The Problem of Latent Attentional Capture: Easy Visual Search Conceals Capture by Task-Irrelevant Abrupt Onsets

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Abstract

Researchers are sharply divided regarding whether irrelevant abrupt onsets capture spatial attention. Numerous studies report that they do and a roughly equal number report that they do not. This puzzle has inspired numerous attempts at reconciliation, none gaining general acceptance. We propose that abrupt onsets routinely capture attention, but the size of observed capture effects depends critically on how long attention dwells on distractor items which, in turn, depends critically on search difficulty. In a series of spatial cuing experiments, we show that irrelevant abrupt onsets produce robust capture effects when visual search is difficult, but not when search is easy. Critically, this effect occurs even when search difficulty varies randomly across trials, preventing any strategic adjustments of the attentional set that could modulate probability of capture by the onset cue. We argue that easy visual search provides an insensitive test for stimulus-driven capture by abrupt onsets: even though onsets truly capture attention, the effects of capture can be latent. This observation helps to explain previous failures to find capture by onsets, nearly all of which employed an easy visual search.

Keywords: attentional capture, abrupt onsets, visual search, visual attention

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In day-to-day life, we assume that flashing lights (*abrupt onsets*), such as police car sirens or lighthouse beacons, automatically draw our visual attention. However, laboratory research on attentional capture paints a more conflicted picture, with two directly opposed theoretical views. Stimulus-driven theorists report that abrupt onsets do capture attention, whereas goal-driven theorists report that abrupt onsets do not. In the current study, we evaluate the possibility that onsets always capture attention but the impact depends critically on search difficulty. Stimulus-driven theorists consistently rely on difficult visual search, whereas goal-driven theorists consistently rely on easy visual search. Importantly, easy visual search may offer an insensitive test of capture by onsets. Under easy search, distractor items no longer resemble a potential target and can thus be quickly rejected. This rapid distractor rejection could result in near-zero effects of capture, even if onsets always capture attention. This *attentional dwelling hypothesis* offers a compelling resolution to an empirical battle waged for over two decades.

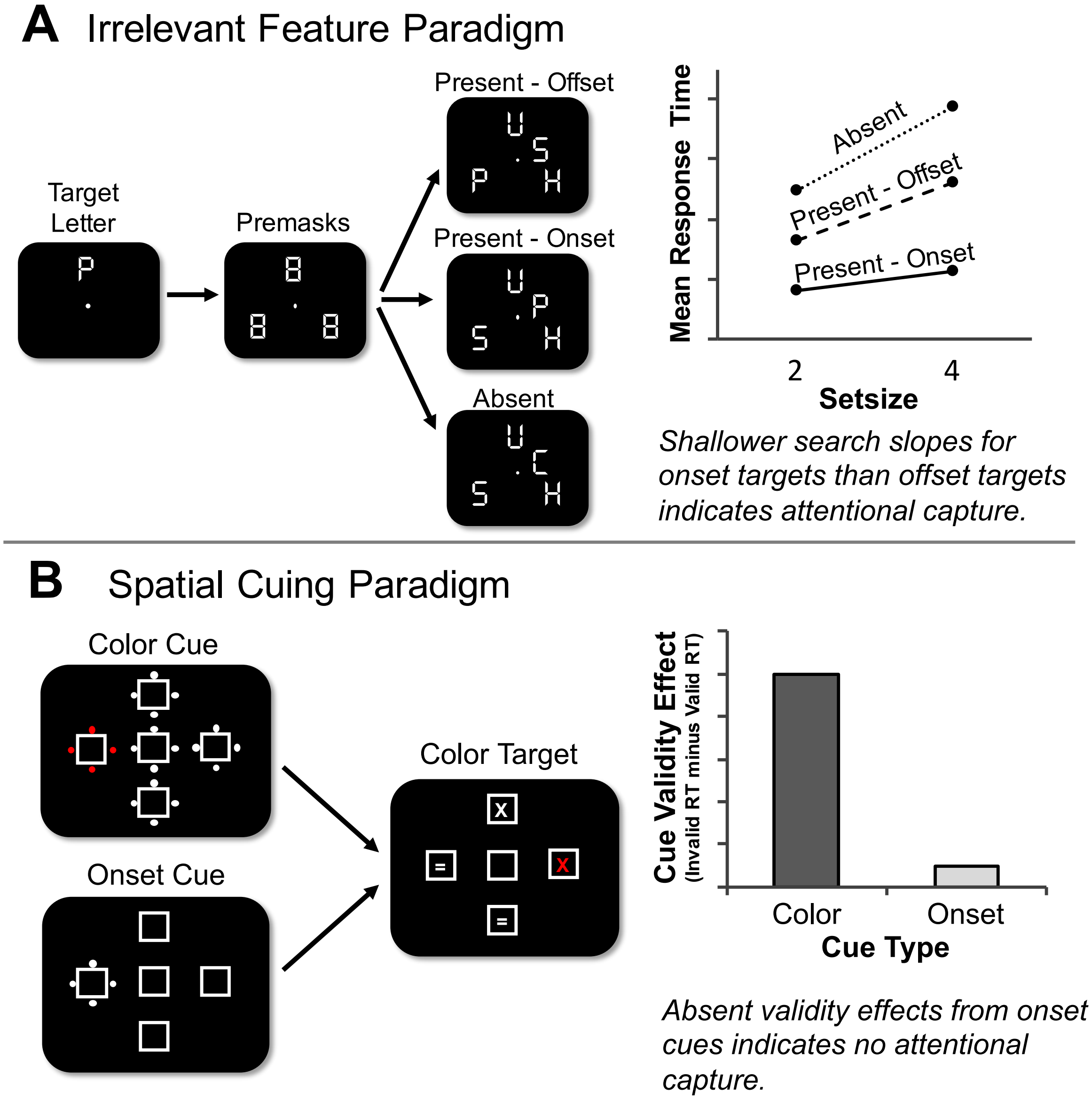
We provide several converging lines of evidence for the attentional dwelling hypothesis. First, we systematically categorize previous studies on abrupt onset capture. Almost all studies using an easy search for color failed to observe capture, whereas almost all using a more difficult search for letters reported capture. Second, we replicate this pattern in spatial cuing experiments controlling for extraneous factors. Third, we show that this pattern stems from differences in search difficulty, not search dimension (color vs. letter). Fourth, and perhaps most critically, we show that search difficulty alters observed capture effects even when participants have no foreknowledge of upcoming search difficulty. This finding rules out several prominent accounts, such as displaywide orienting and rapid disengagement. Altogether, the results indicate that attentional dwelling (a function of search difficulty) can drastically alter the size of observed capture effects, even when the probability of capture remains constant.

Background: The Attentional Capture Debate

Two theoretical accounts dominate attentional capture research. *Stimulus-driven* theories claim that salient stimuli automatically guide spatial attention, regardless of our goals (Franconeri & Simons, 2003; Yantis & Jonides, 1984). These theories predict frequent distraction because spatial attention is at the whim of the most salient item in a scene. Several types of salient stimuli have been proposed to capture attention, but perhaps the most widely agreed-upon are abrupt onsets. Stimulus-driven theories of onset capture largely rely upon results from the irrelevant feature paradigm (Figure 1) in which only one item within the search array onsets abruptly and the rest offset from premasks (Franconeri, Simons, & Junge, 2004; Franconeri & Simons, 2003; Hollingworth, Simons, & Franconeri, 2010; Jonides & Yantis, 1988; Yantis & Jonides, 1984). The key finding is that onset targets produce shallow search slopes (set-size-by-response-time functions), while offset targets produce steep search slopes. These findings imply that onset items automatically capture attention: If the onset item happens to be the target, there is no need for further visual search.

In contrast to stimulus-driven theories, *goal-driven* theories claim that only stimuli matching the observer's immediate goals (the attentional set) capture attention (Folk, Remington, & Johnston, 1992). Accordingly, these theories predict no distraction by salient stimuli, at the cost of missing unexpected salient stimuli, such as warning signals. Goal-driven accounts typically rely on the *spatial cuing paradigm* (Figure 1; Anderson & Folk, 2012; Folk et al., 1992;

Lien, Ruthruff, & Cornett, 2010; Lien, Ruthruff, Goodin, & Remington, 2008; Lien, Ruthruff, & Johnston, 2010). For example, Folk et al. (1992, Experiment 3, color search condition) had participants search for a red target and report its identity (X or =). A salient cue at a random location preceded this search display. If this cue captures attention, participants should respond faster when the cue appears at a target location (valid) than a nontarget location (invalid), called the *cue validity effect*. Interestingly, static red cues produced a large cue validity effect but abrupt onset cues did not, despite their apparent salience. They argued that stimuli mismatching the viewer's attentional set do not capture attention, no matter how salient.



Shallower search slopes for onset targets than offset targets indicates attentional capture.

Absent validity effects from onset cues indicates no attentional capture.

Figure 1. *A comparison of the irrelevant feature paradigm and the spatial cuing paradigm. Both are frequently used to study attentional capture by irrelevant abrupt onsets, yet consistently produce the opposite results.*

Puzzlingly, these two theoretical camps, with roughly equal membership, consistently produce opposite results and reach opposite conclusions. For example, Hollingworth et al. (2010) concluded that, "…salient stimuli can recruit attention independently of, or even in opposition to, an observer's goals…" (p. 1298). Meanwhile, Lien et al. (2008) concluded that, "…attentional capture by an object depends purely on the observer's intentions, not the abruptness of the onset" (p. 528).

