a comprehensive review of the attention capture literature and argued that a displaywide account can best account for the all of the findings in the attention capture literature. In other words, according to Burnham, all capture by irrelevant abrupt onsets is dependent on a displaywide goal for any dynamic feature. Because nearly every capture task uses a search display defined by some dynamic event, it is logically tenable that participants developed some displaywide goal for a dynamic change (e.g., abrupt onsets).

There is reason to doubt that abrupt onsets only capture attention because of a displaywide attentional set. First, abrupt onsets can capture attention even when participants are discouraged from developing a displaywide goal for dynamic objects. For example, Franconeri et al. (2004) conducted a clever study where participants searched static displays of letters that remained present throughout four consecutive trials. At the beginning of each trial, a voice prompt denoted the identity of the target for that trial. Participants reported whether this target letter was backward or forward. Thus, the search array never appeared dynamically, meaning that participants had no incentive to develop a displaywide attentional set for dynamic stimuli. On half of the trials, one letter underwent a sharp contrast change. Participants still showed typical capture effects for this dynamic singleton, suggesting that it did capture attention (for similar study, see also Forster & Lavie, 2011). Also note that most studies that demonstrate onset capture specifically use premasks to prevent the participant from establishing a goal for newly

appearing items (e.g., Franconeri, Hollingworth, & Simons, 2005; Franconeri & Simons, 2003; Hollingworth et al., 2010; Jonides & Yantis, 1988; Yantis & Jonides, 1984)

Second, Burnham assumes that if a display dynamically appears (or sections of premasks disappear), participants will establish an attentional set for dynamic changes and dynamic changes will automatically capture attention. But such an account rampantly overpredicts capture. For example, several goal-driven theorists use target displays that are defined by an abrupt onset, yet find no evidence of capture by irrelevant onsets (e.g., Folk et al., 1992; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010). In my comprehensive examination, I compiled a list of 36 experiments in which the displaywide orienting hypothesis predicts capture, but capture was not found (from Burnham's tables). Of these 36 experiments, 32 predicted a displaywide attentional set for dynamic stimuli, but no capture by dynamic stimuli was found (i.e., 90%). Thus, a majority of Burnham's overpredictions involve abrupt onsets (but not static stimuli like color singletons).

In summary, displaywide theories are widely cited as support that abrupt onsets cannot capture attention in a truly stimulus-driven manner. However, some research suggests that abrupt onsets can capture attention, even when participants are discouraged from developing a displaywide attentional set for onsets. Additionally, other research suggests that abrupt onsets do not capture attention, even when participants should develop a displaywide attentional set for dynamic stimuli (e.g., Folk et al., 1992). So, there is reason to doubt that *all* evidence of capture by abrupt onsets is actually goal-driven, as Burnham (2007) has claimed.

The displaywide orienting hypothesis brings an important theoretical problem to light: it is difficult to determine what the attentional set is when a target is defined by multiple features. In contingent capture studies, the target is typically defined by a single feature (e.g., a specific color), leaving little ambiguity about the proposed attentional set (Folk, Remington, & Johnston, 1992; Lien, Ruthruff, Goodin, & Remington, 2008; Lien, Ruthruff, & Johnston, 2010). However, attentional sets are unclear when: (1) the target is defined by multiple properties (cf. singleton detection mode; Bacon & Egeth, 1994), or (2) participants are additionally assumed to establish attentional sets for displaywide properties. Perhaps the only reason some of these alternative goal-driven accounts appear to be successful (at least in the eyes of the supporting theorists) is that the theories allow too much flexibility in deciding what the attentional set will be.

Onset Rarity

Some researchers have claimed that only rarely-presented salient stimuli can capture attention (Cosman & Vecera, 2010; Horstmann, 2002; Neo & Chua, 2006). For example, Horstmann (2002) had participants search displays for an H or U for 48 trials. On the 49th trial, the target was made a color singleton. Interestingly, participants had smaller RTs for singleton targets than the previous nonsingleton targets. As another example supporting rarity accounts, Neo and Chua (2006) had participants search displays for a centrally-cued character (E vs. H). A frequent onset (75% of trials) at a distractor location did not increase overall RTs, but an infrequent onset (18.75% of trials) did slow overall search for the target.

Onset rarity, however, cannot explain the discrepant capture effects found by stimulus-driven and goal-driven camps. The frequency of onsets is typically similar

between studies that support onset capture (e.g., 50% in Franconeri & Simons, 2003, Experiment 1; 100% of trials in Yantis & Jonides, 1984, Experiment 1) and those that do not (e.g., 50% in Folk et al., 1992, Experiment 3; 50% of trials in Lien et al., 2008, Experiment 3).

Furthermore, drastically reducing the frequency of onsets does not cause them to produce capture effects in the precuing paradigm. For example, Noesen, Lien, and Ruthruff (2014) had participants search displays for a specific colored letter (e.g., red) and identify it (T vs. L). On 20% of trials, the cue display contained a relevant color cue and an abrupt onset cue at different locations. The irrelevant abrupt onset cue did not disrupt cue validity effects from relevant color cues, suggesting that it did not capture attention (see also Lien, Ruthruff, and Johnston, 2010).

To summarize, the rarity account is insufficient to resolve the discrepant findings with abrupt onsets. First, both camps do not use rare stimuli (usually the onset is present on at least 50% of trials). Second, making onsets rare in the precuing paradigm used by goal-driven theorists does not increase capture by abrupt onsets (Noesen et al., 2014).

Conclusion

For the past twenty years, researchers have debated how spatial attention is involuntarily guided (i.e., "captured). Specifically, there is considerable disagreement as to whether salient abrupt onsets (i.e., flashing items) can automatically capture attention. Puzzlingly, both camps produce opposing results. Stimulus-driven theorists consistently find robust capture effects for irrelevant abrupt onsets, whereas goal-driven theorists consistently find none. There have been several proposed reconciliations for the competing accounts of onset capture (e.g., attentional window account, rapid

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disengagement, displaywide orienting, and onset rarity), but none have been widely

accepted. In the next chapter, I will instead propose a new reconciliation to the onset

capture debate.

Chapter 2

The Role of Search Dimension

In the current thesis, I follow a different lead from previous research that has apparently been overlooked: search dimension. In the irrelevant feature paradigm, participants typically search for a target defined by letter shape – this paradigm typically produces onset capture. In the precuing paradigm, however, participants typically search for a target defined by some simple feature dimension such as color – this paradigm typically produces no onset capture. Could the decades of puzzling empirical discrepancies be due merely to a simple, unintentional confound between the different paradigms?

There are several theoretical implications of this hypothesized search dimension effect, which I will discuss later in this thesis. But, before delving into them, it is important to first firmly establish that search dimension is a key factor causing the discrepant results in the onset capture literature. In the first part of this chapter, I report a brief literature review that suggests search dimension (letter vs. color) is an important determinant of onset capture. Note that these search dimensions have never been compared directly. So, in Experiments 1 through 3, I conduct new experiments to directly compare letter and color search using identical stimuli and identical paradigms.

Literature Review

I first assessed this search dimension hypothesis by reviewing the onset capture literature. With the search terms "onset *AND* attention capture", "contingent capture *AND* attention capture", and "new object AND attention capture", PsycINFO search

returned 120 unique articles. From these articles, 43 individual experiments met the

inclusion criteria: (1) assessed attention capture, (2) used abrupt onsets as distracting

stimuli, (3) used a target clearly defined by letter shape or color, and (4) used cue validity

effects or search slopes as an index of capture. I then classified each experiment (see the

Appendix) as demonstrating onset capture (yes vs. no, as reported by the authors) and

search dimension (color vs. letter).

     The results, shown in Table 1, are remarkable: almost all studies demonstrating

capture by onsets used letter search, whereas almost all studies demonstrating no capture

by onsets used color search, $\chi^2 = 19.6$, $p < .001$. In other words, 73% of studies showing

no capture by abrupt onsets used color search and 92% of studies showing capture by

abrupt onsets used letter search. This result highlights the isolation of theoretical camps

– each uses differing search dimensions to support their conclusions.

Table 1

Studies Classified by Observed
Onset Capture and Search
dimension.

Search Dimension	Onset Capture?	
	No	Yes
Color	11	2
Letter	4	25

     The literature review suggests that search dimension can explain the ongoing

discrepancy, but is inconclusive because there are many confounded variables. No

previous study has directly compared these two search dimensions (nor, to my

knowledge, even suggested that it has an impact, or that it systematically varies between camps). Therefore, to test this hypothesized empirical generalization, I used a precuing paradigm in which I cleanly manipulated search dimension, while holding the paradigm and other extraneous variables constant.

Experiment 1

Participants searched for a target in a display of colored letters and reported its identity (E vs. H). In *letter-search* blocks, the target could be found only by letter shape. In *color-search* blocks, the target could be found only by color. An irrelevant onset cue appeared on every trial.

Method

Participants. Forty-two undergraduates from the University of New Mexico participated for course credit. Two participants were removed from the final analysis, one for having an abnormally slow RT and one for having abnormally high error rates (2.5 SDs above the group mean in both cases). In all experiments reported here, participants had normal color vision (as assessed by an Ishihara color vision test) and self-reported normal or corrected-to-normal visual acuity. Of the 40 remaining participants, the mean age was 20.8 years and 27 were female.

Apparatus. A personal computer displayed stimuli on 19-inch CRT monitors. Custom software created with E-Prime (https://www.pstnet.com/eprime.cfm) was used to design and present stimuli.

Stimuli. Letters were presented in a digital-clock font and were 1.9^o (width and height), based on an average viewing distance of 60 cm (see Figure 2). Each display contained one letter in green (RGB value of 0, 153, 0), red (255, 0, 0), blue (40, 40, 255),

and white (255, 255, 255). Placeholders were gray unfilled boxes (2.4^o in width and height). There were five rectangular placeholders (four at search locations and one at fixation),
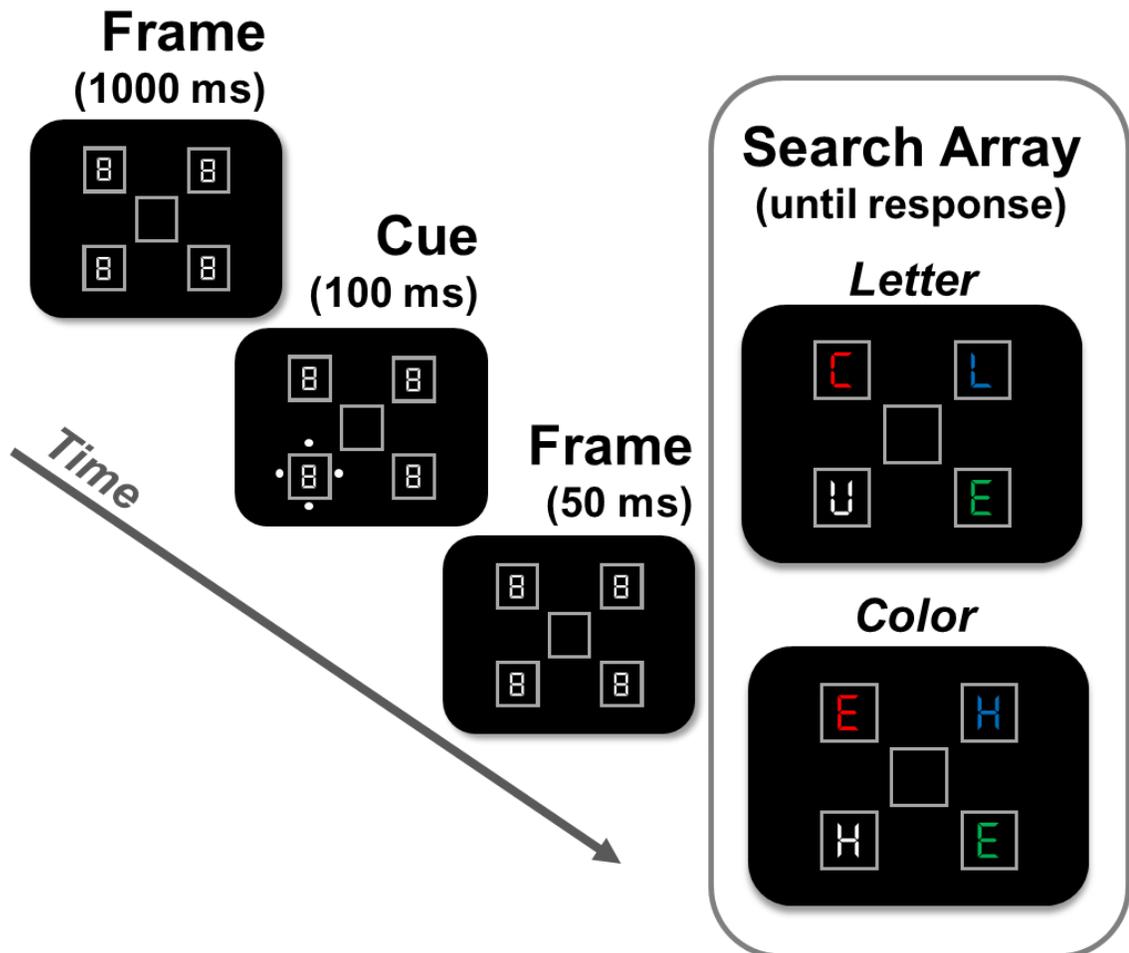
Figure 2. The stimulus display from Experiment 1. In letter-search blocks, the target color was chosen randomly but was the only item with a target identity (E or H). In color-search blocks, the target was always red and matched the shape of the distractors.

aligned at the corners of an imaginary square (10° in width and height). In the cue frame, four white dots ($.5^o$ in diameter) abruptly onset around one of the placeholders (forming an imaginary diamond 3.3^o in height and width). In every frame but the search frame,

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there were white figure 8's which deterred any displaywide attentional set for abrupt onsets.

Design. The experiment was divided into two halves. In *letter-search* blocks, the target letter color (green, blue, red, or white) was chosen with equal probability. Distractor letters were nontargets (J, L, S, C, or U), randomly chosen without replacement. In *color-search* blocks, the target letter was always red. Distractor letters were drawn from the possible targets (E or H; color and identity were randomly chosen with the restriction that each display contain two Es and two Hs). In all conditions, each target identity and location were chosen randomly. Onset precues were present on all trials and were nonpredictive of target location (valid 25% and invalid 75%). Search dimension order was counterbalanced across participants. Each search dimension condition consisted of 1 block of 32 practice trials followed by 4 blocks of 64 regular trials. In total, there were 10 blocks and 574 trials.

Procedure. Participants were instructed to locate the target and report its identity as quickly and accurately as possible by pressing the labeled "E" or "H" key (actual keys: z and m). Participants were also instructed that the precue was nonpredictive of the upcoming target location and, thus, should be ignored. Each trial began with a presentation of the five placeholders for 1000 ms. Then, the abrupt onset precue display appeared for 100 ms, followed by another presentation of the placeholders for 50 ms. The search array then appeared until response. If incorrect, participants heard a tone for 300 ms. Participants also received block-by-block feedback on their mean RT and accuracy. Participants were informed when search dimension changed (e.g., "The target will always be red in this part of the experiment").

Results

Trials with RTs greater than 2000 ms or less than 200 ms (0.4% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 2. Cue validity effects by search dimension condition are shown in Figure 3.

Table 2

Mean Reaction Time (ms) and Percent Error by Search Condition and Cue Validity for Experiment 1

	Color		Letter	
	RT	PE	RT	PE
Invalid	620.3 (13.3)	3.3%	783.4 (17.9)	3.1%
Valid	600.0 (12.4)	3.4%	746.2 (17.4)	3.0%
Validity Effect	20.3 (4.3)		37.2 (7.9)	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid. Standard errors are shown in parentheses.

