Attentional Capture by Abrupt Onsets without a Displaywide Set

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WORD COUNT: 4,197
Abstract

Researchers have long debated whether salient-but-irrelevant stimuli can involuntarily “capture” visual attention. At the center of this debate are bright stimuli that appear suddenly, called abrupt onsets. Interestingly, there is little consensus whether abrupt onsets can actually capture attention in a fully automatic manner. On the one hand, stimulus-driven theorists propose that abrupt onsets will always capture visual attention, no matter the individual’s intentions. On the other hand, goal-driven theorists propose that the ultimate intention of an individual determines whether abrupt onsets can capture visual attention. Problematically, many previous studies demonstrating apparent “stimulus-driven” capture by abrupt onsets may have had a methodological flaw – they may have rendered the abrupt onsets task-relevant, by using search arrays that appear suddenly. In the current study, we rule out this displaywide account. Critically, even when displaywide capture is discouraged, we show large capture effects from abrupt onsets, casting doubt on displaywide accounts of abrupt onset capture.
Attention is the cognitive process that allows us to deal with the thousands of stimuli that we encounter every day. For example, attention allows us to filter through the dozens of flashing business signs and bright, colorful traffic signs that we encounter while driving to work or home. However, the processes that determine when salient stimuli will capture attention are not completely understood. For many years, researchers have debated whether attention is captured involuntarily by salient stimuli. At the helm of this debate are two opposing theoretical camps: the stimulus-driven accounts and the goal-driven accounts.

Stimulus-driven theories propose that salience alone determines whether attention can be captured by a given stimulus (Yantis & Jonides, 1984; Jonides & Yantis, 1988; Yantis & Jonides, 1990; Franconeri & Simons, 2003; Theeuwes, 1991). That is, if a stimulus is particularly salient, then attention will always be involuntarily captured by that stimulus, regardless of one’s immediate goals. For example, this theory proposes that an irrelevant flashing restaurant sign, which can be considered a salient stimulus, will always capture your attention while driving, even if your immediate goal was to find the building of a specific clothing store. One well-studied type of salient stimuli is stimuli that appear suddenly, called abrupt onsets. Studies have shown that abrupt onsets capture attention under circumstances when other salient features do not capture attention. For example, Franconeri and Simons (2003, Exp. 1) had participants perform an irrelevant-feature task. In this task, participants performed a standard visual search task where they searched for a target letter (U or H) amongst multiple distractor letters and reported its identity. In the abrupt onset condition, every item in the search array, but one, had camouflaging premasks, causing one item to uniquely appear as a nonpredictive, abrupt onset. If the onset captured attention, then search should be more efficient when the target was an onset than an offset. This would result in shallow search slopes when the onset is a target, but steep search slopes when the abrupt onset was a distractor. Results of this study found that abrupt onsets did indeed produce such capture effects. Other static salient stimuli, such as uniquely colored items (called color singletons), failed to produce the same capture effects. The authors reasoned that abrupt onsets are a special class of stimuli that can automatically capture attention.

However, not all researchers agree that task-irrelevant onsets can automatically capture attention. Goal-driven theories propose that one’s ultimate intentions can determine whether or not salient stimuli can capture visual attention. If a salient stimulus is irrelevant to one’s immediate goals (called an attentional set), then that stimulus, no matter how salient, will never capture attention. For example, a flashing restaurant sign, although salient, will not capture your attention if your goal is to find the building of a specific clothing store. The flashing restaurant sign is irrelevant to the task of finding the building of the clothing store and, therefore, you won’t attend to it because it will not help your performance on the task of finding the restaurant.

In a seminal study, Folk, Remington, and Johnston (1992, Experiment 3) had participants perform a spatial cuing paradigm. Participants searched for a red target shape amongst white distractors and report it’s identity (X or =). Critically, this search display was preceded by a peripheral precue that was nonpredictive of the target location, meaning that it appeared at the target location on 1/nth of trials, where n is the set size. Thus, at a set size of 4, the cue appeared at the target location on 25% of trials (valid) and appeared at a distractor location on 75% of trials (invalid). If the cue captured attention, then a cue validity effect should occur – that is, participants should have faster response times (RTs) when the cue was valid than when it was invalid. Importantly, there was only a significant cue validity effect for relevant color cues but not irrelevant onset cues. In other words, these results suggest that salient abrupt onsets do not
capture attention unless they are made task-relevant.

To explain apparent instances of capture by task-irrelevant onsets, goal-driven theorists utilize the displaywide-orienting hypothesis. According to this account, a contingency exists between displaywide visual features (the features that signal the appearance of the task-relevant display as a whole) and the visual features that are able to capture attention (Gibson & Kelsey, 1998; Burnham, 2007). In other words, participants may intentionally search for features that signal the appearance of the search display as a whole, and this may lead to any sudden onset to capture attention. Problematically, almost every study of visual attention capture uses search displays that appear suddenly (i.e., abruptly onset). Burnham (2007) thus argued that all evidence of capture by task-irrelevant abrupt onset might be due to an (unintended) attentional set for onsets. Thus, goal-driven theorists utilize displaywide orienting to explain away capture effects from task-irrelevant onsets.