Previous Attempts at Reconciliation

Each theoretical camp promotes "escape hatches" to explain away otherwise disconfirmatory evidence for their position. When onsets fail to produce capture effects, stimulus-driven theorists have claimed that attention initially moved to the onset cue but then quickly disengaged from it (Schreij, Owens, & Theeuwes, 2008; Schreij, Theeuwes, & Olivers, 2010a; Theeuwes, 2010). This *rapid disengagement account* has been strongly criticized (Anderson & Folk, 2012; Chen & Mordkoff, 2007; Folk & Remington, 2006, 2010; Gaspelin, Leonard, & Luck, 2015; Lien et al., 2008). For example, in a spatial cuing paradigm, Chen and Mordkoff (2007) used a very short (35 ms) stimulus onset asynchrony (SOA) between the cue and search array, leaving little time for spatial attention to disengage from onset cues before the search array. Nevertheless, cue validity effects were still negligible.

Another explanation for failures of onsets to capture attention is that the onsets appeared too frequently (Folk & Remington, 2015; Neo & Chua, 2006). For example, Neo and Chua 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. However, Noesen, Lien, and Ruthruff (2014) set up a competition between a task-relevant color and a task-irrelevant onset that was frequent (100%) or rare (20%). Even the rare onsets did not disrupt the allocation of attention to the task-relevant color cue. In short, there are mixed reports as to whether rarity modulates observed capture effects by abrupt onsets. Regardless, the rarity account struggles to explain the discrepant results between stimulus-driven and goal-driven camps. The frequency of onsets is often 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).

Meanwhile, when onsets produce capture effects, goal-driven theorists claim that onsets did not actually capture attention, but merely slowed a decision about where to move attention (Folk, Remington, & Wu, 2009). This *filtering cost account* has also been heatedly disputed (Belopolsky, Schreij, & Theeuwes, 2010; Lamy & Egeth, 2003; Schreij et al., 2010a; Schreij, Theeuwes, & Olivers, 2010b). Problematically, irrelevant onset cues sometimes produce substantial cue validity effects (Gaspelin, Ruthruff, Lien, & Jung, 2012; Lamy & Egeth, 2003; Schreij et al., 2010a), which are widely regarded as a reliable index of attentional capture, insensitive to filtering costs. Moreover, in the irrelevant feature paradigm, onset targets produce search <u>benefits</u>, which cannot easily be explained by a pure filtering cost model (Franconeri & Simons, 2003; Yantis & Jonides, 1984).

When irrelevant onsets do capture attention, goal-driven theorists have an additional out: *displaywide orienting*. When the entire search display abruptly onsets, participants might actively look for onsets, even though abrupt-onsetness contains no predictive information about the target location (Gibson & Kelsey, 1998). Currently, there exists no independent measure of a participant's attentional set, making this account difficult to empirically test (but see Franconeri et al., 2004). Importantly, this account is a poor predictor of onset capture. The irrelevant feature paradigm discourages displaywide sets for onsets by using premasks, yet often produces onset capture (e.g., Franconeri & Simons, 2003; Jonides & Yantis, 1988; Yantis & Jonides, 1984). Studies using the spatial cuing paradigm typically encourage a displaywide set for onsets by using no premasks yet produce no evidence of capture by onsets (Folk et al., 1992; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010; Noesen et al., 2014). In other words, the displaywide account predicts a pattern of capture that is, if anything, opposite to that actually observed in the literature.

In summary, researchers have proposed many different reconciliations, but none are widely accepted, leaving unanswered the basic question of whether abrupt onsets capture attention when task-irrelevant.

The Attentional Dwelling Hypothesis

In the current study, we follow an apparently overlooked reconciliation inspired by the heretofore overlooked) observation that stimulus-driven studies frequently use difficult visual search, whereas goal-driven studies frequently use easy visual search. Importantly, search difficulty may alter how quickly distractor items at the cued location are rejected, modulating the cost of capture without necessarily modulating the probability of capture. Under difficult search, the distractor item at the cued location (hereafter called the *cued distractor item*) is slowly rejected because it resembles the target. For example, in a search for an “E” or “H” target, target-like distractor letters (A, U, or S) roughly resemble the target and are therefore rejected relatively slowly. Furthermore, once the cued item has been rejected, the other distractors must also be searched and rejected (Wolfe, Cave, & Franzel, 1989). This causes long RTs on invalid trials compared to valid trials (where attention was directed to the target) and, thus, large validity effects. Under easy search (characterized by relatively flat search slopes), however, the distractor item at the cued location does not resemble the target and so is quickly rejected. For example, in a search for a red target, blue and green distractor letters can be easily rejected because they do not resemble the target. Additionally, once the cue has been rejected, attention quickly moves to the “popout” target without searching other distractor locations. In short, easy search minimizes the cost of attentional misdirection on invalidly cued trials, resulting in small validity effects.

There is one notable exception to this dwelling effect: easy search does produce large cue validity effects for relevant cues, such as a red box cue when looking for a red target letter. The relevant cue and distractor appear within a short temporal window of one another (typically 150 ms), which might make the color cue and distractor difficult to separate (i.e., a binding problem). Thus, the cued distractor could appear to have the relevant color and therefore be particularly difficult to reject, despite easy visual search. Similarly, because the target color recently appeared in two different locations (the cue location and the target location), the shift from cued distractor to target could be relatively slow.

To summarize, the attentional dwelling hypothesis assumes that irrelevant abrupt onsets reliably capture attention, but cue validity effects will decrease sharply as search difficulty (i.e., search efficiency) decreases. This is because cue validity effects do not merely reflect the probability of capture, as is routinely implicitly assumed, but also the costs of capture.

Attentional Dwelling vs. Rapid Disengagement

Theeuwes (2010) has previously argued along somewhat similar lines (see also Fukuda & Vogel, 2011), claiming that capture might reliably occur yet sometimes produce no observable costs. Specifically, he proposed the possibility of rapid disengagement of attention from the cue, prior to target onset. This account emphasizes dwell time on the cue, whereas the attentional dwelling hypothesis proposed here emphasizes dwell time on the distractor items in the search display, especially the cued search item (see Figure 2). A key assumption of the attentional dwelling model is that spatial attention does not rapidly disengage from the cue but rather lingers until the target display appears. The rationale is that, with no target to shift to, there is no great incentive for spatial attention to leave the current location, which might in fact contain the target a few milliseconds later.

Importantly, the present attentional dwelling model overcomes previous criticisms of Theeuwes' rapid disengagement model. For example, Chen and Mordkoff (2007) found no cue validity effects from onsets even at very short SOAs between the cue and the search array. Although the short SOA prevents rapid disengagement from the cue prior to target onset, it clearly does not prevent rapid rejection of cued distractor items. In their study, the green distractor items differed drastically from the purple target, allowing participants to rapidly reject the cued distractor item and locate the target.

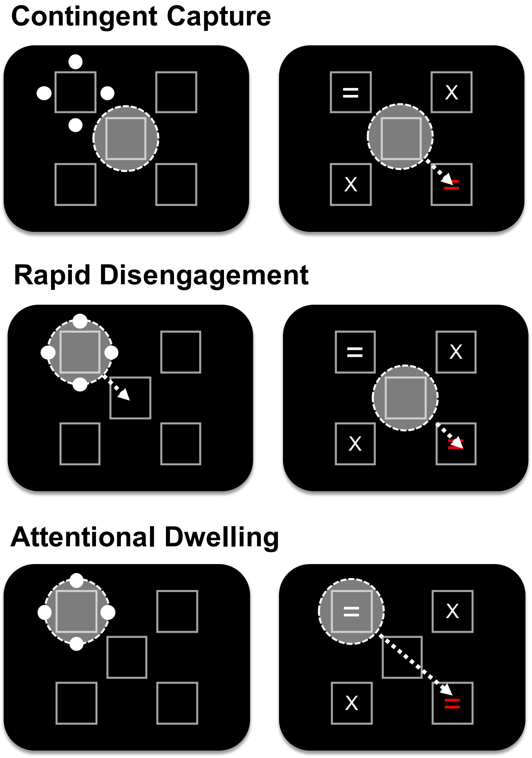


Figure 2. *A graphical depiction of the three competing accounts of cue validity effects in the spatial cuing paradigm (e.g., Folk et al., 1992). Contingent capture theory proposes that spatial attention is never captured by the cue and remains at a neutral position until the search array appears. Rapid disengagement and attentional dwelling differ in the proposed timecourse of dwelling. Rapid disengagement proposes that spatial attention is captured by the cue, but the cued is rapidly rejected as a potential target. Spatial attention shifts to a neutral positon before the search array. Attentional dwelling proposes that spatial attention is captured by the cue, and waits at that location until the search array. Distractor items in the search array are quickly rejected and spatial attention rapidly orients to the target.*

Tabulation of Previous Studies

To demonstrate that stimulus-driven studies frequently use difficult letter search, whereas goal-driven studies frequently use easy color search, we systematically reviewed the previous literature. Using search terms related to onset capture, a PsycINFO search returned 104 experiments that met our inclusion criteria (for details, see the Supplementary Material).

For those 104 experiments, we first assessed the relative prevalence of different paradigms: irrelevant feature (e.g., Yantis & Jonides, 1984), spatial cuing (e.g., Folk et al., 1992), additional singleton (e.g., Theeuwes, 1992), or other. As shown in Figure 3a, onset experiments have primarily used either the spatial cuing paradigm (32%) or the irrelevant feature paradigm (18%). To reduce noise caused by details of individual paradigms, subsequent analyses focus on these two paradigms only.

Next, we assessed the role of paradigm and search dimension (color vs. letter). We included only the 44 experiments that used targets clearly defined by either letter or color (combined $N = 945$). We then classified the outcome - presence/absence of onset capture, as reported by the authors.