RT analysis. A two-way within-subject analysis of variance (ANOVA) with the factors search dimension (letter vs. color) and cue validity (invalid vs. valid) was conducted on mean RTs. Participants responded faster in color-search blocks (610 ms) than letter-search blocks (765 ms), $F(1, 39) = 236.958$, $p < .001$, $\eta_p^2 = .859$, indicating that color search was easier than letter search. Participants also showed cue validity effects, overall, responding more quickly when the cue was valid (702 ms) than when it was invalid (673 ms), $F(1, 39) = 31.945$, $p < .001$, $\eta_p^2 = .45$. Importantly, cue validity effects were greater under letter search (37.2 ms) than color search (20.3 ms), $F(1, 39) = 4.785$, $p < .001$, $\eta_p^2 = .109$.
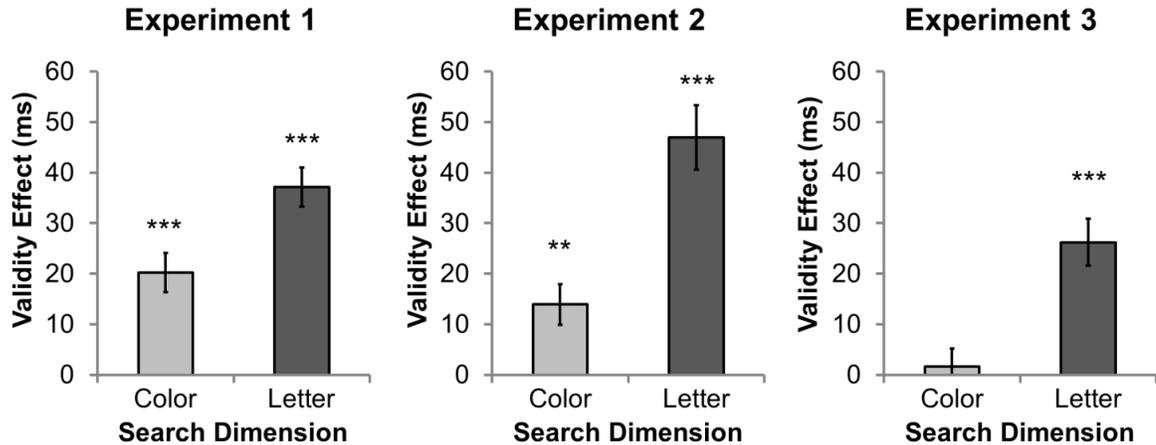
Figure 3. Cue validity effects (ms) by search dimension (color vs. letter) for Experiments 1 through 3. Error bars represent standard error of the mean based upon this within subject error for the search difficulty by validity interaction.

** $p < .01$ *** $p < .001$

Error rate analysis. The same ANOVA was conducted on mean error rates. All interactions and main effects were nonsignificant ($p > .10$).

Discussion

I directly tested the role of search dimension in capture by abrupt onsets. Consistent with the search dimension hypothesis, validity effects showed greater capture under letter search than color search. However, validity effects for abrupt onsets were present under color search ($M = 20.3$ ms, 95% CI[11.8, 28.7]). This finding is at odds with previous goal-driven studies which typically find small validity effects for abrupt onsets (-5 ms in Folk et al., 1992). One key difference between the current study and previous goal-driven precuing studies is the 8 premasks (in digital font). These figure-8 placeholders might actually *encourage* an attentional set for white, and thus cause validity effects by onsets under color search. These masks are frequently used in the irrelevant feature paradigm (which produces evidence of capture; Franconeri & Simons,

2003; Yantis & Jonides, 1984) but not the precuing paradigm (which produce no capture by onsets; Folk et al., 1992; Lien et al., 2008)

Experiment 2

In Experiment 2, we removed the 8 placeholders. Again, if search dimension is a critical determinant of onset capture, validity effects from irrelevant onset cues should be greater under letter search than color search.

Method

Apparatus, Stimuli, Design, and Procedure. This experiment is identical to Experiment 1, except that we removed the placeholders to discourage any attentional set for white.

Participants. Forty-eight undergraduates from the University of New Mexico participated for course credit (mean age: 21.4 years; 30 were female). In all experiments reported here, participants had normal color vision (as assessed by an Ishihara color vision test) and self-reported normal or corrected-to-normal visual acuity.

Results

Trials with RTs greater than 2000 ms or less than 200 ms (0.4% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 3. Cue validity effects by search dimension condition are shown in Figure 3.

RT analysis. I performed the same ANOVA from Experiment 1 on mean RTs. Participants responded faster in color-search blocks (601 ms) than letter-search blocks (682 ms), $F(1, 47) = 89.43$, $p < .001$, $\eta_p^2 = .656$, indicating that color search was easier than letter search. Participants also showed cue validity effects, overall, responding more

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quickly when the cue was valid (626 ms) than when it was invalid (657 ms), $F(1, 47) =$

56.32, $p < .001$, $\eta_p^2 = .545$. Importantly, cue validity effects were greater under letter

search (47.0 ms) than color search (13.9 ms), $F(1, 47) = 23.32$, $p < .001$, $\eta_p^2 = .332$. In

color-search blocks, validity effects for irrelevant onset cues were significant but small

($M = 13.9$ ms, 95% CI[6.1, 21.8]), generally consistent with goal-driven theories. In

letter-search blocks, however, validity effects were very large ($M = 47.0$ ms, 95% CI

[34.5, 59.4]), consistent with stimulus-driven theories.

Table 3
Mean Reaction Time (ms) and Percent Error by Search
Dimension and Cue Validity for Experiment 2

	Color		Letter	
	RT	PE	RT	PE
Invalid	608 (15.0)	4.5%	705 (16.6)	3.4%
Valid	594 (14.3)	4.3%	658 (16.7)	2.5%
Validity Effect	13.9 (4.0)		47 (6.4)	

Note. RT = Reaction Time; PE = Percent Error. Validity
effects were calculated as invalid minus valid. Standard
errors are shown in parantheses.

Error rate analysis. The same ANOVA was conducted on mean error rates.

Participants made more errors in color-search blocks (4.4%) than letter-search blocks

(2.9%), $F(1, 47) = 22.407$, $p < .001$, $\eta_p^2 = .323$. Participants also made more errors on

invalid trials (3.9%) than valid trials (3.3%), $F(1, 47) = 4.835$, $p = .033$, $\eta_p^2 = .093$. The

interaction between cue validity and search dimension was nonsignificant, $F(1, 47) =$

2.731, $p > .10$, $\eta_p^2 = .055$.

Discussion

I directly tested the role of search dimension in capture by abrupt onsets. Essentially, I replicated the key findings from both theoretical camps within a single experiment: capture effects were large with letter search (47.0 ms) and small with color search (13.9 ms). Hence, search dimension could account for the puzzling empirical discrepancies between previous studies.

Experiment 3

I replicated Experiment 2 with several improvements: (1) the search array duration was shortened to prevent eye-movement, (2) white letters were changed to yellow to prevent a possible displaywide attentional set for the white onset cues, and (3) distractor letters were identical in both search conditions.

Method

Participants. Forty-four undergraduates from the University of New Mexico participated for course credit. Two participants were excluded from analysis due to high error rates (more than 2.5 SDs above the group mean). Of the remaining 42 participants, the mean age was 19.4 years and 27 were female.

Apparatus, Stimuli, Design, and Procedure. All methods were similar to those of Experiment 2 except for a few key changes (see Figure 4). First, to prevent eye movement to the target, the search array duration was shortened to 100 ms, so that the total time between the abrupt onset and the target offset was 250 ms. After the search array, a black screen appeared until response. Second, to prevent any displaywide attentional set for white (the color of the onset dots), we no longer allowed the target to be white within letter-search blocks (Burnham, 2007; Gibson & Kelsey, 1998). White

letters were changed to yellow (RGB value: 255, 205, 0). Finally, we addressed the

concern that, in Experiment 1, distractor letters differed between search conditions (Es

and Hs in color search, but nontarget letters in letter search). To ensure that observed

differences in capture were not due to perceptual differences between displays,

Experiment 3 used the exact same distractor letters in both search conditions (J, L, S, C,

and U). Because of this change, participants were no longer forced to search for red (they

could instead search for E/H); however, they should nevertheless continue to do so

because color search is much easier than letter search (see Experiment 1).
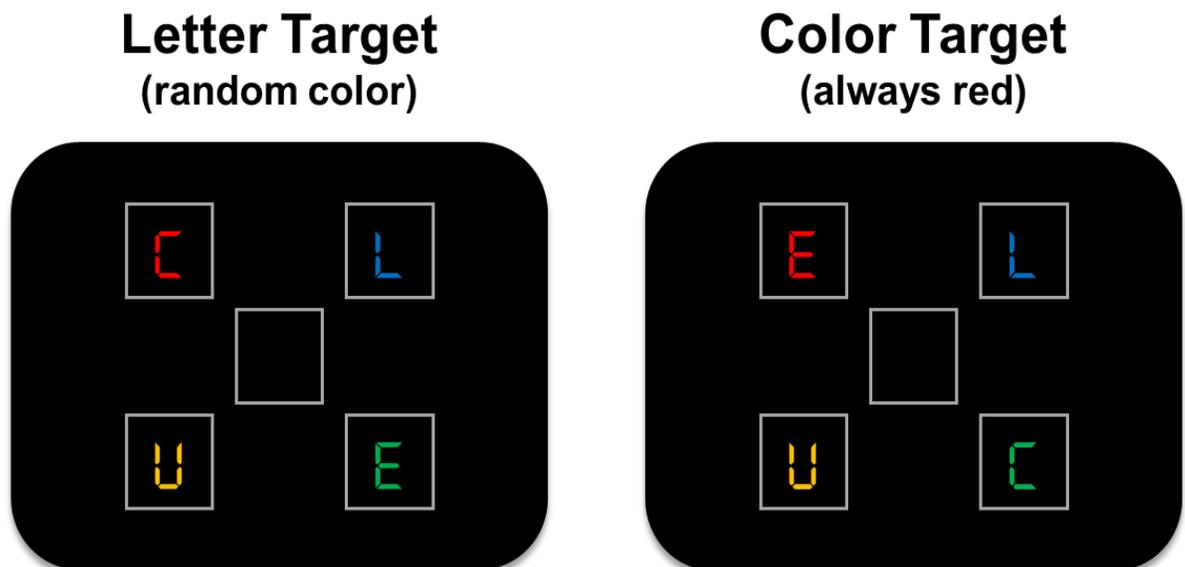
Figure 4. The stimulus displays used in Experiment 3. In letter-search blocks, the target
color was selected randomly. In color-search blocks, the target was always red.

Results

Trials with an RT less than 200 ms or greater than 2000 ms (0.4% of trials) or an

incorrect response were excluded from RT analyses. The resulting mean RTs and error

rates are shown in Table 4. Cue validity effects by search dimension condition are shown

in Figure 3.

RT analysis. I performed the same ANOVA from Experiment 1. Participants responded more quickly in color-search blocks (535 ms) than letter-search blocks (645 ms), $F(1, 41) = 134.0$, $p < .001$, $\eta_p^2 = .766$, indicating that color search was easier than letter search. Participants also responded more quickly when the cue was valid (583 ms) than when it was invalid (597 ms), $F(1, 41) = 18.76$, $p < .001$, $\eta_p^2 = .314$. Importantly, cue validity effects were greater in letter-search blocks (26.2 ms) than color-search blocks (1.6 ms), $F(1, 41) = 22.08$, $p < .001$, $\eta_p^2 = .350$. That is, color search produced no cue validity effects ($M = 1.6$ ms, 95% CI [-5.4, 8.6]), whereas letter search produced large cue validity effects ($M = 26.2$ ms, 95% CI [17.1, 35.3]).

Table 4
*Mean Reaction Time (ms) and Percent Error by Search
Dimension and Cue Validity for Experiment 3.*

	Color		Letter	
	RT	PE	RT	PE
Invalid	535 (9.1)	4.3%	659 (15.6)	7.6%
Valid	534 (9.4)	4.4%	632 (15.3)	6.8%
Validity Effect	1.6 (3.6)		26.2 (4.6)	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid. Standard errors are shown in parentheses.

Error rate analysis. The same ANOVA was conducted on mean error rates. Participants committed more errors in letter-search blocks (7.2%) than color-search blocks (4.4%), $F(1, 41) = 18.13$, $p < .001$, $\eta_p^2 = .307$. Participants also made more errors on invalid trials (6.0%) than valid trials (5.6%), $F(1, 41) < 1$, $p > .10$, $\eta_p^2 = .023$. The interaction of cue validity and search dimension was nonsignificant, $F(1, 41) = 1.94$, $p > .10$, $\eta_p^2 = .045$.

Discussion

With several design improvements, Experiment 3 replicated the finding of large cue validity effects for letter search (26.2 ms) but not for color search (1.6 ms). This finding again demonstrates the importance of search dimension, which can account for previously observed discrepancies in attention capture effects by irrelevant onsets.

General Discussion

Even after two decades of research, attention researchers still disagree as to whether abrupt onsets can automatically capture attention (Folk et al., 1992; Franconeri & Simons, 2003; Lien et al., 2008; Yantis & Jonides, 1984). The inability to predict attention capture is stalling research in related fields of visual cognition. For example, it is difficult to predict which items in a visual scene will receive search priority, or to design visual warning signals for real world applications (e.g., cockpit displays). The unresolved debate has led some researchers to abandon purely stimulus-driven or goal-driven models altogether (Awh, Belopolsky, & Theeuwes, 2012; Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010).

Here, I investigated whether a seemingly innocuous difference between paradigms – search dimension – can explain the discrepant results. As indicated by our literature survey, stimulus-driven theorists typically use letter search, whereas goal-driven theorists typically use simple feature search (e.g., color). However, no previous research has directly investigated the role of search dimension in onset capture.

I found that search dimension strongly modulates onset capture. Combining Experiments 1 through 3, letter search produced large capture effects ($M = 37.3$ ms, 95% CI [29.9, 44.6]), consistent with results reported by stimulus-driven theorists using the

irrelevant feature paradigm. Color search, however, produced small capture effects ($M = 8.2$ ms, 95% CI [0.2, 16.6]), consistent with results reported by goal-driven theorists using the precuing paradigm. Although several researchers have speculated that the other camp's paradigm is flawed (e.g., Belopolsky, Schreij, & Theeuwes, 2010; Folk & Remington, 2010, 1998; Theeuwes, 2010; Yantis, 1993), I propose that the paradigm (precuing vs. irrelevant feature) is actually unimportant. Rather, our results show that the differing capture results can instead be attributed to differences in search dimension.

Evidence Against the Rarity Account

The current results provide further evidence against the rarity accounts of attention capture, which posit that only infrequent onsets can capture attention (e.g., Horstmann, 2002; Neo & Chua, 2006). In the current study, irrelevant onsets were presented on 100% of trials, yet still managed to produce robust validity effects under difficult search. Thus, these findings suggest that rarity is not necessary to produce capture results by abrupt onsets. Furthermore, previous studies suggest that rare onsets (e.g., 10% of trials) do not always capture attention (Noesen et al., 2014). In summary, the rarity hypothesis can be rejected as a viable account of discrepancies in onset capture.

Implications for Philosophy of Science

It is fascinating that the large impact of search dimension went unnoticed for so long and that each camp has consistently relied on the particular search dimension that supports its own theory. This may be an instance of an important philosophy-of-science issue: researchers tend to favor methods that support their own theories and tend to avoid methods that disconfirm them (confirmation bias). Researchers should attempt to falsify

their theories, rather than to confirm them (i.e., scientific progress via falsification, Popper, 1961).

Chapter 3

Search Dimension vs. Search Difficulty

In Experiments 1 through 3, a <u>difficult</u> letter search increased capture effects by irrelevant abrupt onsets, relative to an <u>easy</u> color search. Because search dimension (color vs. letter shape) and search difficulty (easy vs. difficult) were confounded, it is unclear which variable is responsible for modulating validity effects from irrelevant abrupt onsets.

Experiment 4A

In this experiment, I held the search dimension constant (always letter search) but manipulated search difficulty. The search dimension account predicts that cue validity effects should be equal across difficulty conditions (search dimension is always the same). The search difficulty account predicts that cue validity effects should be greater under difficult search than easy search.

Method

Participants. Fifty-six undergraduates from the University of New Mexico participated for course credit (mean age of 20.2 years; 37 were female).

Apparatus, Stimuli, Design, and Procedure. All methods were similar to those of Experiment 3 except for one key change (see Figure 5). The target was always defined by letter shape. In the *difficult letter-search* condition, the target (E or H) was present amongst heterogeneous distractor letters (as in Experiments 1 and 2). In the *easy letter-search* condition, however, the target appeared amongst a homogenous set of target-dissimilar distractors (O's).
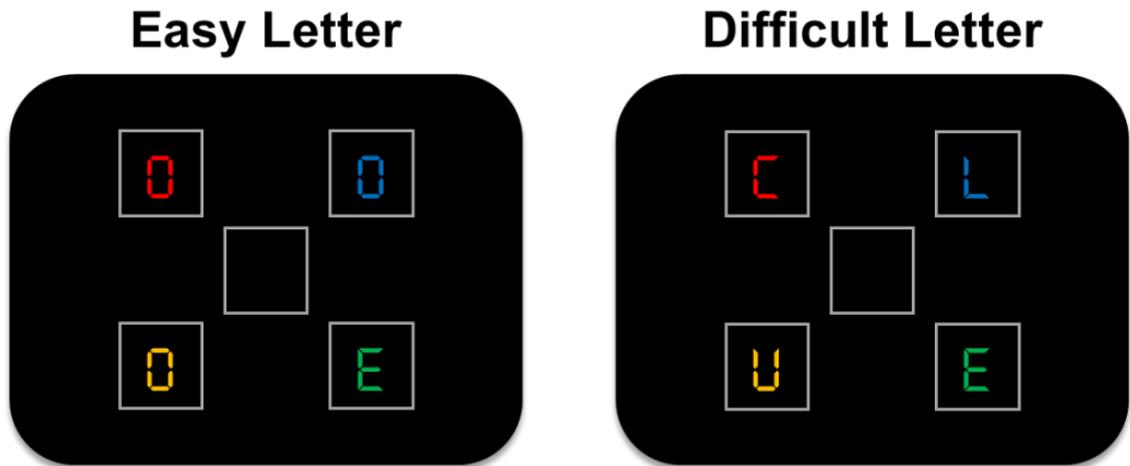
Figure 5. Stimulus displays for Experiment 4A. The target always appeared as a random color. In the easy condition, the target "popped out" from a homogenous set of Os. In the difficult condition, the target was presented amongst heterogenous target-like distractors.
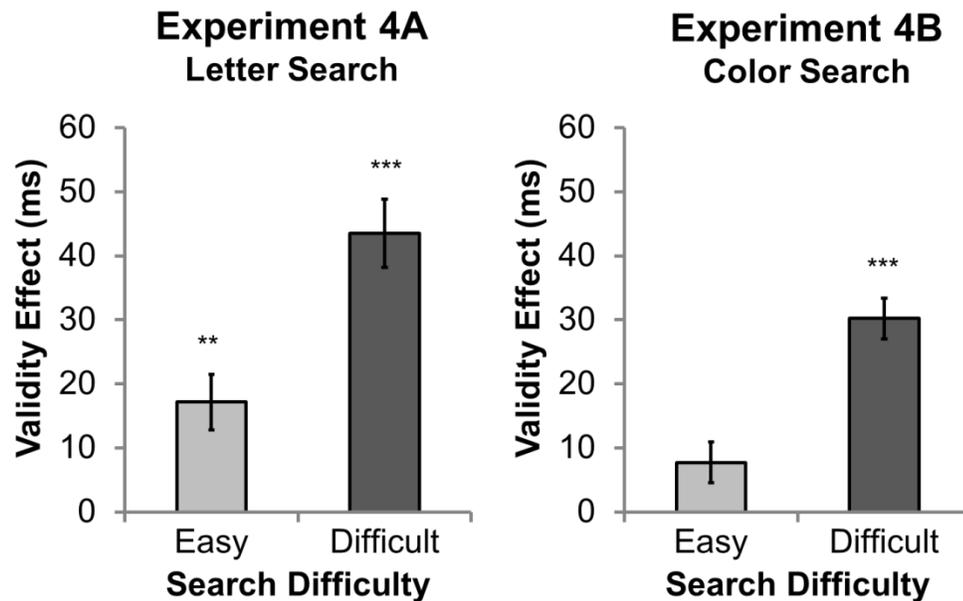
Figure 6. Cue validity effects (ms) by search difficulty (easy vs. difficult) in Experiment 4A (letter search) and 4B (color search). Error bars represent standard error of the mean based upon this within subject error for the search difficulty by validity interaction.

** *p* < .01   *** *p* < .001

Results

Trials with an RT less than 200 ms or greater than 2000 ms (0.4% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 5. Cue validity effects by search dimension condition are shown in Figure 6.

RT analysis. I performed a two-way within-subjects ANOVA on mean RTs with the factors search difficulty (easy vs. hard) and cue validity (invalid vs. valid). Participants responded more quickly in the easy search condition (574 ms) than difficult search condition (657 ms), $F(1, 55) = 92.99$, $p < .001$, $\eta_p^2 = .628$. Participants also responded more quickly when the cue was valid (600 ms) than when it was invalid (630 ms), $F(1, 55) = 69.04$, $p < .001$, $\eta_p^2 = .557$. Importantly, cue validity effects were greater in the difficult search condition ($M = 43.5$ ms, 95% CI[35.0, 52.1]) than the easy search condition ($M = 17.2$ ms, 95% CI[6.8, 27.5]), $F(1, 55) = 17.06$, $p < .001$, $\eta_p^2 = .237$.

Table 5

Mean Reaction Time (ms) and Percent Error by Search
Difficulty and Cue Validity for Experiment 4A.

	Easy Letter		Difficult Letter	
	RT	PE	RT	PE
Invalid	582 (14.0)	5.50%	679 (14.2)	10.70%
Valid	565 (13.9)	3.90%	635 (14.2)	6.90%
Validity Effect	17.2 (5.3)		43.5 (4.4)	

Note. RT = Reaction Time; PE = Percent Error. Validity
effects were calculated as invalid minus valid. Standard errors
are shown in parentheses.

Error rate analysis. The same ANOVA was conducted on mean error rates. Participants committed more errors in difficult search blocks (8.8%) than easy search

blocks (4.8%), $F(1, 55) = 49.59$, $p < .001$, $\eta_p^2 = .474$. Participants also made more errors on invalid trials (8.1%) than valid trials (5.4%), $F(1, 55) = 31.54$, $p < .001$, $\eta_p^2 = .364$. The interaction of cue validity and search difficulty was also significant, $F(1, 55) = 7.73$, $p < .01$, $\eta_p^2 = .123$.

Discussion

I found much larger capture effects under difficult letter-search (43.5 ms) than easy letter-search (17.2 ms). I conclude that, as search becomes more difficult, validity effects from irrelevant onsets increase, regardless of search dimension

Experiment 4B

In Experiment 4A, difficult letter-search produced larger validity effects than easy letter-search. In the current experiment, I further test the search difficulty hypothesis by manipulating search difficulty under <u>color search</u>. This experiment resembled the easy color-search condition of Experiment 1, with an added difficult color-search condition.

Method

Participants. Twenty undergraduates from the University of New Mexico participated for course credit (mean age of 21.2 years; 13 were female).

Stimuli, Design, and Procedure. The design was similar to the color-search Experiment 1, expect for a few key changes. The target was always defined by the color red as in Experiment 1 (Figure 7). I then manipulated the distance of the distractors in color space from the target. On easy color search trials, the red target (RGB value: 255, 0, 0) was surrounded by green (0, 151, 0) and blue (0, 128, 255) distractors, which are both far in color space. On difficult color search trials, the red target was surrounded by pink (210, 0, 80) and orange distractors (210, 80, 0), which are both near in color space.

Distractor colors were chosen at random with the restriction that two distractors were of one color and the remaining distractor was the other color (e.g., two blue and one green). In order to prevent participants from using shape to find the target instead of color (e.g., under difficult color-search), distractor identities were changed to Es and Hs. These identities were chosen at random with the restriction that each display contained two Es and two Hs. Pilot experiment revealed that participants had low accuracy in the difficult-search condition (e.g., below 80%). So, to make the task manageable, the search array appeared until response. Also, at the end of each block, participants were warned if their accuracy dropped below 90%. Participants performed two practice blocks of 64 trials followed by 10 regular blocks of 64 trials (12 blocks of 640 trials total).
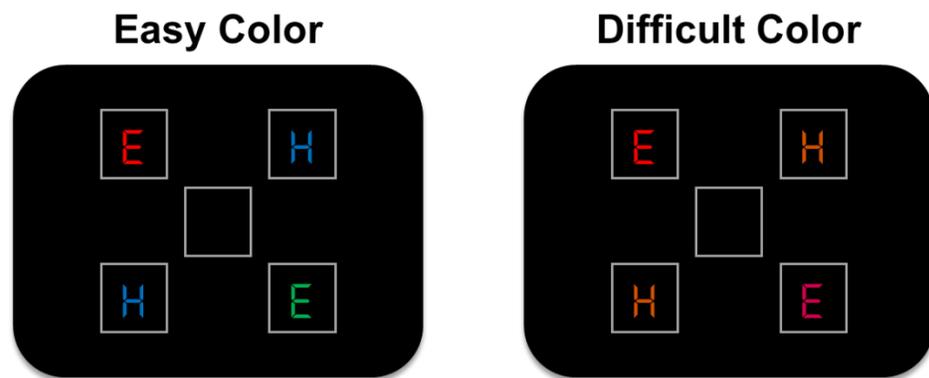
Figure 7. Search displays from Experiment 4B. In both conditions, the target could be found only by its color (red). In easy search, the target was surrounded by blue and green distractors (far in color space). In difficult search, the target was surrounded by pink and orange distractors (close in color space).

Results

The mean RTs and error rates are shown in Table 6. Cue validity effects by search difficulty condition are shown in Figure 6. ANOVAs on RT and error rates were similar to Experiment 4A.

RT analysis. Participants responded more quickly under easy search (572 ms) than difficult search (652 ms), $F(1, 19) = 65.294$, $p < .001$, $\eta_p^2 = .775$. Participants also responded more quickly when the cue was valid (602 ms) than when it was invalid (621 ms), $F(1, 19) = 20.632$, $p < .001$, $\eta_p^2 = .52$. Importantly, cue validity effects were greater under difficult search ($M = 30.2$ ms, 95% CI[18.5, 42.0]) than easy search ($M = 7.7$ ms, 95% CI[-0.8, 16.3]), $F(1, 19) = 12.542$, $p < .01$, $\eta_p^2 = .398$.

Table 6
Mean Reaction Time (ms) and Percent Error by Search Difficulty and Cue Validity for Experiment 4B.

	Easy Letter		Difficult Letter	
	RT	PE	RT	PE
Invalid	575.7 (20.4)	2.9%	667.0 (21.5)	3.3%
Valid	567.9 (18.1)	3.3%	636.8 (18.6)	2.6%
Validity Effect	7.7 (4.4)		30.2 (6.0)	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid. Standard errors are shown in parentheses.

Error rate analysis. The same ANOVA was conducted on mean error rates. No main effects were significant, Fs < 1. The interaction of cue validity and difficulty was significant, $F(1, 19) = 5.465$, $p < .01$, $\eta_p^2 = .223$.

Discussion

When the search dimension was color, I found much larger cue validity effects under difficult search (30.2 ms) than easy search (7.7 ms). I conclude that search dimension is relatively unimportant – rather, search difficulty can explain the discrepant capture results with onsets.

General Discussion

In this experiment, I provided evidence for a key role of search difficulty in onset capture. Pooling the data from Experiments 4A and 4B, easy search ($M = 14.7$ ms; 95% CI[6.7, 22.7]) produced much smaller validity effects than difficult search ($M = 40.0$ ms; 95% CI[32.9, 47.1]). This finding suggests that difficult search leads to greater capture by abrupt onsets than easy search (see also Experiments 5 and 6 for additional support). This finding fits well with Gaspelin, Ruthruff, Lien, and Jung's (2012) finding that capture by onsets was greater under difficult color search than easy color search.

Combining all of the experiments in the thesis thus far (Experiments 1-4), I plotted validity effects as a function of overall RT (Figure 8). Overall RT is used as a proxy for overall search difficulty, which cannot be observed directly from the data. This approach seems reasonable given that the search dimension varied but the response selection (manual responses to E or H) was held constant. Thus, a search difficulty account would predict that as overall RT increases, so should cue validity effects. Indeed, this prediction is correct, $R = 0.84$, $F(1,9) = 18.592$, $p < .01$.
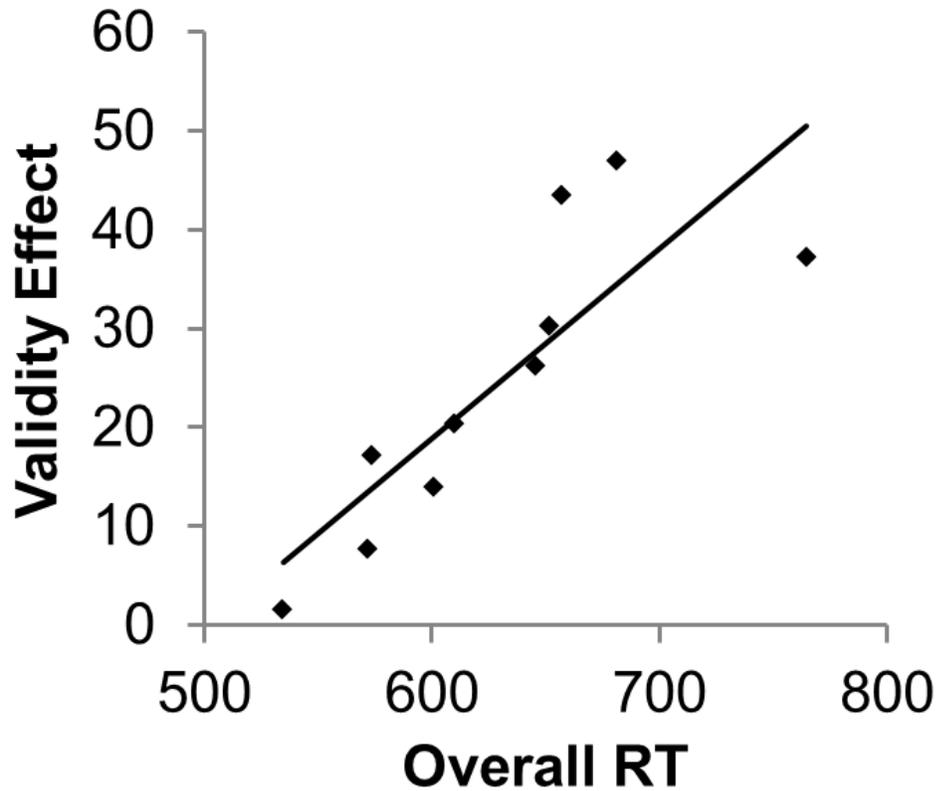
Figure 8. Cue validity effects (a proxy for attention capture) as a function of overall reaction time (a proxy for search difficulty). Validity effects for abrupt onsets increase with overall reaction time.