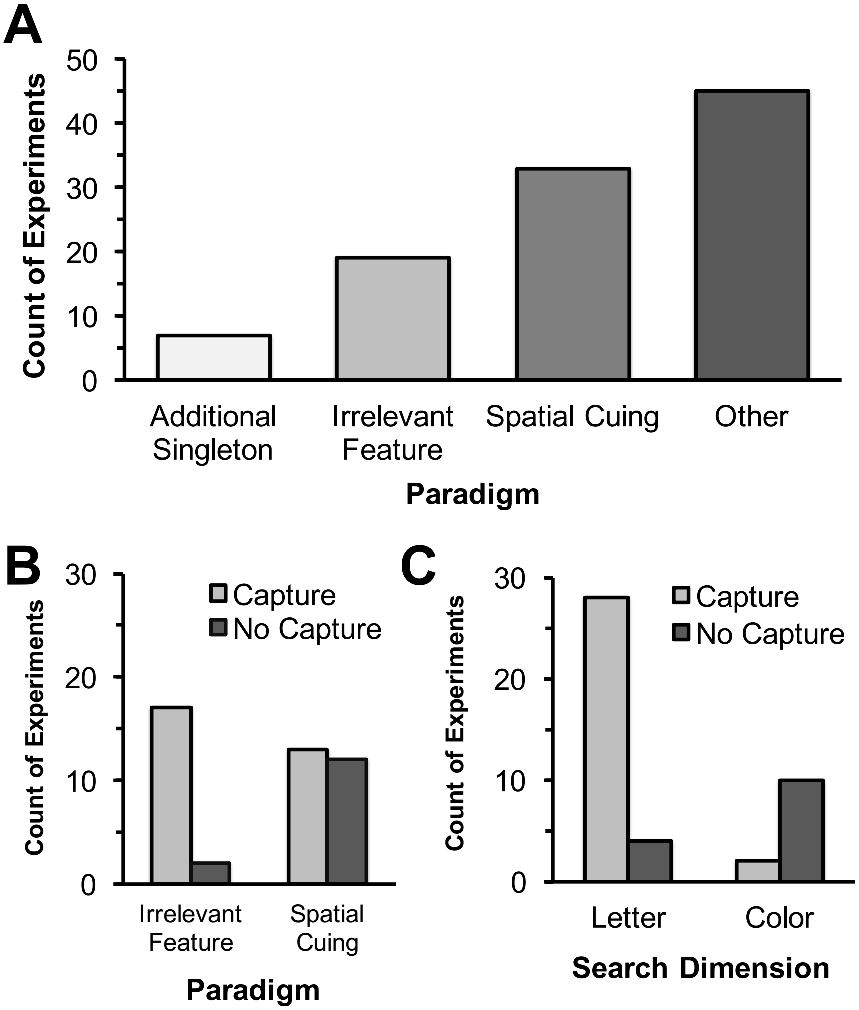


Figure 3. *Results from the literature review on attentional capture by abrupt onsets. (A) Number of experiments of onset attentional capture by paradigm. (B) Number of irrelevant-feature paradigm and spatial cuing paradigm experiments observing attentional capture by onsets. (C) Number of irrelevant-feature paradigm and spatial cuing paradigm experiments observing attentional capture by onsets by search dimension.*

As shown in Figure 3b, paradigm is a relatively poor predictor of capture by irrelevant abrupt onsets. Of the 19 experiments using the irrelevant feature paradigm, 89% produced capture by onsets, whereas of the 25 studies using the spatial cuing paradigm, 52% produced capture. As shown in Figure 3c, search dimension is a strong predictor of whether onsets will capture attention. Of the 32 experiments using letter search, the vast majority found onset capture (88%). Of the 12 experiments using color search, only a minority found onset capture (17%). Overall, search dimension correctly predicts the outcome of studies 87% of the time, even without knowing the paradigm. This is remarkably accurate, given that one would expect some Type I or Type II errors, even with a large effect size (Schimmack, 2012). This striking effect of search type on capture is highly significant, $\chi^2 = 20.2$, $p < .0001$.[1] Interestingly, adding paradigm type (spatial cuing vs. irrelevant feature) to this model adds no additional predictive value.

Finally, we assessed whether search dimension is confounded with search difficulty. Unfortunately, attentional capture studies rarely report a reliable indicator of search difficulty (e.g., search slopes). Among the exceptions, however, letter search produced much steeper search slopes (e.g., 33-35 ms per item; Franconeri & Simons, 2003; Yantis & Jonides, 1984) than color search (e.g., 6-9 ms per item; Gaspelin, Ruthruff, Lien, & Jung, 2012; Lien, Ruthruff, & Johnston, 2010).

The Current Study

The preceding literature review suggests a dominant role of search difficulty in determining whether onsets capture attention or fail to do so. Even more remarkable than the strength of the difficulty effect is the fact that, to our knowledge, no previous researcher has commented on the pattern. Although this pattern is consistent with a dwelling hypothesis, many variables were confounded across studies, preventing definitive conclusions. In the present study, therefore, we manipulated search difficulty, while holding extraneous variables constant. According to the attentional dwelling hypothesis, cue validity effects should increase with overall search difficulty, by boosting the RT-based costs of being captured without changing the probability of capture.

Experiment 1

We compared easy color search and difficult letter search in a spatial cuing paradigm. Participants searched for a target in a display of colored letters (see Figure 4a) and reported its identity (E vs. H). In the *color search* phase*,* the target could be found by its red color. In the *letter search* phase*,* the target could be found only by letter shape, because its color was random. Except for this correlation between target identity and color within the color phase, the two displays were identical. The color search phase was analogous to previous spatial cuing studies from goal-driven theorists (e.g., Folk et al., 1992; Lien et al., 2008), whereas the letter search phase was similar to previous irrelevant-feature paradigm studies used by stimulus-driven theorists (e.g., Yantis & Jonides, 1984).

We measured the cue validity effect produced by an irrelevant onset cue, which appeared on every trial. According to the attentional dwelling hypothesis, cue validity effects should be greater in the letter search phase (difficult) than the color search phase (easy). Purely goal-driven accounts predict that cue validity effects should be absent under both search conditions, because irrelevant onsets cannot capture attention.

Methods

Participants. Forty-four University of New Mexico undergraduates participated for course credit. Two were excluded due to high error rates (>2.5 SDs above the group mean), leaving 42 participants (27 females; mean age: 19.4 years). In all experiments, participants had normal color vision (assessed by an Ishihara color vision test) and self-reported normal or corrected-to-normal visual acuity.

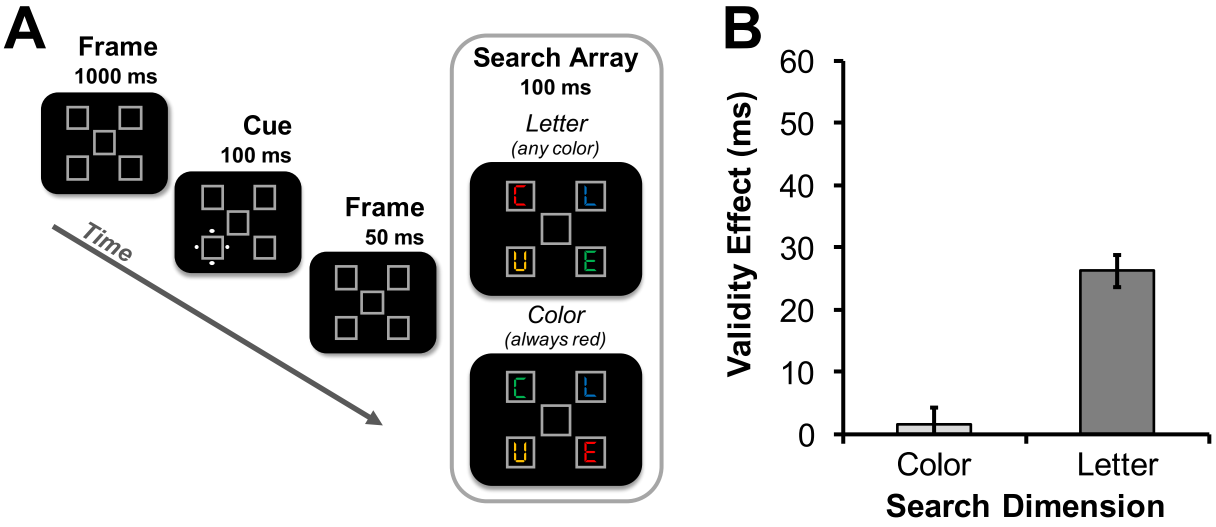


Figure 4. *Experiment 1 stimulus displays and results. (A) In the letter search phase, the target color was chosen randomly. In the color search phase, the target color was fixed (always red). (B) Cue validity effects (ms) by search dimension condition (color vs. letter) for Experiment 1. In all Figures, error bars represent the within-subjects 95% confidence interval (Loftus & Masson, 1994).*

Apparatus and Stimuli. Stimuli were presented on 19-inch monitors using personal computers. Letters, presented in a digital-clock font, were 1.9° (width) × 1.9° (height), based on an average viewing distance of 60 cm. Each display contained one letter in green (RGB value of 0, 153, 0), red (255, 0, 0), blue (40, 40, 255), and yellow (255, 205, 0). Placeholders were gray (138, 138, 138) unfilled boxes (2.4° × 2.4°). There were four rectangular placeholders at the corners of an imaginary square (10° × 10°) and one at fixation. In the cue frame, four white dots (255, 255, 255; 0.5° in diameter) abruptly onsetted around one of the four outer placeholders (forming an imaginary diamond 3.3° × 3.3°).

Design. Each session was divided into two phases, one for each search condition. Search phase order was counterbalanced across participants. Each phase consisted of 1 block of 32 practice trials followed by 4 blocks of 64 regular trials (576 total trials). In both phases, search displays contained a target letter (E or H) and three distractors (C, L, S, or U randomly chosen without replacement), each in a unique color (blue, green, red, or yellow). Target identity and location were randomized. In the letter search phase, target letter color (green, blue, red, or yellow) was randomly intermixed, so participants had to find the target based upon its letter shape alone. In the color search phase, the target was always red, so participants could merely search for red.