Evidence Against the Attentional Window Account

The attentional window account predicts that capture effects should be greater under "parallel" search than "serial" search (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, 1991). Note that this capture account exclusively relies on support from studies of color singletons. In the current study, I show a pattern *opposite* to that predicted by the attentional window account: greater capture by irrelevant onsets under difficult "serial" search than easy "parallel" search (for other evidence that window size does not affect onset capture, see Gaspelin, Ruthruff, Lien, et al., 2012b; Lamy &

Egeth, 2003). Thus, I argue that the attentional window account can be excluded as a

viable account of capture by abrupt onsets.

Chapter 4: Remaining Models

In the previous section, I demonstrated that, as search becomes more difficult, validity effects from abrupt onsets increase (which I will call the *search-difficulty-by-cue-validity interaction)*. Several possible accounts, some pre-existing and some new, can explain this data pattern. Below, I have classified each one of these accounts by two criteria (Figure 9): (1) whether it requires foreknowledge of the upcoming search difficulty (strategic vs. nonstrategic), and (2) whether it predicts that differences in cue validity effects reflect changes in the percentage of trials where capture is observed (probability of capture) or changes in consequences of being captured (cost of capture). Below, I will briefly explain how each candidate models can account for the search-difficulty-by-cue-validity interaction.

	Strategic	Nonstrategic
Probability of Capture	Adjustable Threshold Displaywide Orienting	none
Cost of Capture	Rapid Disengagement	Search Time

Figure 9. Candidate theories of the search-difficulty-by-cue-validity interaction.

Strategic Accounts

Adjustable Threshold Model

The *adjustable threshold model* is a new hybrid account of attention capture that I proposed. It is loosely based on Wolfe's Guided Search model of visual attention (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994, 2007). In this model, each item in the visual field receives a weighting indicating its priority for receiving spatial attention. This *priority weight* is determined both by an item's top-down relevance and bottom-up salience. Top-down relevance refers to how well the item matches the attentional set of the participant compared to its neighbors. Bottom-up salience refers to how an item differs from its neighbors in simple preattentive features (e.g., color, luminance, or shape). This priority weight rating can be likened to a z-score, where a highly salient item would be many standard deviations from the net mean of all the items on some feature dimension.

A critical assumption of the model is that, to elicit an involuntary shift of spatial attention, an item must exceed a certain threshold level (called the *capture threshold*). Items above this capture threshold will be attended in order of their priority weight. This effectively results in a tug-of-war between relevant and irrelevant salient items, which is probabilistic due to random variation in the perceived relevance and salience across trials. A critical assumption in this theory is that an observer can *adjust* his or her capture threshold. This strategic adjustment largely depends on task demands and is nonconcious (i.e., the observer has no awareness of the change).

This account can easily explain the search-difficulty-by-cue-validity interaction (see Figure 10). Under easy search, the attentional set is clearly defined and the target is

the only item in the visual field matching the attentional set. Thus, the target has an extremely high relevance rating. Note that under some forms of easy search (e.g., as in Experiment 4) the target will additionally have a high salience rating, resulting in an extremely large priority weight (not shown in the figure). The onset, however, has a high salience rating but a low relevance rating. Thus, the observer can adjust their capture threshold to fall above the onset priority weight, resulting in no capture. Under difficult search, the attentional set for the target feature is poorly defined and the target is not the only item in the visual field matching the set.   Thus, the target has only a moderate relevance rating. Because the onset has a high salience rating, it could have an overall priority weight equal to or even exceeding that of the target. Thus, the onset might often exceed the capture threshold.
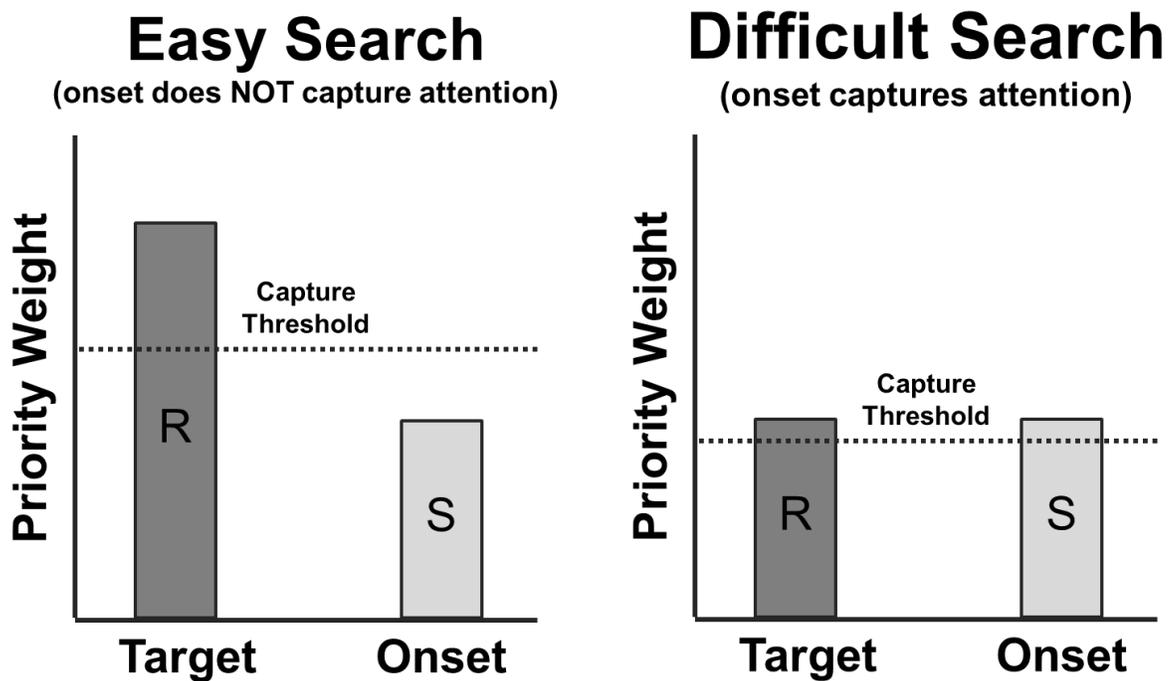
Figure 10. The adjustable threshold model's explanation of the search-difficulty-by-cue-validity interaction.

This account can also explain why relevant color cues capture attention more strongly than irrelevant color cues (i.e., contingent capture effects). Relevant color cues are both salient and relevant, and thus have a high priority weight. This high priority weight would frequently fall above the capture threshold (even under easy search), causing relevant cues to capture attention. Irrelevant color cues, however, have a low relevance rating (lower than onsets shown above; e.g., Yantis, & Jonides, 1984; Franconeri & Simons, 2003). Irrelevant color cues may rarely surpass the capture threshold, and will thus rarely capture attention. The only way that color cues will capture attention is if they are made relevant (e.g., by switching from feature detection mode to singleton detection mode), which would give them an extra boost in priority weight.

This account is strategic: participants must have foreknowledge of the upcoming trial type in order to adjust their capture threshold. They might additionally need a run of trials (i.e., blocked manipulation) to establish a strategy. Note that the onset appears before the search array in the precuing paradigm, thus the adjustment must happen before the search array appears in order to affect onset capture. This account also proposes that differences in cue validity effects reflect differences in probability of capture: participants are more likely to be captured under difficult search than easy search.

Displaywide Orienting

As explained in the Introduction, the displaywide orienting account is a goal-driven account. This account proposes that participants can establish an attentional set for any feature that distinguishes the search array from the rest of the trial (Burnham, 2007). For example, Gibson and Kelsey (1998) had participants search displays of red

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letters for a target letter (E vs. H). Even though the color red and onset-ness could not be used to locate the target, validity effects were present for red color cues and onset cues. They argued that participants established a displaywide attentional set for red and dynamic features.

The displaywide account can also explain the search-difficulty-by-cue-validity interaction.[1] Perhaps difficult search encourages a displaywide attentional set for abrupt onsets, while easy search does not. For example, when search is easy, participants develop an attentional set only for the feature that distinguishes the target from distractor items (i.e., E or H-ness in Experiment 4). This attentional set for target-like features prevents irrelevant abrupt onsets from capturing attention and thus causes small validity effects. However, when search is difficult, participants might additionally use displaywide features to help them find the target. For example, participants might use the onset of the search array to help them determine when to start searching. This displaywide attentional set for any dynamic change would enable abrupt onset cues to capture attention, and thus lead to capture.

The displaywide-orienting account is strategic: the participant must have knowledge of the upcoming search display difficulty in order to adjust their attentional set. Also, this account proposes that differences in validity effects are caused by a change in the probability of capture by onset cues: there are few or no instances of capture under easy search, but there are several instances of capture under difficult search.

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[1] I thank Charles Folk and Bryan Burnham for suggesting this possibility at the Annual Meeting of Psychonomic Society.

Rapid Disengagement

As explained in the Introduction, Theeuwes and colleagues have proposed that participants rapidly disengage from irrelevant salient cues in the precuing paradigm (Theeuwes, 2010). Thus, even though salient items capture attention, they do not produce observable validity effects. Relevant cues also capture attention, but are difficult to disengage from because they match the proposed attentional set. Thus, relevant cues do produce observable validity effects. Although such an account has received considerable criticism (e.g., Chen & Mordkoff, 2007; Folk & Remington, 2006; Lien et al., 2008), it deserves consideration here.

Such an account can also explain the search-difficulty-by-cue-validity interaction.[2] According to this account, the onset always captures attention. In easy search, participants quickly reject the onset cue as a potential target (is not red) and rapidly disengage spatial attention from the item. This results in an absence of cue validity effects (even though the onset captured attention). In letter search, however, participants cannot easily reject the onset cue (because of an unclear attentional set). This results in large cue validity effects. This account could be extended to the search difficulty effect. When search is easy, participants may have a clear attentional set for the target-finding feature, allowing them to rapidly disengage from irrelevant onset cues. When search is difficult, however, participants may have only a weak attentional set for the target-finding feature, preventing participants from quickly rejecting the irrelevant onset cue.

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[2] I thank Jan Theeuwes for suggesting this possibility at the Annual Meeting of Psychonomics Society.

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The rapid disengagement account is strategic: participants must have foreknowledge of the upcoming search display in order to rapidly disengage from the cue (which appears before the search array). Unlike the previously mentioned accounts, this account proposes that the probability of capture remains roughly constant across search conditions – onsets always capture attention. The cost of being captured, however, is greater under difficult search than easy search.

Nonstrategic Accounts

Search Time Model

According to the *search time model*, onsets frequently capture attention under both easy and difficult search, with equal probability. However, the <u>costs</u> of being captured vary with search difficulty (see Figure 11). Under easy search, the invalidly cued search item is easy to reject (low relevance rating) and the target is subsequently easy to find (because it has a high relevance rating).[3] This causes small cue validity effects. Under difficult search, however, the invalidly cued search item is difficult to reject (high relevance rating) and the target is subsequently difficult to find (high relevance rating but no salience rating). Thus cue validity effects are large.

The search time model is nonstrategic: the participant needs no foreknowledge of the upcoming search display type. This account also proposes that the probability of capture is roughly consistent across search conditions. Rather participants are disproportionately slowed by invalid cues under difficult search compared to easy search.

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[3] As previously mentioned, under some forms of easy search the target will additionally have a high salience rating because it differs from its neighbors on some simple feature dimension (e.g., Experiment 4).

Next, I will detail in more depth regarding the two basic subcomponents of this model: search item rejection and target finding.

Easy Search   Difficult Search
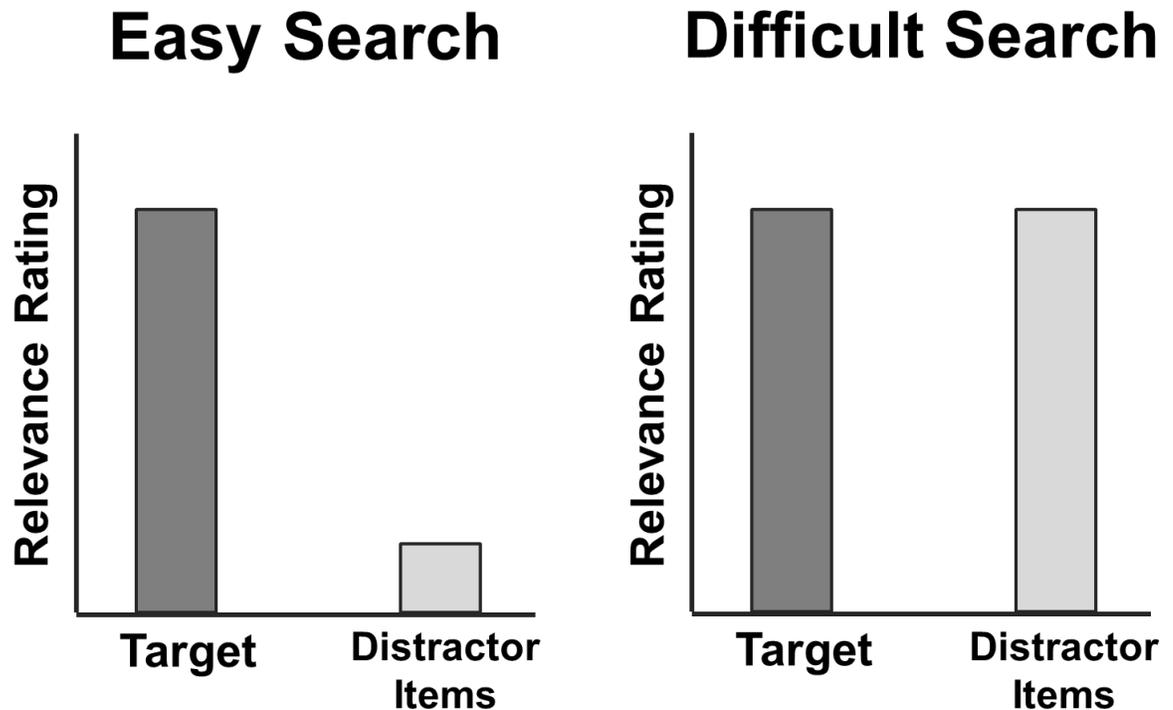
Figure 11. The search time model. Under easy search, distractor items are easy to reject. This allows participants to quickly move from an invalidly cued search item to the target (small validity effects). Under difficult search, distractor items are difficult to reject. This causes participants to slowly move from invalidly cued search item to the target (large validity effects).

Search Item Rejection

Validity effects may be influenced by how difficult the cued <u>search item</u> (e.g., the letter in the target display) is to reject as a potential target (Figure 12). Under easy search, the invalidly cued search item has a low priority weight (it is neither salient nor relevant) and thus may be quickly rejected. This rapid rejection of invalidly cued search items would cause small validity effects. Under difficult search, however, invalidly cued

search items have a high priority weight (they are relevant because they look like the target) and will thus be slowly rejected. This slow rejection of the invalidly cued item would cause large validity effects.

This account can also explain why relevant cues produce large validity effects even under easy search. According to this account, the relevant cue boosts the relevance rating of the item that appears (150 ms later, in our case) at the invalidly cued location. For example, if participants are looking for a red target, and the cue is red, participants will have difficulty determining that the letter at the cued location is not in fact red.

This search item rejection account resembles Theeuwes' rapid disengagement account. A critical distinction, however, is that the rapid disengagement account assumes that spatial attention disengages from the <u>cue</u>, whereas the cued location rejection account assumes that spatial attention waits at the cue and instead differentially disengages from the <u>search item</u> (i.e., the letter in the search display). In other words, spatial attention is lazy – it moves to the cued location and waits for the target to appear elsewhere before disengaging. In terms of priority weights, spatial attention prefers not move from a high priority weight location (the salient cue) to a low priority weight location (an empty location before the search display appears). But rather it waits to move until a higher priority location (i.e., the relevant target) appears. Sometimes the distractor item is quickly rejected (under easy search). Sometimes it is slowly rejected (under difficult search).