Procedure. Participants were instructed to locate the target and report its identity as quickly and accurately as possible by pressing the key labeled “E” or “H” (actual keys: z and m, respectively). Each trial began with a presentation of the five placeholders for 1000 ms, followed by a 100-ms presentation time of the abrupt onset cue. Then, the abrupt onset cue then disappeared, leaving the placeholders alone for 50 ms. The search letters then appeared for 100 ms. Thus, the total time between the abrupt onset and target offset was 250 ms. If incorrect, then participants heard an error beep (225 Hz) for 300 ms. Participants also received block-by-block feedback on mean response time (RT) and accuracy. Participants were informed when, after half a session, search dimension changed.

Results

In all experiments, RTs less than 200 ms or greater than 2000 ms (less than 0.4% of trials) were excluded from RT and error rate analyses. Errors were also excluded from RT analyses. Table 1 shows the resulting mean RTs and error rates. Figure 4b shows cue validity effects by search dimension. Within-subject analysis of variances (ANOVAs) with the factors search dimension (letter vs. color) and cue validity (invalid vs. valid) were conducted on mean RTs and error rates. Cohen's *d* (hereafter reported as *d*) is reported as a measure of effect size, where less than .2 represents a relatively small effect and greater than .8 represents a relatively large effect.

Table 1

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

	Color		Letter	
	RT	PE	RT	PE
Invalid	535	4.3%	658	7.6%
Valid	533	4.4%	632	6.8%
Validity Effect	2		26	

Note. RT = Response Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. Participants responded more quickly in the color search phase (534 ms) than the letter search phase (645 ms), $F(1, 41) = 134.01$, $p < .001$, $\eta_p^2 = .766$, indicating that color search was much easier than letter search. Participants also responded more quickly following valid cues (583 ms) than invalid cues (597 ms), $F(1, 41) = 18.76$, $p < .001$, $\eta_p^2 = .314$.

The key question was whether color search would produce a smaller cue validity effect than letter search. Cue validity effects were generally larger under letter search than color search. The interaction of search dimension and cue validity was significant, $F(1, 41) = 22.08$, $p < .001$, $\eta_p^2 = .350$. Preplanned *t* tests compared invalid cue and valid cue trials for each search phase (color and letter). Cue validity effects were negligible for color search (2 ms), $t(41) < 1$, $p > .10$, $d = .027$, but large for letter search (26 ms), $t(41) = 5.7$, $p < .001$, $d = .262$.

Error rate analysis. Participants committed more errors under letter search (7.2%) than color search (4.4%), $F(1, 41) = 18.13$, $p < .001$, $\eta_p^2 = .307$. The interaction of cue validity and search dimension was nonsignificant, $F(1, 41) = 1.94$, $p > .10$, $\eta_p^2 = .045$.

Discussion

We directly compared, for the first time, the color search used by goal-driven theorists with the letter search used by stimulus-driven theorists. Color search produced shorter RTs and lower error rates than letter search, indicating that color search was easier. Importantly, color search produced a negligible cue validity effect (2 ms) whereas letter search produced a substantial cue validity effect (26 ms). This remarkably strong effect is consistent with the attentional dwelling hypothesis, which predicts that as search becomes more difficult cue validity effects from onsets should increase. These findings are inconsistent with purely goal-driven accounts, which assert that onsets never capture attention.

Experiment 2

Experiment 1 used the typical parameters of a spatial cuing paradigm – no premasks and a 150-ms SOA between the cue and search array. In Experiment 2, we aimed to replicate these findings using the typical parameters of the irrelevant-feature paradigm – premasks before the search array and a 0-ms SOA between the cue and search array.

Participants. Thirty-eight University of New Mexico undergraduates participated for course credit. One was excluded due to a high error rate and another was excluded due to a high overall mean response time (>2.5 SDs above the group mean), leaving 36 participants (25 females; mean age: 21.5 years).

Apparatus, Stimuli, Design, and Procedure. The methods were identical to Experiment 1 except for two key changes (see Figure 5a). First, gray Figure-8 premasks were presented in the placeholder frame and cue frames preceding the search display. Pilot participants had low accuracy (< 85%), presumably because forward masking made it difficult to perceive the briefly presented (50 ms) search letters. To boost overall accuracy, we presented the search display until response. Second, rather than using a 150-ms SOA, onsets appeared with the search display, yielding an SOA of 0 ms.

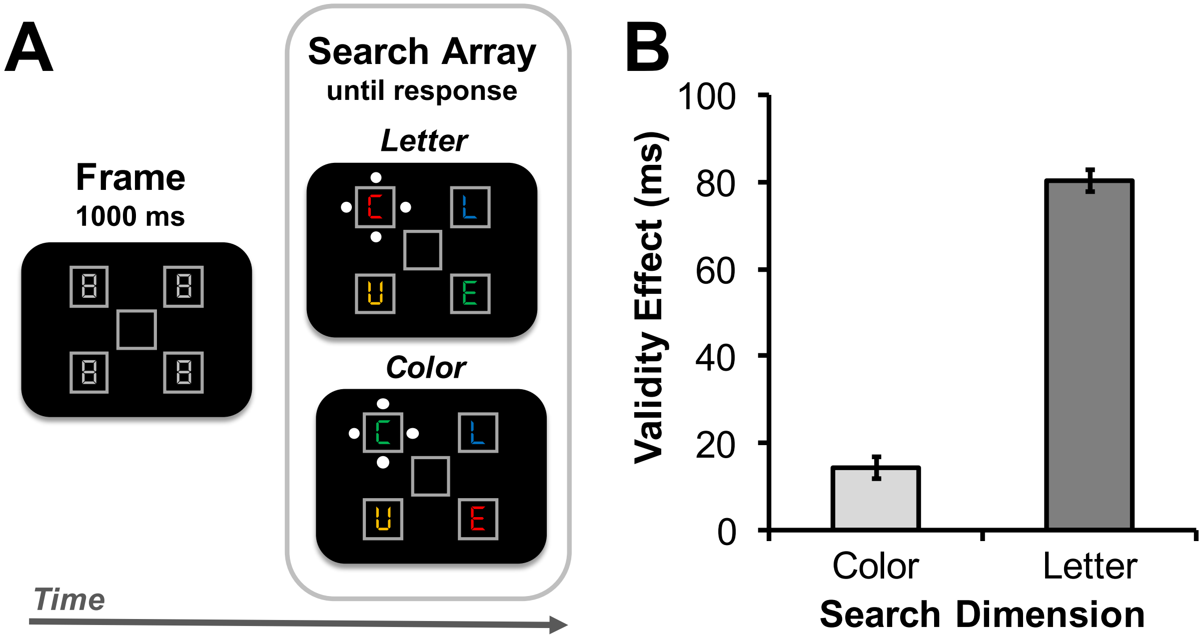


Figure 5. *Stimulus displays and results for Experiment 2. (A) The target color was fixed in the color search phase (always red), but varied randomly by trial in the letter search phase. (B) Cue validity effects (ms) by search dimension condition (color vs. letter) for Experiment 1*

Results

Table 2 shows mean RTs and error rates. Figure 5b shows cue validity effects. Within-subject ANOVAs with the factors search dimension (color vs. letter) and cue validity (invalid vs. valid) were conducted on mean RTs and error rates.

RT analysis. Participants responded more quickly in the color search phase (568 ms) than letter search phase (734 ms), $F(1, 35) = 176.04$, $p < .001$, $\eta_p^2 = .834$. Participants also responded more quickly when the cue was valid (627 ms) rather than invalid (675 ms), *F*(1, 35) = 137.10, $p < .001$, $\eta_p^2 = .797$.

Table 2

Mean Response Time (ms) and Percent Error by Search Condition and Cue Validity for Experiment 2.

	Color		Letter	
	RT	PE	RT	PE
Invalid	575	3.2%	774	3.3%
Valid	560	4.5%	694	3.2%
Validity Effect	15		80	

Note. RT = Response Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

Importantly, onsets produced a much smaller cue validity effect under color search (15 ms) than letter search (80 ms), *F*(1, 35) = 80.62, $p < .001$, $\eta_p^2 = .697$. Preplanned *t* tests compared invalid-cue and valid-cue trials for each search phase (color and letter). Cue validity effects were significant under color search, *t*(35) = 4.87, $p < .001$, $d = .219$, and letter search, *t*(35) = 11.27, $p < .001$, $d = .740$.

Error rate analysis. Participants did not commit significantly more errors under color search (3.9%) than letter search (3.2%), *F*(1, 35) = 3.42, $p > .05$, $\eta_p^2 = .089$. Participants also did not commit significantly more errors on invalid trials (3.2%) than valid trials (3.8%), *F*(1, 35) = 3.65, $p > .05$, $\eta_p^2 = .035$. Consistent with the RT effects, the interaction of cue validity and search difficulty was significant, *F*(1, 35) = 6.35, $p < .05$, $\eta_p^2 = .154$.

Discussion

We tested whether letter search produces larger validity effects than color search. Unlike Experiment 1, we used the presentation parameters typically employed in the irrelevant feature paradigm. As in Experiment 1, color search again led to shorter overall RTs than letter search, indicating that it is easier. Importantly, color search produced a much smaller cue validity effect than letter search (15 ms vs. 80 ms). These data support the attentional dwelling hypothesis, which predicts that cue validity effects should increase with search difficulty. Again, these data are inconsistent with purely goal-driven accounts, which predict no capture by abrupt onsets.

Experiment 3

In Experiments 1 and 2, letter search was more difficult than color search, as indexed by increases in overall RT and error rates. Experiment 3 therefore tested the assumption of the attentional dwelling hypothesis that the critical determinant of onset capture is not search dimension (letter vs. color), per se, but rather search difficulty. Specifically, the difficult letter search condition from Experiment 1 was compared to a much easier letter search with homogenous O distractors. The attentional dwelling hypothesis predicts that cue validity effects should be larger under difficult search than easy search. This is because difficult search boosts the response-time costs after initial capture, without altering probability of capture.

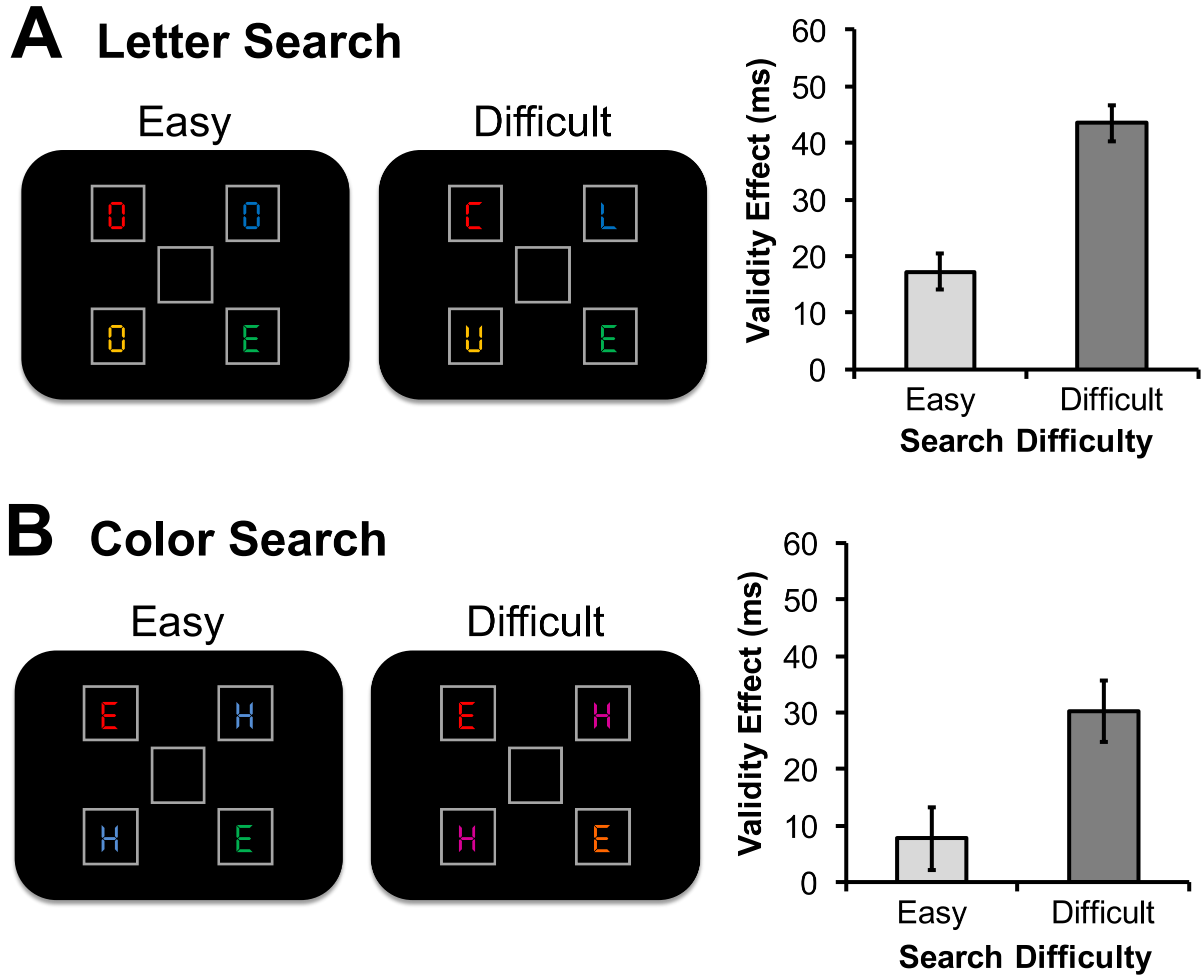


Figure 6. *Stimulus displays and results for Experiments 3 and 4. (A) In Experiment 3, the target could only be found by its letter shape (E or H). In the easy search phase, the target was surrounded by a homogenous set of O's. In difficult search phase, the target was surrounded by heterogenous distractor letters. (B) In Experiment 4, the target could be found only by its color (always red). In the easy search phase, the target was surrounded by blue and green distractors. In difficult search phase, the target was surrounded by pink and orange distractors.*

Methods

Participants. Fifty-six University of New Mexico undergraduates participated for course credit (37 females; mean age: 20.2 years).

Apparatus, Stimuli, Design, and Procedure. All methods were identical to Experiment 1, except that search difficulty was manipulated rather than search dimension (see Figure 6a). In the difficult search phase, the target (E or H) was presented amongst heterogeneous distractor letters (C, L, S, or U as in Experiment 1). In the easy search phase, the target was presented amongst homogenous, target-dissimilar distractors (O's).

Results

Table 3 shows mean RTs and error rates. Figure 6a shows cue validity effects. Within-subject ANOVAs with the factors search difficulty (easy vs. difficult) and cue validity (invalid vs. valid) were conducted on mean RTs and error rates.

Table 3

Mean Response Time (ms) and Percent Error by Search Difficulty and Cue Validity for Experiment 3

	Easy		Difficult	
	RT	PE	RT	PE
Invalid	582	5.5%	679	10.7%
Valid	565	3.9%	635	6.9%
Validity Effect	17		44	

Note. RT = Response Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. Participants responded more quickly in the easy search phase (574 ms) than difficult search phase (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) rather than invalid (631 ms), $F(1, 55) = 69.04, p < .001, \eta_p^2 = .557$.

Importantly, easy search produced a small cue validity effect (17 ms), whereas difficult search produced a large cue validity effect (44 ms), $F(1, 55) = 17.06, p < .001, \eta_p^2 = .237$. Preplanned t tests revealed compared invalid-cue and valid-cue trials for each search difficulty phase (easy and difficult). Cue validity effects were significant under easy search, $t(55) = 3.24, p < .01, d = .164$, and difficult search, $t(55) = 9.98, p < .001, d = .410$.

Error rate analysis. Participants committed more errors with difficult search (8.8%) than easy search (4.7%), $F(1, 55) = 49.59, p < .001, \eta_p^2 = .474$. Participants also made more errors on invalid trials (8.1%) than valid trials (5.4%), $F(1, 55) = 31.54, p < .001, \eta_p^2 = .364$. Consistent with the RT data, the interaction of cue validity and search difficulty was significant, $F(1, 55) = 7.73, p < .01, \eta_p^2 = .123$.

Discussion

In this experiment, the target was defined only by letter identity. Importantly, the cue validity effect was larger under difficult letter search than under easy letter search. As predicted by our attention dwelling account, we propose that the critical determinant of cue validity effects is not search dimension (letter vs. color) but rather search difficulty is.

Experiment 4

Whereas Experiment 3 tested the role of search difficulty under letter search, the current experiment examined color search.

Participants. Twenty University of New Mexico undergraduates participated (13 females; mean age: 21.2 years).

Stimuli, Design, and Procedure. The design was similar to Experiment 1, expect for a few key changes (Figure 6b). The target was always red. We manipulated the distance of the distractors in color space from the red target (RGB value: 255, 0, 0). In the easy search phase, the target was surrounded by green (0, 151, 0) and blue (0, 128, 255) distractors, far in color space from the red target. In the difficult search phase, the target was surrounded by pink (210, 0, 80) and orange distractors (210, 80, 0), near in color space to the red target. Distractor colors were chosen at random with the restriction that each color be used at least once per trial (e.g., two blue and one green). This prevented participants from using singleton-detection mode to find the target. To prevent participants from using shape to find the target instead of color, distractor identities were changed to Es and Hs. Letter identities were chosen at random with the restriction that each display contain two Es and two Hs. A pilot experiment with 100-ms target displays produced low accuracy (below 80%) in the difficult-search phase, so we allowed the search array to remain until response. The practice block increased from 32 trials (as in previous experiments) to 64 trials.

Results

Table 4 shows mean RTs and error rates. Figure 6b shows cue validity effects. Analyses matched those of Experiment 3.

Table 4

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

	Easy		Difficult	
	RT	PE	RT	PE
Invalid	576	2.9%	667	3.3%
Valid	568	3.3%	637	2.5%
Validity Effect	8		30	

Note. RT = Response Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. Participants responded more quickly under easy search (572 ms) than difficult search (652 ms), $F(1, 19) = 65.29, p < .001, \eta_p^2 = .775$. Participants also responded more quickly when the cue was valid (603 ms) rather than invalid (622 ms), $F(1, 19) = 20.63, p < .001, \eta_p^2 = .521$.

Easy search produced a smaller cue validity effect (8 ms) than difficult search (30 ms), $F(1, 19) = 12.54, p < .01, \eta_p^2 = .398$. Preplanned t tests on the cue validity for each search condition revealed a significant effect for difficult search, $t(19) = 5.04, p < .001, d = .337$, but not easy search, $t(19) = 1.76, p = .09, d = .090$.

Error rate analysis. Only the interaction of cue validity and difficulty was significant, $F(1, 19) = 5.77, p < .05, \eta_p^2 = .233$, consistent with the RT results.

Discussion

When the search dimension was color, we again found a much larger cue validity effect under difficult search than easy search. We conclude that large differences in cue validity effects between those who use letter search and those who use color search stems not from differences in search dimension (letter vs. color) per se, but rather differences in search difficulty.

Experiment 5

In Experiments 3 and 4, search difficulty was blocked into two consecutive phases. In one phase, participants performed easy search and, in the other phase, participants performed difficult search. Although the results were predicted by the attentional dwelling hypothesis, they could also be explained post-hoc by two alternative accounts: displaywide orienting and rapid disengagement. Below we explained each of the three candidate accounts and then described a critical test between them.