Easy Search
small cue validity effects

Difficult Search
large cue validity effects
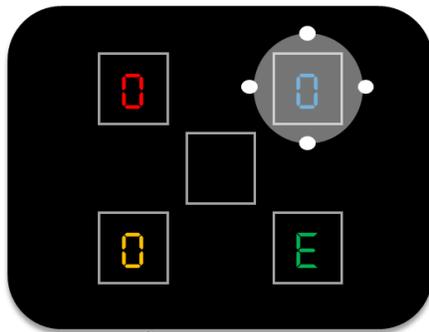
Cued location is quickly rejected: the invalidly cued item looks dissimilar to the target.
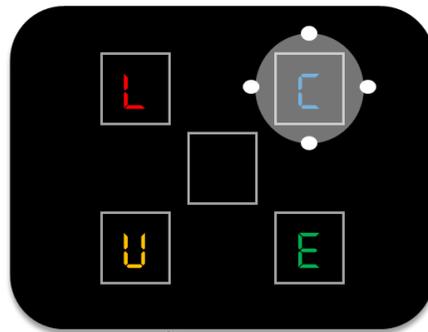
Cue item is slowly rejected: the invalidly cued item looks similar to the target.

Figure 12. Effects of search item rejection. Gray circles represent the spotlight of spatial attention. The cue and search display are shown in the figure for illustrative purposes.

Target Finding

Cue validity effects may also be influenced by how quickly the target is found after capture by an invalid onset cue (Figure 13). According to this account, the onset cue captures spatial attention on a high proportion of trials. Under easy search, the target is the only item in the visual field that matches the attentional set. After rejecting the item at the invalidly cue location, spatial attention would move directly to the target. This results in relatively short mean RTs on invalid trials, and thus small cue validity effects. Under difficult search, however, several search items match the attentional set. Spatial attention may be reluctant to move to the target (which has a roughly equal

relevance rating with other search items). Similarly, spatial attention may move to

distractor locations before moving to the target.
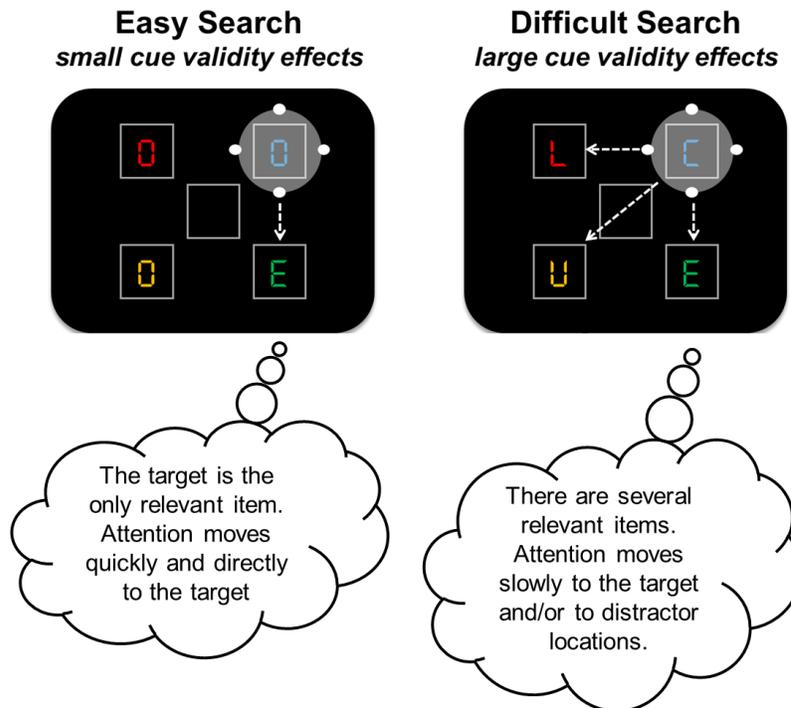
Figure 13. The target finding component of the search time model. Gray circles

represent the "spotlight" of spatial attention. The cue and search display are shown in

the figure for illustrative purposes.

Summary

To summarize, there are several models that could explain the search-difficulty-

by-cue-validity interaction. Note that these models are not mutually exclusive. As

outlined above, most of these models are strategic (attentional window, displaywide

orienting, and adjustable threshold) – in order to work, participants must have

foreknowledge of the upcoming search frame – while one model is nonstrategic (search

time model). In the next chapter, to test between classes of viable models, I will

determine whether the search-difficulty-by-cue-validity interaction is strategic.

Chapter 5

Strategic vs. Nonstrategic Models

In this section, I test whether the search-difficulty-by-cue-validity interaction is strategic or nonstrategic by varying search difficulty randomly <u>by trial</u>. Thus, participants have no knowledge of the upcoming search difficulty when the salient onset cue is presented. This should prevent any strategy-based adjustment of the capture threshold (adjustable threshold model), changes to the attentional set (displaywide orienting model), or disengagement from the cue (rapid disengagement). Thus, strategic models predict no difference in validity effects between search conditions. The nonstrategic model search time model, however, predicts large differences in validity effects between search conditions. In Experiment 5, participants performed easy vs. difficult <u>letter</u> search. In Experiment 6, participants performed easy vs. difficult <u>color</u> search.

Experiment 5

In this experiment, participants performed easy vs. difficult letter search (as in Experiment 4). However, rather than dividing the experiment into two halves (one half easy and one half difficult), we manipulated search difficulty randomly by trial.

Method

Participants. Forty-five undergraduates from the University of New Mexico participated for course credit. One participant was excluded from analysis due to high error rates (more than 2.5 SDs above the group mean). Of the remaining 44 participants, the mean age was 20.4 years and 32 were female.

Apparatus, Stimuli, Design, and Procedure. All methods were identical to those of Experiment 4, except that search difficulty was manipulated randomly by trial.

Results

Trials with an RT less than 200 ms or greater than 2000 ms (0.9% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 7. Cue validity effects by search difficulty condition are shown in Figure 14.

Table 7

Mean Reaction Time (ms) and Percent Error by Search Difficulty and Cue Validity for Experiment 5.

	Easy Letter		Difficult Letter	
	RT	PE	RT	PE
Invalid	585.7 (10.0)	5.3%	654.7 (10.8)	8.5%
Valid	576.5 (10.2)	5.0%	621.8 (10.9)	8.7%
Validity Effect	9.3 (3.6)		32.9 (5.9)	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid. Standard errors are shown in parentheses.

RT analysis. I performed a two-way within-subjects ANOVA on mean RTs with the factors search difficulty (easy vs. difficult) and cue validity (invalid vs. valid). Participants responded more quickly on the easy search trials (581 ms) than difficult search trials (638 ms), $F(1, 43) = 230.346$, $p < .001$, $\eta_p^2 = .843$. Participants also responded more quickly when the cue was valid (599 ms) than when it was invalid (620 ms), $F(1, 43) = 29.596$, $p < .001$, $\eta_p^2 = .408$. Importantly, cue validity effects were greater on the difficult search trials ($M = 32.9$ ms, 95% CI[21.3, 44.5]) than the easy search trials ($M = 9.3$ ms, 95% CI[2.1, 16.4]), $F(1, 43) = 15.13$, $p < .001$, $\eta_p^2 = .26$.

Error rate analysis. The same ANOVA was conducted on mean error rates. Participants committed more errors in difficult search blocks (8.6%) than easy search blocks (5.1%), $F(1, 43) = 59.863$, $p < .001$, $\eta_p^2 = .582$. All other interactions and main effects were nonsignificant, $F(1, 43) < 1$, $p > .50$.
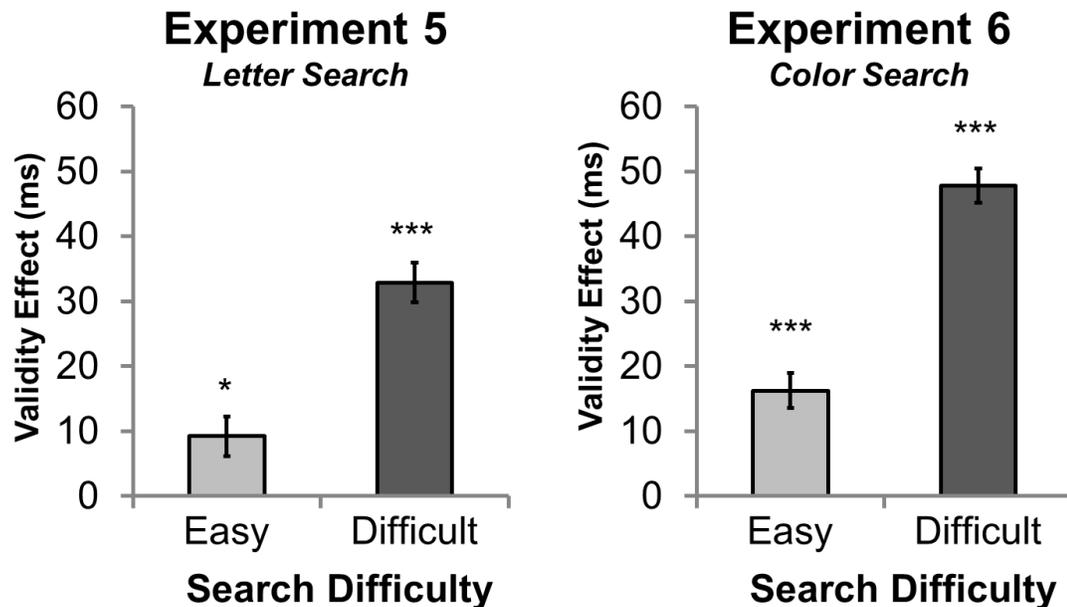
Figure 14. Cue validity effects (ms) by search difficulty (easy vs. difficult) for Experiments 4 and 5. Error bars represent standard error of the mean based upon this within subjects error for the search difficulty by validity interaction.

*$p < .05$ *** $p < .001$

Discussion

Even when search difficulty was manipulated by trial, preventing strategic adjustment of the capture threshold, validity effects were greater on difficult letter search trials (32.9 ms) than easy letter search trials (9.3 ms). This experiment provides evidence against strategic accounts of the search-difficulty-by-cue-validity effect and provides support for nonstrategic, cost-of-capture accounts.

Experiment 6

In this experiment, we again manipulated search difficulty by trial. But instead of using letter search, we used <u>color</u> search. As in Experiment 5, strategic accounts predict no difference in validity effects between search difficulty conditions, because participants have no foreknowledge of the upcoming trial type when the abrupt onset cue is presented.

Method

Participants. Thirty-four undergraduates from the University of New Mexico participated for course credit (mean age: 20.4 years and 32 were female).

Apparatus, Stimuli, Design, and Procedure. Custom software was created using Allegro gaming libraries (https://www.allegro.cc/) for the C programming language (see next paragraph for reasons why). All methods were similar to those of Experiment 4B (see Figure 15). Participants performed one practice block of 64 trials followed by 12 regular blocks of 64 trials (768 trials total).

Again, pilot experiments revealed that participants could not maintain high accuracy on difficult search trials. To boost accuracy, we implemented three changes. First, the search array was displayed until response. Second, participants heard a rewarding chime if they were correct, and a punishing low tone if they were incorrect (additionally, the experiment paused for 500 ms for incorrect experiments). Third, after each block, participants received block performance feedback in the form of two gauges, one for speed and one for accuracy (with three labels: "good", "great", or "awesome"; Figure 15). The gauge needle slowly rose until it reached a position based upon the performance in the block. The needle never dropped below "good." The accuracy gauge ranged from 85% (lower limit) to 100% (upper limit). The RT gauge ranged from 1000
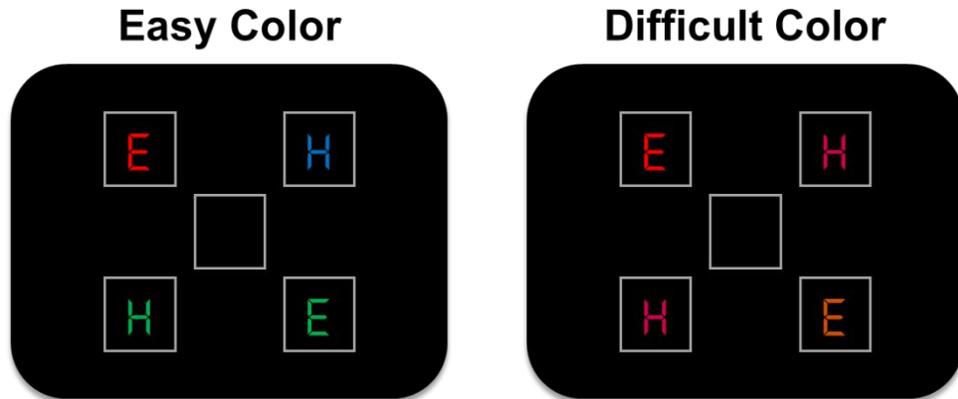
ms to 500 ms.
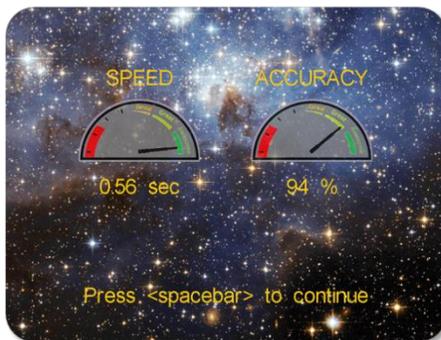
Figure 15. Displays for Experiment 6. (A) Search displays for Experiment 6. (B) End-of-block accuracy and reaction time feedback gauges.

Results

Trials with an RT less than 200 ms or greater than 2000 ms (0.2% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 8. Cue validity effects by search difficulty condition are shown in Figure 14.

RT analysis. I performed a two-way within-subjects ANOVA on mean RTs with the factors search difficulty (easy vs. difficult) and cue validity (invalid vs. valid).

Participants responded more quickly on the easy search trials (559 ms) than difficult

search trials (622 ms), $F(1, 33) = 114.51$, $p < .001$, $\eta_p^2 = .776$. Participants also

responded more quickly when the cue was valid (575 ms) than when it was invalid (607

ms), $F(1, 33) = 33.141$, $p < .001$, $\eta_p^2 = .501$. Importantly, cue validity effects were

greater on the difficult search trials ($M = 47.8$ ms, 95% CI[32.7, 63.0]) than the easy

search trials ($M = 16.2$ ms, 95% CI[8.2, 24.3]), $F(1, 33) = 34.561$, $p < .001$, $\eta_p^2 = .512$.

Table 8

Mean Reaction Time (ms) and Percent Error by Search
Difficulty and Cue Validity for Experiment 6.

	Easy Color		Difficult Color	
	RT	PE	RT	PE
Invalid	567.4 (9.2)	3.2%	646.3 (14.9)	3.6%
Valid	551.2 (8.3)	3.1%	598.5 (10.5)	2.7%
Validity Effect	16.2 (4.1)		47.8 (7.7)	

Note. RT = Reaction Time; PE = Percent Error. Validity effects
were calculated as invalid minus valid. Standard errors are
shown in parentheses.

Error rate analysis. The same ANOVA was conducted on mean error rates. All

main effects were nonsignificant. There was a trend for participants to show larger

validity effects on difficult trials (0.9%) than easy trials (0.1%), $F(1, 33) = 3.319$, $p =$

$.078$, $\eta_p^2 = .091$.