First, difficult search might encourage participants to adopt a displaywide attentional set for abrupt onsets. For example, when the target is difficult to locate based on its defining property, participants (arguably) might incorporate additional properties common to all display elements, such as their abrupt onset, into their attention set. This adoption of an attentional set for onsets would naturally induce capture by onset cues in that block. The displaywide-orienting account of our findings is inherently strategic. Participants must have knowledge of the upcoming search display difficulty to adjust the attentional set.

Second, rapid disengagement could also potentially explain the search difficulty effect. The key assumption is that capture is involuntary and bottom-up, but subsequent disengagement is subject to top-down control. Under easy search, spatial attention might shift to the onset cue but then quickly reject it as a potential target and rapidly disengage. This would minimize cue validity effects, because attention returns to a neutral position prior to target onset. In difficult search, however, an observer might have more difficulty rejecting the white onset cue, due to adoption of a broader attentional set, producing large cue validity effects. This post-hoc assumption of a broad attentional set under difficulty search is not an entirely obvious implication of the model, but is at least plausible. The rapid disengagement account of the difficulty effect is strategic. Participants must have foreknowledge of the upcoming search display to alter their top-down set to rapidly disengage from the cue, which appears before the search array. If upcoming search difficulty is unknown at the time of cue presentation, then disengagement time would necessarily be equivalent (at least for the 150 ms prior to target display onset).

Whereas the above two alternative accounts depend on strategic adjustments in response to search difficulty, the attention dwelling account does not. It asserts that onset cues frequently capture spatial attention under both levels of search difficulty. Once captured, spatial attention waits at the cued location until the appearance of the search array. The costs of capture are then determined by how quickly the cued search item can be rejected and how quickly the target can be found. Thus, the attentional dwelling hypothesis requires no strategic adjustments to the attentional set. Indeed, difficult search should increase capture effects even if search difficulty were manipulated randomly trial-by-trial, preventing foreknowledge of the upcoming search difficulty.

In Experiment 5, therefore, we tested whether the difficulty effect occurs even when difficulty levels are randomly intermixed, preventing foreknowledge of upcoming difficulty at the time of the cue. Strategic accounts, such as displaywide orienting and rapid disengagement, predict no difference in validity effects between search difficulty conditions. The attentional dwelling hypothesis, however, is nonstrategic and thus uniquely predicts that validity effects will still be much larger under difficult search than easy search.

Methods

Participants. Forty-five undergraduates from the University of New Mexico participated for course credit. One participant was excluded from final 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 3, except that search difficulty was manipulated randomly by trial. Participants searched for a letter target that was surrounded either by homogenous O distractors (easy search) or by heterogeneous letter distractors (difficult search).

Results

Table 5 shows mean RTs and error rates. Figure 7a shows cue validity effects. Analyses matched those of Experiment 3.

Table 5

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

	Easy		Difficult	
	RT	PE	RT	PE
Invalid	586	5.3%	655	8.5%
Valid	577	5.0%	622	8.7%
Validity Effect	9		33	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. Participants responded more quickly under easy search (582 ms) than difficult search (639 ms), $F(1, 43) = 230.346$, $p < .001$, $\eta_p^2 = .843$. Participants also responded more quickly when the cue was valid (600 ms) rather than invalid (621 ms), $F(1, 43) = 25.596$, $p < .001$, $\eta_p^2 = .408$.

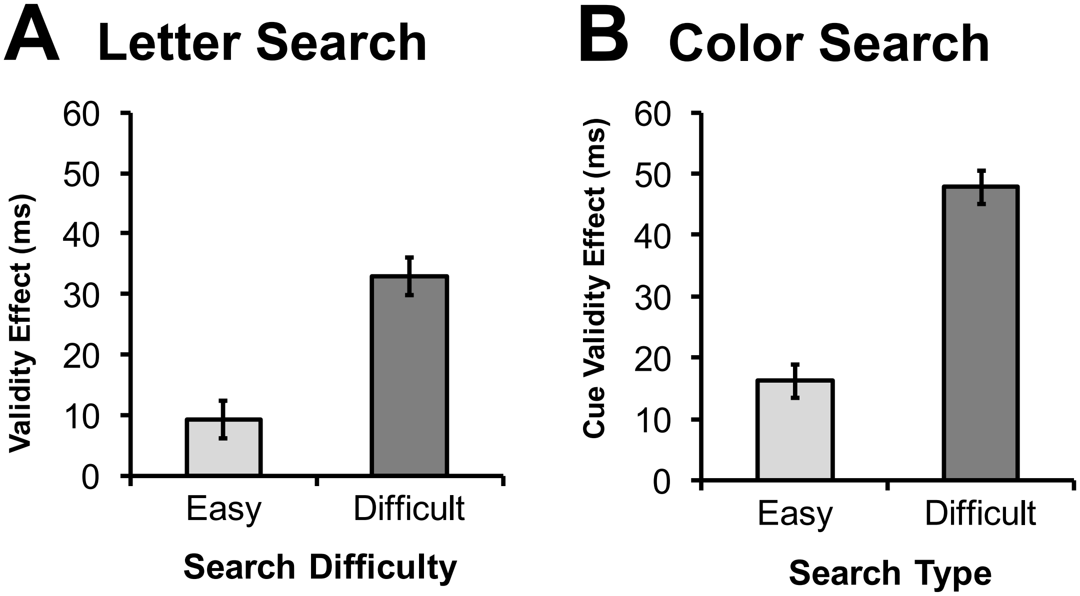


Figure 7. *Results for Experiments 5 and 6, in which search difficulty varied randomly by trial. (A) In Experiment 5, the target could only be found by its letter shape. (B) In Experiment 6, the target could only be found by its color (always red).*

Critically, easy search produced a smaller cue validity effects (9 ms) than difficult search (33 ms), *F*(1, 43) = 15.13, $p < .001$, $\eta_p^2 = .26$. Preplanned *t* tests on the cue validity effect for each search condition revealed that effects were significant under both easy search, *t*(43) = 2.55, $p < .05$, $d = .138$, and difficult search, *t*(43) = 5.54, $p < .001$, $d = .457$.

Error rate analysis. Participants committed more errors in difficult search blocks (8.6%) than easy search blocks (5.2%), *F*(1, 43) = 59.863, $p < .001$, $\eta_p^2 = .582$. All other interactions and main effects were nonsignificant, *F*s < 1.

Discussion

Search difficulty varied randomly across trials, preventing any strategic adjustments to the attentional set. The strategy in place during cue presentation (which occurred prior to target presentation) must have been identical for the easy and difficult search conditions. Still, cue validity effects were much greater on difficult search trials than easy search trials. This result is highly problematic for all strategic accounts of the difficulty effect, such as displaywide orienting and rapid disengagement. Put another way, the findings argue against any account that assumes differential probability of capture in the easy and difficulty search conditions.

Instead, these results support the attentional dwelling hypothesis, the only nonstrategic account for the search-difficulty effect on onset capture. We conclude that onsets generally capture attention, regardless of search difficulty, but the impact of that capture depends greatly on difficulty encountered during the subsequent visual search.

Experiment 6

The current experiment assesses the robustness of the findings of Experiment 5. We again manipulated search difficulty trial-by-trial. But, instead of using letter search, we used color search. Only the attentional dwelling hypothesis predicts larger cue validity effects under difficult search than easy search.

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. All methods were identical to those of Experiment 4, except that search difficulty was manipulated randomly by trial. Participants searched for a red target surrounded by either dissimilar-colored distractors (blue and green; easy search) or similar-colored distractors (orange and pink; difficult search).

Results

Mean RTs and error rates are shown in Table 6. Cue validity effects by search difficulty condition are shown in Figure 7b.

Table 6

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

	Easy		Difficult	
	RT	PE	RT	PE
Invalid	567	3.2%	646	3.6%
Valid	551	3.1%	598	2.7%
Validity Effect	16		48	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. 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) = 33.14, $p < .001$, $\eta_p^2 = .501$.

The cue validity effect was greater on the difficult search trials (48 ms) than the easy search trials (16 ms). Preplanned *t* tests revealed compared invalid-cue and valid-cue trials for each search difficulty condition (easy and difficult). Cue validity effects were significant under both easy search, *t*(33) = 3.97, $p < .001$, $d = .320$, and difficult search, *t*(33) = 6.19, $p < .001$, $d = .645$.

Error rate analysis. All main effects were nonsignificant. There was a trend for larger validity effects on difficult trials (0.9%) than easy trials (0.1%), *F*(1, 33) = 3.32, $p = .078$, $\eta_p^2 = .091$.

Discussion

This experiment confirmed the findings of Experiment 5. Even though participants had no foreknowledge of upcoming search difficulty when the cue was presented, the cue validity effect increased with search difficulty. Put another way, search difficulty could not possibly affect attentional allocation during the cue presentation because difficulty was not yet known at that time. This finding provides further evidence against strategic accounts of the difficulty effect, such as displaywide orienting and rapid disengagement. This finding instead supports nonstrategic accounts, such as the attentional dwelling hypothesis.

Experiment 7

Experiment 7 was designed to replicate the previous experiments with a different manipulation of difficulty. Furthermore, we varied difficulty across a wider range and used three levels rather than just two. To accomplish this, we manipulated target-distractor similarity in a graded manner (Duncan & Humphreys, 1989; Proulx & Egeth, 2006). Participants searched displays of elliptical shapes for a perfect circle. Target-distractor similarity was decreased by adjusting the distractor shapes further from perfect circularity, and making them more elliptical. Three levels of target-distractor similarity varied randomly trial-by-trial: low similarity (easy search), medium similarity (medium search), and high similarity (difficult search). The attentional dwelling hypothesis predicts that increasing target-distractor similarity increases overall response time. In turn, this will lead to gradually increasing dwell times on distractor items and gradually increasing capture effects.