Discussion

We can draw two important conclusions from the current experiment. First, these

findings further confirm Experiments 4A and 4B. When assessing capture, the search

dimension (color vs. letter) is unimportant; rather, differences in capture reflect

differences in search difficulty.   Second, this experiment also confirms the findings of

Experiment 5, which provided evidence against strategic accounts of the search-

difficulty-by-cue-validity effect. It instead supports nonstrategic, cost-of-capture accounts.

General Discussion

In the current experiments, I manipulated search difficulty by trial, preventing foreknowledge of the upcoming trial type (easy vs. difficult). Because there is no longer any room for strategic adjustments between conditions, strategic accounts predict that the search-difficulty-by-cue-validity interaction should disappear – cue validity effects should be no greater under difficult search than easy search. The nonstrategic search time account, however, predicts that that the search-difficulty-by-cue-validity interaction should remain – cue validity effects should be greater under difficult search than easy search.

The results support nonstrategic accounts. Pooling the data from Experiment 5 and 6, validity effects were considerably smaller under easy search ($M = 12.3$ ms, 95% CI [7.0, 17.6]) than difficult search ($M = 39.4$ ms, 95% CI [30.0, 48.8]). Participants clearly do not need foreknowledge of the upcoming search difficulty in order to show a strong search-difficulty-by-cue-validity interaction.   Note that all accounts proposing that the probability of capture by onsets is modulated are strategic. Thus, because the search-difficulty-by-cue-validity interaction is nonstrategic, these experiments leave little room for probability of capture accounts to explain the search difficulty effect.

Additional Support for Search Difficulty

When each search condition of the current experiments is plotted by overall RT (a measure of search difficulty) and validity effects, the model still shows the same general trend of greater capture under easy search than difficult search, $R = 0.757$, $F(1,13) =$

15.632, $p < .01$ (Figure 16). These experiments also clearly demonstrate that no matter what the search dimension (color or letter), validity effects will be greater under difficult search.
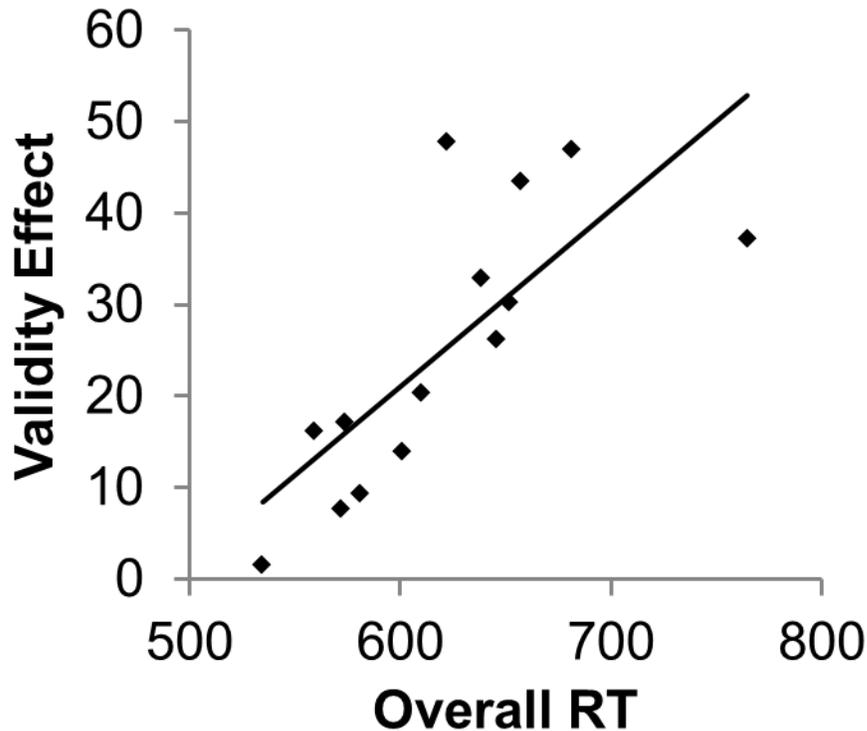
Figure 16. Cue validity effects (a proxy for attention capture) as a function of overall reaction time (a proxy for search difficulty) for Experiments 1-6. Validity effects for abrupt onsets increase with overall reaction time.

Conclusion

In the present experiments, the search-difficulty-by-cue-validity interaction is largely nonstrategic. Note that all nonstrategic models are costs-of-capture models. Thus, the differences in cue validity effects do not reflect modulation of probability of capture. Next, I will further test whether the identity of the cued search item can affect overall cue validity effects.   This key component of the search time model is important to establish.

Chapter 6

Cued Search Item Rejection

In the current experiment, I evaluate whether cued search item rejection is an important component of cue validity effects. Participants performed a difficult letter search. At set size 3, the invalid cues could either point to a target-like distractor letter or an empty placeholder box (i.e., blank location; see Figure 16). If the identity of the cued location is important, participants should reject blank placeholders faster than target-like letters. In other words, participants should respond more quickly on invalid-blank trials than invalid-letter trials. If cued location rejection is <u>not</u> an important determinant of validity effects, participants should respond no faster on invalid-blank trials than invalid-letter trials (e.g., as in the adjustable threshold or rapid disengagement models).

Experiment 7

Method

Participants. Fifty-six undergraduates from the University of New Mexico participated for course credit. One participant was excluded for having an unusually high error rate (2.5 SDs above the group mean). Of the remaining 55 participants, the mean age was 19.1 years and 39 were female.

Apparatus, Stimuli, Design, and Procedure. Custom software was created using Allegro gaming libraries for the C programming language. The design of this experiment was similar to the difficult letter search condition of Experiment 5 (see Figure 17). Participants searched for a letter target that could appear in a random color. Distractor items were a heterogeneous set of target-like letters. The setsize could be either 3 items

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or 4 items. When the set size was 3, only three of the 4 potential locations had letters. At this set size, the onset cue could point toward the target (valid; 25% of trials), a distractor letter (invalid; 50% of trials), or a blank location (invalid; 25% of trials). Participants performed 1 practice block of 64 trials followed by 12 blocks of 64 trials (768 total regular trials). The feedback sounds and end-of-block feedback gauges were the same as in Experiment 6.
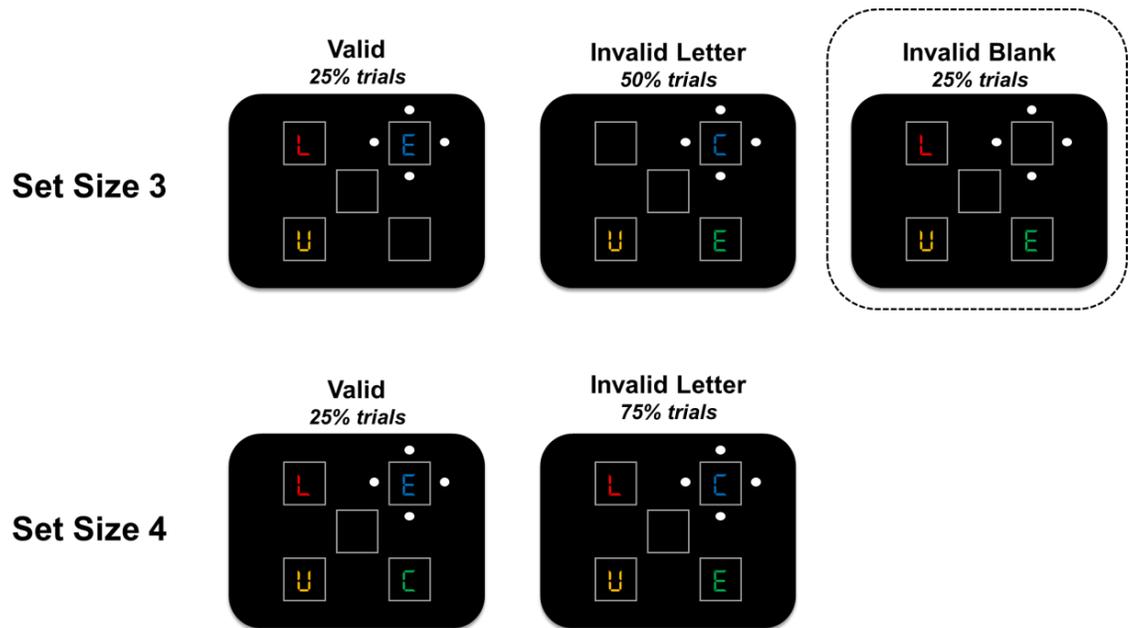
Figure 17. Stimulus displays from Experiment 7. The cue frame and search frame are combined for illustrative purposes.

Results

Trials with an RT less than 200 ms or greater than 2000 ms (0.2% of trials) or an incorrect response were excluded from RT analyses. The resulting mean RTs and error rates are shown in Table 9.

Set-size Analysis. I conducted a two-way repeated measures ANOVA with the factors set size (3 vs. 4) and cue validity (invalid vs. valid) on trials where a letter appeared at the cued location. Participants responded more quickly at set-size 3 (583 ms)

than set-size 4 (616 ms), $F(1, 54) = 188.608$, $p < .001$, $\eta_p^2 = .777$. Participants also

responded more quickly on valid trials (579.4 ms) than invalid trials (619.7 ms), $F(1, 54)$

$= 105.352$, $p < .001$, $\eta_p^2 = .661$. There was also a trend for validity effects to be greater at

set size 4 (43.3 ms) than set size 3 (37.1 ms), $F(1, 54) = 3.241$, $p = .077$, $\eta_p^2 = .057$.

Table 9

Mean Reaction Time (ms) and Percent Error by Set Size and Cue
Validity for Experiment 7.

	Set Size 3		Set Size 4	
	RT	PE	RT	PE
Invalid - Letter	601.5 (9.2)	6.20%	637.8 (10.3)	7.80%
Invalid - Blank	588.3 (9.0)	5.10%	--	--
Valid	564.4 (8.8)	5.00%	594.5 (9.6)	4.80%

Note. RT = Reaction Time; PE = Percent Error. Standard errors are
shown in parentheses.

Cued Location Identity Analysis. Recall that the cued rejection location account

predicts longer RTs on invalid-letter trials than invalid-blank trials. Indeed, at set size 3,

participants were faster on invalid-blank cue trials (588.3 ms) than invalid-letter cue

trials (601.5 ms), $t(54) = 4.35$, $p < .001$ (see Table 10). In other words, if we use the set

size 3 valid trials to calculate validity effects, validity effects were smaller for invalid-

blank trials (23.9 ms) than invalid-letter trials (37.1 ms).

Table 10

Validity Effects (ms) by Set Size for Experiment 7.

	VE
Set Size 4 -- Letter	43.3
Set Size 3 -- Letter	37.1
Set Size 3 -- Blank	23.9

Note. At set size 4, validity effects were calculated as
invalid minus valid. At set size 3, validity effects were
calculated as invalid (letter vs. blank) minus valid.

Error Rate Analysis. The same ANOVA from above was also conducted on mean error rates. Participants committed fewer errors at set size 3 (5.6%) than set size 4 (6.3%), $F(1, 54) = 4.737$, $p < .05$, $\eta_p^2 = .081$. Participants also made fewer errors on valid trials (4.9%) than invalid trials (7.0 %), $F(1, 54) = 54.194$, $p < .001$, $\eta_p^2 = .501$. Participants also had larger validity effects at set size 4 (3.0%) than set size 3 (1.2%), $F(1, 54) = 3.241$, $p < .001$, $\eta_p^2 = .224$.

Discussion

In the current experiment, I tested whether presence or absence of a letter at the cued location plays a role in validity effects. As shown here, participants were much faster to reject invalidly cued blanks (24.0 ms) than letters (37.1 ms). This directly demonstrates an important role of cued search item rejection in the size of validity effects. Thus, validity effects do not merely reflect whether spatial attention moved, but also the speed of object recognition. As far as we know, this is the first direct evidence for the importance of cued search item rejection.

Mathematical Modelling a Search Time Account

In the present experiment, I demonstrated an important role of cued location rejection. However, as I previously noted, another component to the search time model are RT costs from target-finding. It is difficult to imagine a scenario where it takes considerable time to decide if the cued item is a target, but it takes no time to determine whether a distractor item is a target, or in which the time to find the target is not also sensitive to search difficulty.

With a few assumptions, a unified model of cued search item rejection and target finding (i.e., search time model) can provide an eloquent mathematical model of costs of

capture. In other words, we assume that cue validity effects (RT_i - RT_v) reflect both cued

search item rejection (CR) and target-finding (TF):

$$RT_i - RT_v = CR + TF$$

There are a few underlying assumptions of this model. First, search is serial

rather than parallel. We also assume that search is random with memory; each location

has an equal probability of selection and previously searched locations are not revisited.

We also assume that the onset captures attention on all trials (probability of capture is

100%) and that the time to reject each item searched is roughly equal. Finally, blank

locations are not searched at all.

The number of items to be searched (K) is a function of setsize (n). On absent

trials (not used in this study), the function is as follows:

$$K_a = \frac{n+1}{2}$$

For example, if the set size was 4, then on average only 2.5 items would be searched. But

on invalid-letter trials, the cued location is mandatorily searched (1 item) and then the

remaining items are searched afterwards.

$$K_{i\ letter} = 1 + \frac{n+1-1}{2}$$

$$K_{i\ letter} = \frac{n+2}{2}$$

For example, if the set size is 4, 3 items are searched on average. On invalid blank trials,

the cued item is not searched. Thus, the function is as follows:

$$K_{i\ blank} = \frac{n+1}{2}$$

On valid trials, the participant is directed toward the target location, so only 1 item is searched (i.e., $K_v = 1$). Thus, according to this model, we can express cue validity effects as a function of the number of items to be searched and the time taken to reject each item (r).

$$RT_i - RT_v = (K_i - K_v)r$$

Given that $K_{i\,blank} = \frac{n+1}{2}$, $K_{i\,letter} = \frac{n+2}{2}$, and $K_v = 1$, the predicted cue validity effects ($RT_i - RT_v$) are as follows for each condition:

Set Size 4 Letter Cued: $2r$

Setsize 3 Letter Cued: $1.5r$

Setsize 3 Blank Cued: $1r$

Given these equations, I calculated (using a C program) cue validity effects from all values of r ranging from 0 to 50 (by increments of .01). For each r value, I calculated the error for all three predicted validity effects (calculated as actual validity effect minus
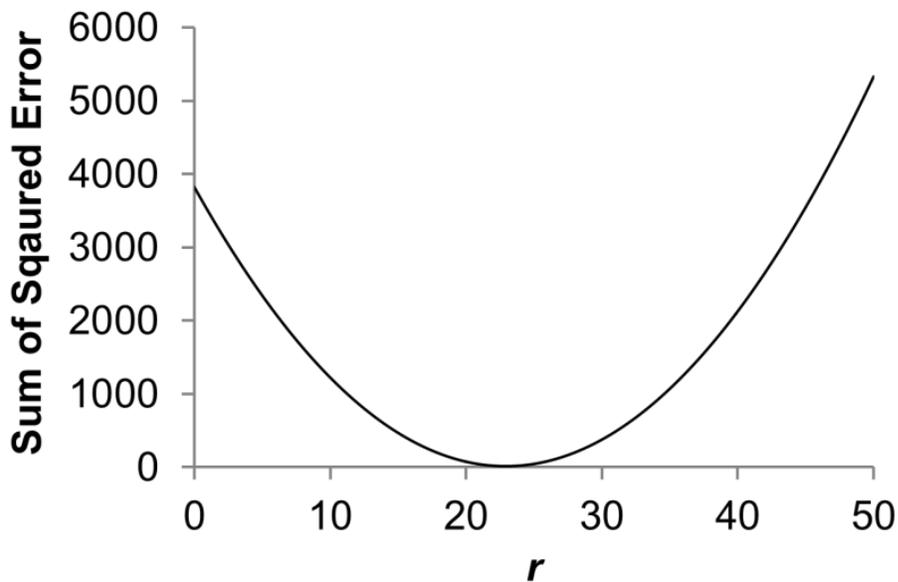
Figure 18. The sum of squared errors for each r value. As can be seen here, the best-fitting value was 22.93.

predicted validity effect), squared them, and summed the squares.   Figure 18 plots sum of square errors by the value of *r.*
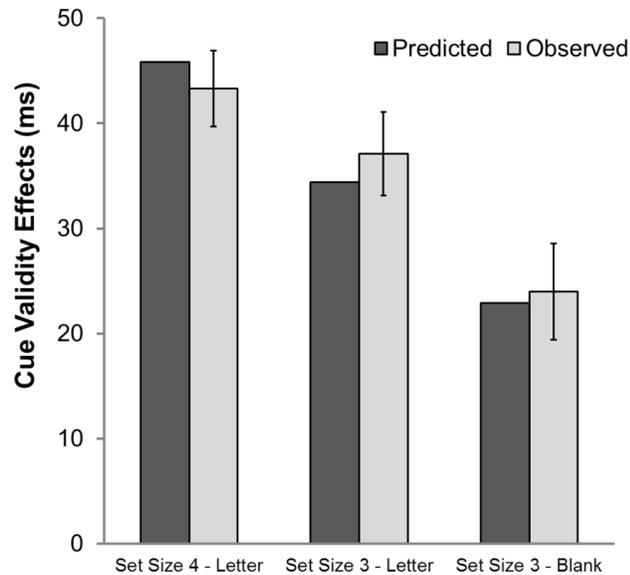
Figure 19. Predicted vs. observed validity effects from Experiment 7. Predicted validity effects were calculated using the best-fitting *r* value of 22.92 ms. Error bars represent standard error of the mean.