Method

Participants. Thirty-three undergraduates from the University of New Mexico participated for course credit. Four participants were excluded for having abnormally low accuracy (less than 80%). Of the remaining 29 participants, the mean was 19.7 years and 19 were female.

Apparatus, Stimuli, Design, and Procedure. All methods were similar to those of Experiments 4 and 6, changing only the stimuli in the search array. Participants searched for a red circle (1.3° in diameter) surrounded by red ellipses and reported whether a small black dot inside (0.1°) appeared on the left or right side of the shape (0.1° from the outside). Three levels of distractor ellipses were created by gradually increasing the target circle width and decreasing its height: high similarity (1.6° x 1.0°), medium similarity (1.8° x 0.8°), and low similarity (2.1° x 0.5°). Distractor type varied randomly trial-by-trial, preventing any strategic adjustment to the attentional set in anticipation of difficulty level. Participants performed 12 blocks of 64 trials, with the first two blocks being practice blocks.

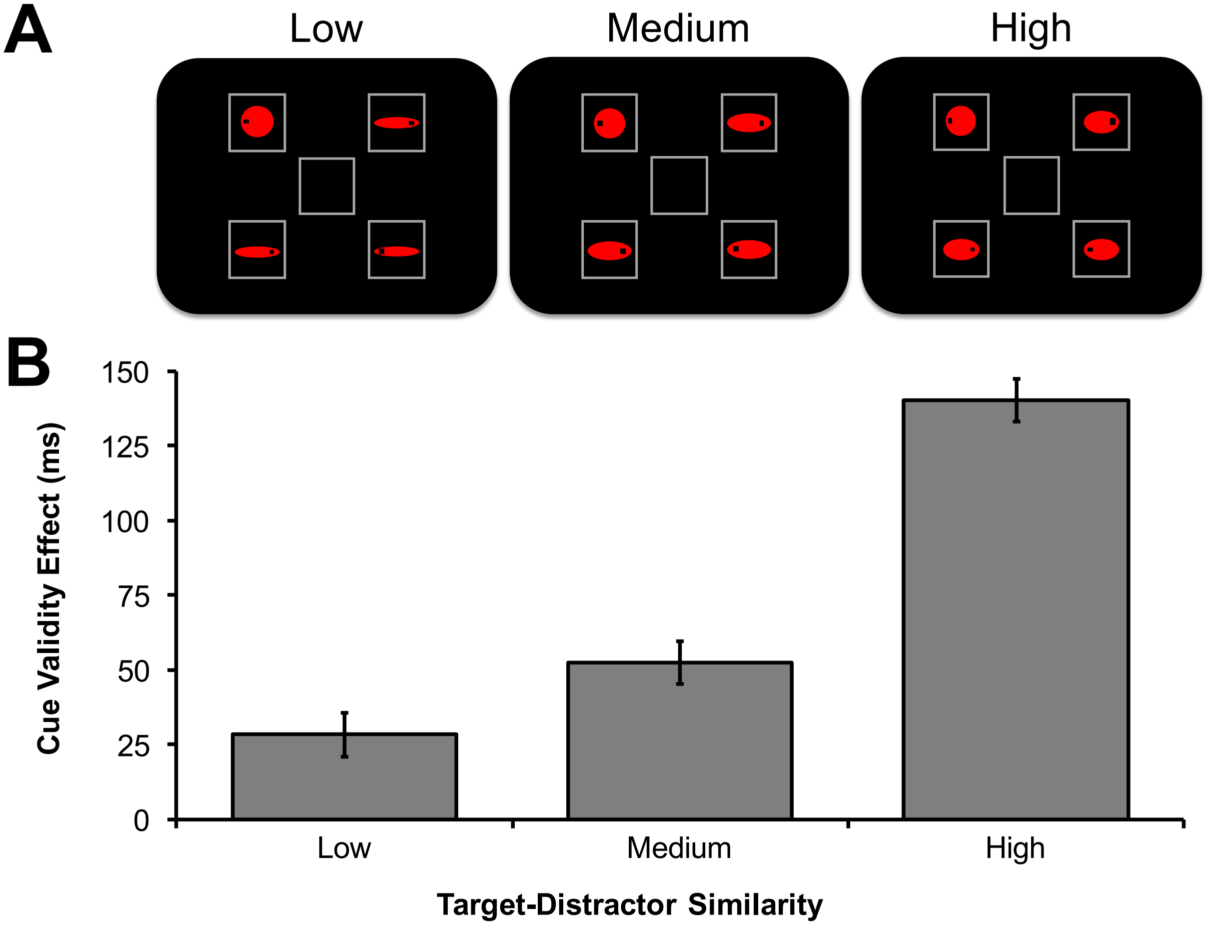


Figure 8. *Stimulus displays and results for Experiment 7. (A) The target was now a perfect circle with elliptical distractors. Importantly, there were three levels target-distractor similarity: low, medium, and high. (B) Cue validity effects increased gradually with target-distractor similarity.*

Results

Mean RTs and error rates are shown in Table 7. Cue validity effects by search difficulty condition are shown in Figure 8. Within-subject ANOVAs with the factors distractor-target similarity (low, medium, vs. high) and cue validity (invalid vs. valid) were conducted on mean RTs and error rates.

Table 7

Mean Reaction Time (ms) and Percent Error by Target-Distractor Similarity and Cue Validity for Experiment 7.

	Low Similarity		Medium Similarity		High Similarity	
	RT	PE	RT	PE	RT	PE
Invalid	652	3.7%	718	2.8%	996	4.3%
Valid	624	2.8%	666	3.0%	855	2.7%
Validity Effect	28		52		141	

Note. RT = Reaction Time; PE = Percent Error. Validity effects were calculated as invalid minus valid.

RT analysis. Overall RT gradually increased as with target-distractor similarity – participants responded more quickly on the low similarity trials (638 ms) than medium (692 ms) or high similarity trials (925 ms), $F(2, 56) = 436.52, p < .001, \eta_p^2 = .940$. Participants also responded more quickly when the cue was valid (715 ms) than when it was invalid (789 ms), $F(1, 28) = 103.88, p < .001, \eta_p^2 = .788$.

Importantly, the attentional dwelling hypothesis predicts that, as target-distractor similarity increases, cue validity effects should gradually increase. Consistent with this prediction, cue validity effects gradually increased as a function of target-distractor similarity, $F(2, 56) = 33.55, p < .001, \eta_p^2 = .545$: low similarity (28 ms), medium similarity (52 ms), and high similarity (141 ms). Preplanned *t* tests compared cue validity effect for each level of target-distractor similarity. Cue validity effects were significantly larger on medium similarity trials than low similarity trials, $t(28) = 3.14, p < .01$. Additionally, cue validity effects were significantly larger on high similarity trials than medium similarity trials, $t(28) = 5.40, p < .001$.

A series of preplanned *t* tests compared invalid and valid cue conditions for each level of target-distractor similarity. Cue validity effects at each level of similarity were as follows: low similarity, $t(28) = 5.63, p < .001, d = .36$, medium similarity, $t(28) = 6.54, p < .001, d = .62$, and high similarity, $t(28) = 8.47, p < .001, d = 1.16$. .

Discussion

We used a graded manipulation of target-distractor similarity, varied randomly trial-by-trial. The attentional dwelling hypothesis predicts that, as target-distractor similarity increases, so should observed cue validity effects. Consistent with this prediction, cue validity effects gradually increased with target-distractor similarity. As will be discussed later, this increase is roughly linear with mean RT.

General Discussion

Researchers are sharply divided regarding whether abrupt onsets automatically capture attention (Folk et al., 1992; Franconeri & Simons, 2003; Yantis & Jonides, 1984). Previous reports that onsets do not capture attention have relied almost exclusively on paradigms with a particularly easy search (Folk et al., 1992; Lien et al., 2008; Lien, Ruthruff, & Johnston, 2010). However, easy search reduces the dwell time on invalidly cued distractors, after initial capture, minimizing the impact of capture on RT. This attentional dwelling hypothesis raises the intriguing possibility that capture occurred in all these studies, but the costs of capture were too small to be reliably detected.

An analysis of the previous literature indeed revealed a methodological strong bias between camps. Stimulus-driven researchers frequently rely on letter search, whereas goal-driven researchers frequently rely on color search. This bias is consistent with the attentional dwelling hypothesis, though the relationship is merely correlational. To establish a causal relationship between search difficulty and capture effects, we manipulated search type in Experiments 1 and 2, holding extraneous variables constant. In both experiments, letter search was more difficult than color search, as indexed by longer overall RTs and higher error rates. Importantly, validity effects from irrelevant onsets were larger under letter search than color search.

Experiments 1 and 2 deliberately confounded search dimension (letter vs. color) and search difficulty (easy vs. difficult), mimicking the typical searches used by stimulus-driven and goal-driven researchers. Experiments 3 and 4, therefore, manipulated search difficulty within each search dimension. Regardless of search dimension, difficult search produced a much greater cue validity effect than easy search, just as predicted by the attentional dwelling hypothesis.

Experiments 5 and 6 tested whether the difficulty effect on capture is strategic or nonstrategic, allowing us rule out several alternatives. We varied search difficulty randomly, trial-by-trial. Because the search array appeared after the cue display, participants had no foreknowledge of the upcoming search difficulty during presentation of the onset cue. Thus, strategic accounts of the difficulty effect, such as that offered by rapid disengagement or displaywide orienting, predict equal capture effects in both difficulty conditions. The attentional dwelling hypothesis, however, is nonstrategic. Spatial attention frequently moves to the onset but can rapidly reorient from the cued search item under easy visual search. Consistent with nonstrategic accounts, cue validity effects were much larger for difficult search trials than easy search trials in both experiments. Because the cue appears before the search frame (i.e., before the difficulty level is apparent to the participant), this difficulty effect cannot result from differing probabilities of capture under easy and difficulty search. The differences in validity effects can only be explained by differing dwell times after initial capture.