The resulting best-fitting *r*-value was 22.92 ms. As can be seen Table 11 and Figure 19, the predicted data fit the observed data quite well (sum of squared errors = 14.81). In each case, the predicted value is well within one standard error of the mean.

Table 11
Predicted and Observed Validity Effects (ms) by Set Size and Cue Condition

	Set Size 4 - Letter	Set Size 3 - Letter	Set Size 3 - Blank
Predicted	45.8	34.4	22.9
Actual	43.3	37.1	23.9
Error	2.5	-2.7	-1.0

Error terms were calculated as predicted validity effect minus actual validity effect.

Conclusion

To briefly summarize, the current data clearly suggest a role of cued location rejection. However, cued location rejection alone cannot entirely explain the data. When the cued location in the target display is blank, there is still a residual validity effect (24.0 ms). If we instead combine the cued rejection model and target-finding models (which are not mutually exclusive and in fact fit nicely together) into a unified <u>search time model</u>, we are able to mathematically model the current data with considerable precision.

Chapter 7

General Discussion

A central issue in visual attention research is how salient stimuli produce distraction (i.e., involuntary capture of attention). *Stimulus-driven* theories propose that "super" salient stimulus features can automatically capture attention (Yantis & Jonides, 1984). *Goal-driven* theories, however, propose that only items matching what a viewer is looking for can capture attention (Folk, Remington, & Johnston, 1992). These competing theories make vastly different predictions about attention capture in the real-world. Stimulus-driven theories predict that visual attention will frequently be captured by salient "physical" features — sometimes informative (e.g., a yellow 'wet floor" sign) but often distracting (e.g., a flashing web advertisement) — whereas goal-driven theories predict that these salient signals will be routinely missed. Interestingly, researchers from both theoretical camps consistently produce opposing results, with little resolution. Thus, although attentional capture is a basic cognitive phenomenon that occurs in nearly all waking situations, researchers cannot agree what features capture attention.

The inability to establish a coherent model of attention capture is perhaps the greatest problem plaguing visual attention research. The inability to predict capture is impeding research in related vision sciences. For example, it is currently difficult to model visual search in complex environments (e.g., baggage security checkpoints), because it is unclear which search items will receive priority (Speed, Gaspelin, & Ruthruff, 2012). Similarly, it is difficult to design effective visual warning signals (e.g., on car dashboards), because it is unclear what type of signals will automatically draw the

attention of a busy operator. Better understanding visual attention capture could benefit several fields and would have a large impact on our day-to-day lives.

In the current thesis, I have focused specifically on the case of abrupt onsets (i.e., flashing stimuli), which seem to be the most promising candidate for stimulus-driven capture (Franconeri & Simons, 2003; Jonides & Yantis, 1988). Previous research has been sharply divided on whether abrupt onsets can capture attention in a truly stimulus-driven manner. Some researchers claim that abrupt onsets can capture attention (Franconeri et al., 2005, 2004; Franconeri & Simons, 2003; Hollingworth et al., 2010; Jonides & Yantis, 1988; Yantis & Jonides, 1984; Yantis, 1993), while others maintain that abrupt onsets cannot (Folk et al., 1992; Folk & Remington, 2010; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010). No previous reconciliations have been widely accepted. The goal of the current thesis was to provide a new reconciliation to the discrepant results.

Search Dimension: Letter vs. Color

This thesis began with the observation that different theoretical camps consistently use paradigms with different search dimensions: letter vs. color (see Table 1). In Chapter 2, I empirically tested the role of search dimension in the attention capture debate. Participants performed a precuing paradigm with irrelevant abrupt onsets. I manipulated only the search dimension (letter vs. color). Pooling the data from Experiments 1 through 3, letter search produced large validity effects ($M = 37.3$ ms, 95% CI [29.9, 44.6]), consistent with results reported by stimulus-driven theorists using the irrelevant feature paradigm. Color search, however, produced small validity effects ($M =$

8.2 ms, 95% CI [7.2, 16.6]), consistent with results reported by goal-driven theorists

using the precuing paradigm.

What was once a confusing, enigmatic picture is now crystal clear. The precuing

paradigm and irrelevant paradigms produce different results because they use different

search dimensions, which in turn strongly modulate the size of observed capture effects

by irrelevant abrupt onsets. Whereas previous researchers have suggested that something

is wrong with the other camp's paradigm (e.g., Belopolsky, Schreij, & Theeuwes, 2010;

Folk & Remington, 2010, 1998; Theeuwes, 2010; Yantis, 1993), we argue that the

paradigm is relatively unimportant. Rather the search dimension favored by the different

camps is the key to the discrepant findings. In Experiments 1-3, I was able to strongly

modulate capture effects – all within the precuing paradigm.

Search Difficulty: Easy vs. Difficult

In Chapter 3, I explored the role of search difficulty onset capture. In Chapter 2,

easy color search produced small validity effects while difficult letter search produced

large validity effects. Because search dimension (letter vs. color) and search difficulty

(easy vs. difficult) were confounded, it was unclear which variable caused the modulation

of validity effects from abrupt onsets.

In Experiments 4A and 4B, I directly tested the role of search difficulty by

holding search dimension constant (letter search in 4A and color search in 4B). Pooling

across experiments, easy search (M = 14.7 ms; 95% CI[6.7, 22.7]) produced much

smaller validity effects than difficult search (M = 40.0 ms; 95% CI[32.9, 47.1]). This

finding demonstrates the key importance of difficult search in yielding capture effects by

onsets. It is corroborated by a strong correlation between overall reaction time

(indicative of overall search difficulty) and validity effects in Experiments 1 through 4. Furthermore, the later Experiments 5 and 6 provided additional evidence for this claim – the target defining property was unimportant (color vs. letter) but difficult search always produced larger validity effects than easy search.

Nonstrategic Costs of Capture: The Search Time Model

In Chapter 4, I reviewed several different theoretical accounts that could explain the search-difficulty-by-cue-validity interaction (summarized in Figure 9). At a broad level, these models could be classified as either strategic (i.e., require foreknowledge of the upcoming trial type) or nonstrategic. In Chapter 5, to shrink the pool of potential models, I evaluated whether the search-difficulty-by-cue-validity interaction is strategic or nonstrategic. Instead of varying search difficulty by block (as in Experiments 1 – 4), I varied search difficulty by trial. Thus, participants had no foreknowledge of the upcoming search difficulty when the onset cue appeared. Surprisingly, the search-difficulty-by-cue-validity interaction remained. Pooling the data from Experiments 5 and 6, validity effects were considerably smaller under easy search (M = 12.3 ms, 95% CI [7.0, 17.6]) than difficult search (M = 39.4 ms, 95% CI [30.0, 48.8]). Thus, the effect seems to be largely nonstrategic. Importantly, all probability of capture models were strategic models. Thus, the remaining nonstrategic model (the search time model) assumes that the cost of capture (not the probability of capture) is modulated by search difficulty.

In Experiment 7 of Chapter 6, I tested the role of cued location rejection. Participants performed a difficult letter search precuing paradigm, with two possible set sizes (3 vs. 4). Critically, at the set size 3, the invalid cue could either point to a target-

like letter or a blank location. Cued location rejection models predict that participants should be faster to reject blank locations than a letter. Participants were significantly faster to reject invalidly cued blank items (24.0 ms) than invalidly cued letters (37.1 ms). This suggests a key role of cued location rejection.

Cued location rejection alone, however, cannot completely explain the search-difficulty-by-cue-validity interaction – when the cued location was maximally easy to reject (a blank item), cue validity effects were still 24 ms. Therefore, I tested a mathematical model of that unified both cued location rejection and target finding costs (i.e., the search time model). As can be seen in Table 9, this model performed well, predicting validity effects with less than 3-ms errors.

Costs of Capture: A Key Insight

Costs of capture represent a new way to theorize about attention capture. Previously, researchers largely assumed that cue validity effects merely reflect whether and where spatial attention shifts (i.e., probability of capture), and that the costs of being captured to a location largely remain constant across different paradigms and tasks (with the exception of Theeuwes' rapid disengagement account). For example, Folk and Remington (2006) state, "In the [precuing] paradigm, any [cue validity] effects can be attributed to the involuntary capture of attention by the distractor…" (p. 447). But, as demonstrated in the present study, cue validity effects are not merely an indication of whether spatial attention was captured. Validity effects also reflect other aspects of visual processing and visual search (e.g., object recognition and efficiency at finding the target). Thus, any successful model of attention capture will need to consider not only the likelihood that attention moved to a given location, but also the relative costs of moving

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attention to that location. These costs of capture have been largely uncontrolled in previous attention capture research. For example, the precuing paradigm and irrelevant feature paradigm both invoke wildly different costs of capture, but are both frequently used to assess whether onsets capture attention. The important role of this uncontrolled variable, which previously led to much confusion, is now clear.

Directions for Future Research on Onset Capture

The typical goal-driven precuing paradigm, which uses easy search, may provide an insensitive test of whether onsets (or any salient stimulus of interest) capture attention. In this precuing paradigm, participants search for a simple feature that is easily identified from the distractor. This approach does have advantages. A clearly-defined target leaves little question about the presumed attentional set (i.e., if the target is easily identified by red-ness, then researchers can comfortably assume participants searched for red). But this tactic could also decrease sensitivity to detecting capture by abrupt onsets. Easy search minimizes the costs associated with attention capture and thus will reduce overall cue validity effects from irrelevant cues.

One might question then, how relevant cues produce significant validity effects under easy visual search (Folk et al., 1992; Lien et al., 2008). As explained previously (in the Search Model section of Chapter 5), relevant color cues might give the cued search location an extra boost in relevance weighting. Even though the letter might be a poor match for the attentional set, the relevant cue matches the attentional set quite well. Thus, the relevant cue might cause momentary confusion about whether the cued location is the target (slowing the cued location's rejection as a target). For example, in Folk et

al., participants might have had difficulty determining that the cued item was white and that the relevant cue box was red.

In summary, researchers assessing attention capture by onsets should use difficult visual search as it sets up the most sensitive test for abrupt onset capture. Even if the probability of capture onsets is relatively low, the large costs of capture allow for small cue validity effects.

A Possible Residual Role of Strategy?

The current data certainly suggest an important role of nonstrategic capture costs in cue validity effects – especially under difficult visual search. However, such an account may require additional assumptions to explain all of the empirical data in the attention capture literature. For example, many precuing studies find essentially 0-ms validity effects from irrelevant onset cues, with very narrow error bars (e.g., Chen & Mordkoff, 2007; Folk et al., 1992). Such findings are troubling for a purely nonstrategic cost of capture account – moving spatial attention to an invalidly cued location should be associated with at least a small RT cost, even when the cued location is easy to reject and the target is easy to find.

One possibility is that the onset cue produces visual interference (i.e., forward masking). Forward masking from the cues would artificially decrease cue validity effects. On valid trials, the target is forward masked, slowing overall RT. On invalid trials, the target is not forward masked, decreasing overall RT. In other words, a 0-ms validity effect could actually reflect a small validity effect (e.g., 10-20 ms) when forward masking is controlled. Future research should investigate the role of masking in the precuing paradigm (which seems to have gone largely undiscussed).

Another possibility is that there is some remaining role for strategic factors, in combination with non-strategic effects. When search difficulty is manipulated by trial (as in Experiments 5 and 6), participants may lower their capture threshold (as in the adjustable threshold account) or establish a displaywide attentional set for onsets. In other words, every upcoming trial is strategically treated like a difficult search trial. Thus, a lowered capture threshold would increase the probability of capture by abrupt onsets in both difficulty conditions (including easy search), while difficulty would still modulate the costs of capture between conditions (as in the search time model).

There are some reasons to suspect that the probability of capture is low in studies using only easy search. For example, Lien et al. (2008) demonstrated compelling evidence that irrelevant onsets do not capture attention under blocked easy visual search using event-related potentials. Participants performed a precuing paradigm where they searched for a target defined by color (e.g., always red) and report its identity (T vs. L). This study measured an event-related potential component called the *N2-posterior-contralateral* (N2pc), which is a well-established index of attentional allocation (Luck, 2012). In several experiments, cue validity effects and N2pc effects were present for relevant cues, suggesting that they captured attention. In Experiment 3, these researchers assessed whether abrupt onsets could capture attention. Both onsets and relevant color singletons were pitted against one another, appearing at separate locations in the same cue display. [4] The presence of abrupt onsets cues did not disrupt these validity effects or

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[4] In event-related potential studies, it is critical to balance the stimulus-energy in displays to assure that any observed effect is attentional and not perceptual (e.g., Luck, 2005). This presents special challenges to studying abrupt onsets (which are an imbalance in

N2pc effects toward relevant cues, suggesting that onsets did not actually capture attention.
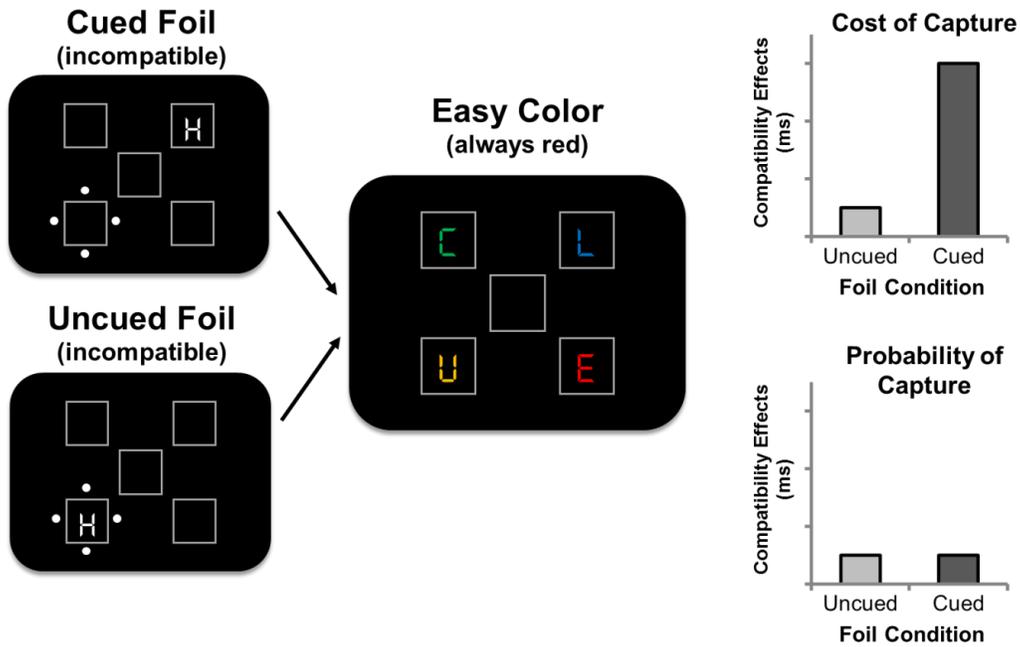
Figure 20. An identity intrusion experiment where easy color search. Note that this previous previously produced no cue validity effects (Experiment 3). The prediction of the competing accounts (probability of capture vs. costs of capture).

Future investigations might use the *identity intrusion technique* to assess whether the onset cue is attended or unattended under blocked easy search (e.g., Folk & Remington, 1998, 2006; Theeuwes & Burger, 1998). In this technique, a foil letter is presented at a random location within the cue frame (see Figure 20). This foil letter can

stimulus energy). Any differential activity between the contralateral and ipsilateral region of space (e.g., the N2pc effect) cannot appropriately be interpreted as an attentional effect. Thus, it is difficult to directly assess attention capture by abrupt onsets using the N2pc effect.

have a compatible or incompatible identity with respect to the present target. If the onset cue is truly attended under easy search, foil compatibility effects should be larger when it is cued than uncued (Gaspelin, Ruthruff, & Jung, in press). If the onset cue is truly unattended, however, foil compatibility effects should be equal when it is cued and uncued (i.e., no enhancement of processing by the cue). This technique would allow us to assess the relative probability of capture, independently of the costs of capture.[5]

A Comprehensive Theory of Attention Capture

To conclude, I will propose a comprehensive theory of attention capture based upon the findings of the current thesis. First, I propose that relevant-colored stimuli capture attention frequently and with large costs. Several studies have demonstrated that attention capture is strongly biased toward relevant-colored stimuli (Anderson & Folk, 2010; Bacon & Egeth, 1994; Becker, Folk, & Remington, 2010; Egeth et al., 2010; Folk & Anderson, 2010; Folk et al., 1992; Folk, Remington, & Wu, 2009; Folk, Leber, & Egeth, 2002, 2008; Folk & Remington, 1999, 2006, 2010; Gibson & Kelsey, 1998; Leber & Egeth, 2006; Lien, Gemperle, et al., 2010; Lien, Ruthruff, & Cornett, 2010; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010). In fact, nearly every study that has compared capture from relevant stimuli and irrelevant salient stimuli demonstrates stronger capture effects from relevant items (e.g., Folk et al., 1992; Gaspelin et al., 2012; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010). Note that many capture paradigms (e.g., the additional singleton paradigm or irrelevant feature paradigm) do not include relevant distractors for comparison with irrelevant salient distractors (Franconeri & Simons, 2003; Theeuwes, 1992, 1994; Yantis & Jonides, 1984).

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[5] I am currently conducting an identity intrusion study.

Although some studies have claimed to find capture by irrelevant color singletons (Belopolsky, Schreij, & Theeuwes, 2010; Burnham & Neely, 2008; Horstmann & Ansorge, 2006; Horstmann, 2002, 2005; Theeuwes, Atchley, & Kramer, 2000; Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002, 2002; Theeuwes, 1992, 1994, 2004), there is reason to doubt these supposed instances of stimulus-driven (see also the Attentional Window section in the Chapter 1). First, the typical present-absent costs associated with color singleton capture could reflect *filtering costs* (i.e., a slowing of a decision about where to move attention) instead of actual attention capture (Becker, 2007; Folk & Remington, 1998; Kahneman et al., 1983; Treisman et al., 1983). Second, color singletons seem to capture attention only under easy "parallel" visual search (e.g., see Gaspelin et al., 2012; Theeuwes, 1992). Because the target is usually also a singleton itself in these studies, any evidence of capture could reflect a broadened attentional set for any type of feature singleton (i.e., singleton detection mode; Bacon & Egeth, 1994). Therefore, I conclude there has been no compelling evidence for capture by irrelevant color singletons.

Given that both the probability of capture and costs of capture by irrelevant color singletons are low, color singletons should not be used as warning signals in the real-world. A neon yellow wet floor sign may hold attention once it is noticed, but its bright color alone does not guarantee that it will be attended. The consequences of exclusively relying on color singletons to attract attention could be catastrophic. Instead, designers may opt to continuously use the same colors as a warning signal (e.g., neon orange or red), as it allows observers to develop attentional sets for that stimulus.

Although spatial attention is able to block visual distraction from irrelevant color

singletons, spatial attention is unable to block distraction by irrelevant abrupt onsets. The cause of the seemingly contradictory results of goal-driven and stimulus-driven camps is now clear: the camps used differing search difficulty, which greatly modulates the costs of capture. Thus, the current thesis demonstrates that, under certain circumstances such as difficult search, spatial attention is involuntarily biased toward abruptly appearing objects in a visual scene. Instead, differences in validity effects reflect nonstrategic costs of capture. Note that, unlike the capture effects observed by color singletons, the observed pattern of greater capture by onsets here is likely not due to filtering costs (cue validity effects seem to reflect actual shifts of spatial attention; Becker, 2007; Folk & Remington, 1998; Lien et al., 2008) or singleton detection mode (which would predict greater capture under easy search – opposite the pattern observed here; Bacon & Egeth, 1994; Gaspelin, Ruthruff, Lien, et al., 2012).

Importantly, costs of capture by irrelevant onsets are modulated strongly by search difficulty. According to our search time model, probability of capture generally remains high across search difficulty. However, the costs of being captured will increase with search difficulty. We believe that it is safe to conclude that abrupt onsets are an effective warning signal in the real-world. For example, flashing police beacons will effectively cause nearby drivers to orient to them.

Abrupt onsets may not be the only type of stimuli to capture attention. Several researchers have shown that dynamic stimuli (e.g., motion and looming stimuli) have the ability to capture attention under difficult visual search (e.g., Franconeri & Simons, 2003; but see Folk et al., 1994). It is possible that abrupt onsets are part of a larger class of dynamic stimuli that can capture spatial attention. Although most attention capture

research focuses on abrupt onsets and color singletons, future research should also explore other types moving stimuli.

Conclusion

Researchers have long debated whether abrupt onsets can capture attention against the will of the viewer. Paradoxically, both camps consistently have produced opposing results. In the current thesis, I investigated the role of search difficulty while holding the paradigm constant. Validity effects were consistently greater under difficult search than easy search. Thus, I have clearly demonstrated an important role of search difficulty in capture by abrupt onsets. This difficulty effect is largely attributable to differences in nonstrategic capture costs (as shown in Chapters 5 and 6). Specifically, spatial attention has difficulty rejecting items that appear at invalidly cued locations, as well as difficulty locating the target, under difficult search. The neglected role of capture costs has enormous implications for future models of attention capture and future research on spatial attention.   In short, the most parsimonious interpretation of the current results is that onsets can capture attention, contrary to previous research using the precuing paradigm. This thesis helps to resolve a twenty-year debate about the nature of attentional control.

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   changing attentional control settings. *Journal of Experimental Psychology:

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Appendix

Articles Included in the Literature Review

Article	Exp.	Reported Onset Capture?	Target Type	Paradigm
Al-Aidroos, N., Harrison, S., & Pratt, J. (2010). Attentional control settings prevent abrupt onsets from capturing visual spatial attention. The Quarterly Journal of Experimental Psychology, 63(1), 31–41.	1	N	Color	Precue
Chen, P., & Mordkoff, J. T. (2007). Contingent Capture at a very short SOA: Evidence against Rapid Disengagement. Visual Cognition, 15(6), 637–646.	1	N	Color	Precue
Chua, F. K. (2009). A new object captures attention—But only when you know it's new. Attention, Perception, & Psychophysics, 71(4), 699–711.	1B	Y	Letter	IFP
Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 18(4), 1030–1044.	1	N	Color	Precue
Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 18(4), 1030–1044.	3	N	Color	Precue
Franconeri, S. L., & Simons, D. J. (2003). Moving and looming stimuli capture attention. Perception & Psychophysics, 65(7), 999–1010.	1	Y	Letter	IFP

Franconeri, S. L., Hollingworth, A., & Simons, D. J. (2005). Do New Objects Capture Attention? Psychological Science, 16(4), 275–281.	1	Y	Letter	IFP
Franconeri, S. L., Hollingworth, A., & Simons, D. J. (2005). Do New Objects Capture Attention? Psychological Science, 16(4), 275–281.	2	Y	Letter	IFP
Franconeri, S. L., Simons, D. J., & Junge, J. A. (2004). Searching for stimulus-driven shifts of attention. Psychonomic Bulletin & Review, 11(5), 876–881.	2	Y	Letter	IFP
Gellatly, A., Cole, G., & Blurton, A. (1999). Do equiluminant object onsets capture visual attention? Journal of Experimental Psychology: Human Perception and Performance, 25(6), 1609–1624.	1	Y	Letter	IFP
Gellatly, A., Cole, G., & Blurton, A. (1999). Do equiluminant object onsets capture visual attention? Journal of Experimental Psychology: Human Perception and Performance, 25(6), 1609–1624.	2	Y	Letter	IFP
Gibson, B. S., & Kelsey, E. M. (1998). Stimulus-driven attentional capture is contingent on attentional set for displaywide visual features. Journal of Experimental Psychology: Human Perception and Performance, 24(3), 699–706.	1	Y	Letter	Precue
Gibson, B. S., & Kelsey, E. M. (1998). Stimulus-driven attentional capture is contingent on attentional set for displaywide visual features. Journal of Experimental Psychology: Human Perception and Performance, 24(3), 699–706.	2	Y	Letter	Precue

Hollingworth, A., Simons, D. J., & Franconeri, S. L. (2010). New objects do not capture attention without a sensory transient. Attention, Perception, & Psychophysics, 72(5), 1298–1310.	2	Y	Letter	IFP
Humphreys, G. W., Olivers, C. N. L., & Yoon, E. Y. (2006). An onset advantage without a preview benefit: Neuropsychological evidence separating onset and preview effects in search. Journal of Cognitive Neuroscience, 18(1), 110–120.	1	Y	Letter	IFP
Juola, J. F., Koshino, H., & Warner, C. B. (1995). Tradeoffs between attentional effects of spatial cues and abrupt onsets. Perception & Psychophysics, 57(3), 333–342.	1	Y	Letter	Precue
Juola, J. F., Koshino, H., & Warner, C. B. (1995). Tradeoffs between attentional effects of spatial cues and abrupt onsets. Perception & Psychophysics, 57(3), 333–342.	2	Y	Letter	Precue
Lamy, D., & Egeth, H. E. (2003). Attentional capture in singleton-detection and feature-search modes. Journal of Experimental Psychology: Human Perception and Performance, 29(5), 1003–1020.	2	Y	Color	Precue
Lamy, D., & Egeth, H. E. (2003). Attentional capture in singleton-detection and feature-search modes. Journal of Experimental Psychology: Human Perception and Performance, 29(5), 1003–1020.	3	Y	Color	Precue
Lamy, D., & Egeth, H. E. (2003). Attentional capture in singleton-detection and feature-search modes. Journal of Experimental Psychology: Human Perception and Performance, 29(5), 1003–1020.	4	Y	Color	Precue

Lien, M.-C., Gemperle, A., & Ruthruff, E. (2011). Aging and involuntary attention capture: Electrophysiological evidence for preserved attentional control with advanced age. Psychology and Aging, 26(1), 188–202.	1	N	Color	Precue
Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2010). Attentional capture with rapidly changing attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 36(1), 1–16.	1	N	Color	Precue
Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2010). Attentional capture with rapidly changing attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 36(1), 1–16.	2	N	Color	Precue
Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2010). Attentional capture with rapidly changing attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 36(1), 1–16.	3	N	Color	Precue
Lien, M.-C., Ruthruff, E., Goodin, Z., & Remington, R. W. (2008). Contingent attentional capture by top-down control settings: Converging evidence from event-related potentials. Journal of Experimental Psychology: Human Perception and Performance, 34(3), 509–530.	3	N	Color	Precue
Martin-Emerson, R., & Kramer, A. F. (1997). Offset transients modulate attentional capture by sudden onsets. Perception & Psychophysics, 59(5), 739–751.	1	Y	Letter	IFP
Martin-Emerson, R., & Kramer, A. F. (1997). Offset transients modulate attentional capture by sudden onsets. Perception & Psychophysics, 59(5),	2	N	Letter	IFP

739–751.

Martin-Emerson, R., & Kramer, A. F. (1997). Offset transients modulate attentional capture by sudden onsets. Perception & Psychophysics, 59(5), 739–751.	3	N	Letter	IFP
Pratt, J., & Bellomo, C. N. (1999). Attentional capture in younger and older adults. Aging, Neuropsychology, and Cognition, 6(1), 19–31.	1	N	Color	Precue
Pratt, J., & Bellomo, C. N. (1999). Attentional capture in younger and older adults. Aging, Neuropsychology, and Cognition, 6(1), 19–31.	2	N	Color	Precue
Schreij, D., Theeuwes, J., & Olivers, C. N. L. (2010). Abrupt onsets capture attention independent of top-down control settings II: Additivity is no evidence for filtering. Attention, Perception, & Psychophysics, 72(3), 672–682.	3	Y	Color	Precue
Yantis, S., & Gibson, B. S. (1994). Object continuity in apparent motion and attention. Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 48(2), 182–204.	1	Y	Letter	IFP
Yantis, S., & Johnson, D. N. (1990). Mechanisms of attentional priority. Journal of Experimental Psychology: Human Perception and Performance, 16(4), 812–825.	1	Y	Letter	IFP
Yantis, S., & Johnson, D. N. (1990). Mechanisms of attentional priority. Journal of Experimental Psychology: Human Perception and Performance, 16(4), 812–825.	2	Y	Letter	IFP

Yantis, S., & Johnson, D. N. (1990). Mechanisms of attentional priority. Journal of Experimental Psychology: Human Perception and Performance, 16(4), 812–825.	3	Y	Letter	IFP
Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10(5), 601–621.	1	Y	Letter	IFP
Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10(5), 601–621.	3	Y	Letter	IFP
Yeh, S.-L., & Liao, H.-I. (2010). On the generality of the displaywide contingent orienting hypothesis: Can a visual onset capture attention without top-down control settings for displaywide onset? Acta Psychologica, 135(2), 159–167.	2	Y	Letter	Precue
Yeh, S.-L., & Liao, H.-I. (2010). On the generality of the displaywide contingent orienting hypothesis: Can a visual onset capture attention without top-down control settings for displaywide onset? Acta Psychologica, 135(2), 159–167.	1A	Y	Letter	Precue
Yeh, S.-L., & Liao, H.-I. (2010). On the generality of the displaywide contingent orienting hypothesis: Can a visual onset capture attention without top-down control settings for displaywide onset? Acta Psychologica, 135(2), 159–167.	1B	Y	Letter	Precue
Yeh, S.-L., & Liao, H.-I. (2010). On the generality of the displaywide contingent orienting hypothesis: Can a visual onset capture attention without top-down control settings for displaywide onset?	1C	Y	Letter	Precue

Acta Psychologica, 135(2), 159–167.				
Yantis, S., & Gibson, B. S. (1994). Object continuity in apparent motion and attention. Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 48(2), 182–204.		Y	Letter	IFP