Experiment 7 further tested the attentional dwelling hypothesis using a graded manipulation of target-distractor similarity that varied randomly by trial. The attentional dwelling hypothesis predicts that, as target-distractor similarity decreases, spatial attention should more easily reorient from the cued search item, shrinking overall cue validity effects. Consistent with this prediction, cue validity effects gradually decreased as distractors became less target-like. Because participants had no foreknowledge of upcoming target-distractor similarity, this effect likely results from differing dwell times after initial capture. This experiment provides a valuable replication of the previous experiments, using entirely different search stimuli and stimulus-response mappings, as well as a much wider range of difficulty levels.

The current study reveals that search difficulty is a powerful determinant of the size of cue validity effects from onsets. Pooling the data from Experiments 1 through 6 ($N = 232$), cue validity effects were four times as large under difficult search (*M* = 44 ms; *95% CI* [38 ms, 49 ms]) than easy search (*M* = 11 ms; *95% CI* [8 ms, 15 ms]). Within each level of difficulty (easy vs. difficult), cue validity effects varied across experiments. To evaluate this idea, Figure 9a shows validity effects in each condition of Experiments 1 through 7 as a function of mean RT for that condition, which serves as a proxy for search difficulty. As overall RT increased, cue validity effects consistently increased, $R^2 = 0.947$, $p < .001$. The relationship is strikingly consistent and linear.

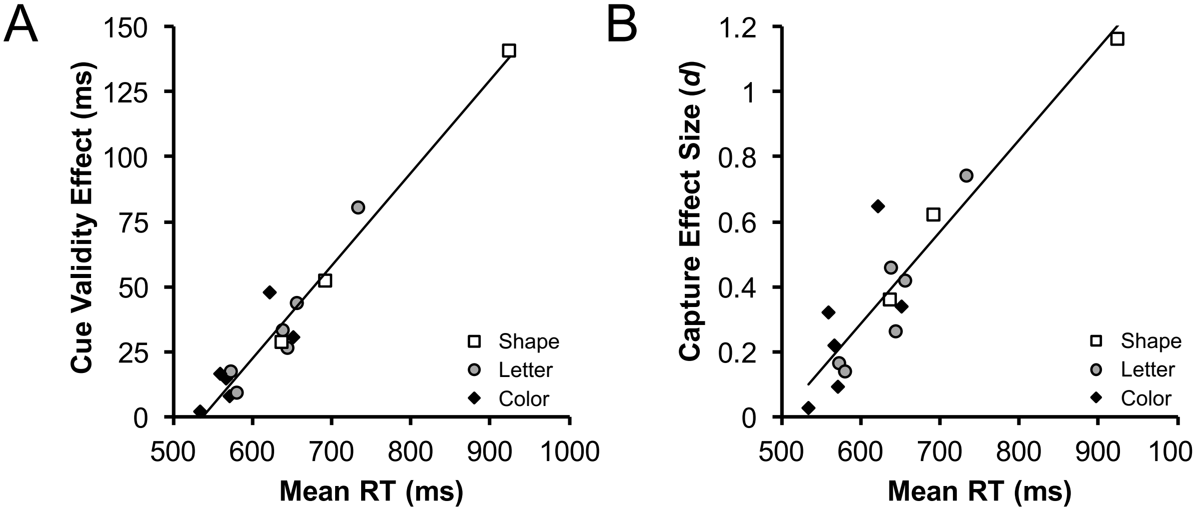


Figure 9. *Capture effects (a proxy for attentional capture) as a function of overall response time (a proxy for search difficulty) in each search condition of Experiments 1-7. (A) Cue validity effects for abrupt onsets increase with overall response time. Note this effect is constant over three different types of visual search (color, letter, and shape). (B) Capture effect size (cue validity effect over pooled standard deviation) also increases with overall response time, ruling out purely statistical accounts.*

To provide further evidence that the pattern of increasing capture effects is due specifically to the duration of the search stage (as specifically assumed by the attention dwelling account) and not just increases in overall RT, we conducted two further analyses. First, we show in Figure 9b that effect sizes for cue validity effects (Cohen's *d*) increase sharply as overall RT increases, $R^2 = .843$, $p < .001$. Second, we note that variability in RT across subjects is essentially uncorrelated with capture effects under easy search, $R^2 = .003$, $p > .10$. Most of the RT variability is likely due to the response selection stage rather than search stage, especially for easy search (Van Selst, Ruthruff, & Johnston, 1999). Thus, the dwelling account correctly predicts longer RTs should no longer be associated with larger capture effects.

In summary, we conclude that differences in search difficulty systematically lead to corresponding differences in cue validity effects. This effect arises primarily due to differing dwell times on search items after initial capture to an invalid location.

Relationship to Previous Theories

The current study directly contradicts strong versions of goal-driven theories (Folk et al., 1992), which state that task-irrelevant objects, no matter how salient, cannot capture attention. In all of the above experiments, task-irrelevant abrupt onsets produced large cue validity effects under difficult search. Importantly, these cue validity effects cannot be attributed to a mere filtering cost – abrupt onsets produced cue validity effects, a reliable index of attentional capture (Folk & Remington, 1998). The capture effects also cannot be attributed to singleton-detection mode (Bacon & Egeth, 1994), because the target was a nonsingleton under difficult search. Capture effects can also not be attributed to displaywide orienting (Gibson & Kelsey, 1998), because the effects were apparent even when premasks were used. Also, this effect was apparent even with within-block manipulations of difficulty, when participants could not strategically adjust the displaywide attentional set in anticipation of search difficulty.

Although top-down goals cannot prevent capture by task-irrelevant onsets, they nevertheless might influence attentional capture by abrupt onsets and other stimuli. Future research is needed to determine the precise contribution of top-down goals in attentional capture. Note, also, that strong versions of contingent capture may still apply to color singletons (Lien, Ruthruff, & Johnston, 2010), which seem to be a generally weaker class of salient stimuli than abrupt onsets (Folk & Remington, 2015; Franconeri & Simons, 2003; Jonides & Yantis, 1988).

Oculomotor Capture by Abrupt Onsets

Previous studies of oculomotor capture by abrupt onsets generally support the conclusion that abrupt onsets capture overt attention (Hunt, von Mühlenen, & Kingstone, 2007; Theeuwes & Burger, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Wu & Remington, 2003). These studies offer particularly convincing evidence of capture because the measure of capture (e.g., angular deviation of the first saccade) is direct, and cannot be attributed to mere filtering costs. The attentional dwelling hypothesis directly predicts longer dwell times when the target and salient distractor are difficult to discriminate. Consistent with the prediction, Geng and DiQuattro (2010) found longer dwell times on target-like distractors than color singleton distractors. Although overt and covert attentional shifts may differ in important ways, the ability to directly observe dwell times via eye tracking makes this an attractive direction for future search.

Exceptions to the Dwelling Account?

While the vast majority of studies reviewed are consistent with the attentional dwelling hypothesis (87%; see the Supplementary Material), some studies seem inconsistent with our account (Cosman & Vecera, 2009; Proulx & Egeth, 2006; Schreij et al., 2008, 2010a). Upon closer inspection, however, these studies may not actually be contradictions. For example, Proulx and Egeth (2006) investigated capture by luminance singletons while manipulating search difficulty in a graded manner (easy, medium, and difficult). The authors noted that capture effects were statistically significant only under easy (14 ms/item difference) and medium (20 ms/item difference) search difficulty. Interestingly, however, capture effects were numerically largest under difficult search (30 ms/item difference), despite being statistically nonsignificant. Schreij et al. (2008, Experiment 1) used a seemingly easy search in the spatial cuing paradigm, yet concluded in favor of onset capture. However, the singleton-presence cost from irrelevant onsets was only about 10 ms. Although this effect is statistically significant, it is small and actually fits neatly with the mean capture effects from our easy search conditions (see Figure 9a).

Other seemingly inconsistent studies used blocked manipulations of search difficulty (e.g., Cosman & Vecera, 2009), which allow participants to make strategic adjustments to the attentional set. Such adjustments could lead to strategies (e.g., singleton detection mode) that increase the probability of capture under easy search. Although we propose that onsets can reliably capture attention even with features search, singleton-detection mode further boosts the probability of capture (see Gaspelin, Leonard, and Luck, 2015). Although we have demonstrated a prominent role for search difficult (modulating attention dwelling times), other factors and their interaction with search difficulty will also need to be explored.

Concluding Remarks

To summarize, the current study makes several empirical and theoretical contributions. First, we demonstrated a strong methodological bias in the extant literature on abrupt onset capture. Goal-driven theorists tend to use easy color search whereas stimulus-driven theorists tend to use difficult letter search. Second, we provided evidence for the high importance of this variable using controlled behavioral experiments. Third, we demonstrated that this effect actually stems from search difficulty (easy vs. difficult), not search dimension (letter vs. color). Fourth, we demonstrated that this difficulty-by-validity interaction occurs even when easy and difficult searches are randomly intermixed within blocks. Because the cue appears *before* the search array (which reveals the difficulty level), we argue that the search difficulty effect is due to variable dwell times after initial capture by the cue. Additionally, the present study provides an important methodological warning: Easy search is relatively insensitive to capture and therefore might lead researchers to drastically underestimate the true probability of capture.

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Footnotes

[1] Note that this search dimension effect remains even if we include paradigms other than the spatial cuing and irrelevant feature paradigm that used letter search and color search (59 experiments). Note that many of these experiments may have used unreliable measures of attentional capture. Still, of the experiments using letter search, a majority found onset capture (83%). Of the experiments using color search, a majority did not find onset capture (69%). In other words, when including all capture paradigms, 79% of experiments can be explained by search dimension.