A few previous studies have attempted to demonstrate attentional capture by abrupt onsets that cannot be due to displaywide orienting. For example, Franconeri, Simons, and Junge (2004, Experiment 2) had participants perform a modified irrelevant feature paradigm. In the study, participants searched for a target letter (H or U) among other nontarget letters and reported the identity of the target. At the end of every trial, participants made saccades to a point below the search display while the search displays changed for the next trial. Thus, the participants never witnessed any changes to the search displays because they made large saccades to another location during this period of change. By not allowing the participants to view the abrupt appearance of the search display, these participants had no incentive to develop a displaywide attentional set for abrupt onsets. Yet, abrupt onsets still produced robust capture effects—search slopes were shallower when the abrupt onset appeared at a valid location than an invalid location. The authors concluded that the task-irrelevant onsets were able to capture attention, even when there was no benefit to the performance of the participant in the task. One criticism of this technique is that participants may have still perceived the search array as an abrupt onset. Even though the participants did not view the abrupt change of the display as a whole, they did view a new image that appeared suddenly on the retina when the saccade returned to the screen. Thus, it is unclear if the authors truly ruled out a displaywide orienting account.

Forster and Lavie (2011) used a different tactic to rule out displaywide orienting: they eliminated any onset of the search display (see also Franconeri & Simons, 2003, Experiment 1). At the beginning of each trial, participants were presented with a matrix of characters. Participants then responded to indicate whether each character was a letter or a digit. On some trials, a task-irrelevant cartoon character abruptly appeared in the periphery. Even though the primary task required no displaywide set for onsets, responses to were slowed when the cartoon character was present rather than absent. Although present-absent cost on RT is consistent with attentional capture, it is also possible that the distractor did not truly capture attention, but merely slowed a decision about where to move spatial attention (called a filtering cost; Becker, 2007; Folk & Remington, 1998). In other words, this study failed to use a spatial index of attentional capture.

In the current study, our goal was to provide key evidence of stimulus-driven capture by onsets that cannot be attributed to a displaywide attentional set. To accomplish this, we developed a new paradigm to assess attentional capture that combines aspects of the rapid serial visual presentation paradigm (RSVP; Leber & Egeth, 2006) and the spatial cuing paradigm (Folk, Remington, & Johnston, 1992). To ensure that participants would not develop a displaywide attentional set for abrupt onsets, we did not have the search display as a whole
appear suddenly, like an abrupt onset. Rather, the circles within the search display changed colors randomly every 200 ms. Participants monitored this stream of changing circles for a specific color and reported the location of a dot inside (left versus right). In this paradigm, a displaywide attentional set for an abrupt onset would be detrimental to performance, as multiple changes in random locations are happening every 200 ms. Critically, a spatial onset cue could precede this display at a random location. We predicted that if stimulus-driven attentional capture occurred, then participants should show a cue validity effect, with faster response times when the cue appeared at the target location (valid) than when the cue appeared at a nontarget location (invalid). Cue validity effects should also be especially large when the onset appears just before the target display (e.g., 100 ms SOA). However, if no attentional capture occurred, then participants should show no cue validity effect at any SOAs.

**Experiment 1**

Experiment 1 was designed to determine if attention could be captured by abrupt onset stimuli, even when the task discouraged the establishment of a displaywide attentional set for onsets more generally. Participants were shown an array of randomly changing, colored circle shapes and asked to report on the location of the black dot inside of the target color circle. Participants were also instructed to not attend to the onset cue, a white box, which would appear in the array. If participants attended to this onset cue and attentional capture occurred, then response times were predicted to increase as the attention of the participant was shifted to this cue and not the target. If no attentional capture occurred, then response times were predicted to decrease, providing evidence that the attention of the participant was not captured by the onset cue.

**Methods**

**Participants.** We chose an a priori sample size of 25 participants based on prior behavioral research on attentional capture in our laboratory (e.g., Gaspelin, Leonard, & Luck, 2015). We collected data from 25 University of California, Davis students who were given credit for participating. One participant was replaced for having abnormally high manual response times and another participant was replaced for having abnormally low accuracy (both were more 2.5 standard deviations from the group mean). Of the 25 final participants, 20 were female and 5 were male. All participants had normal color vision and had normal or corrected-to-normal visual acuity. The mean age was 19.7 years.

**Apparatus.** Stimuli were presented using PsychToolbox (Brainard, 1997) for Matlab on an LCD monitor with a black background that was placed at a viewing distance of approximately 70 cm. A photosensor was used to measure the timing delay of the monitor (32 ms), and this delay was subtracted from all latency values reported here.

**Stimuli & Procedure.** The stimuli are illustrated in Figure 1. Each search display contained 4 search items, all of which were designed to be photometrically isoluminant, distributed at equal distances around a notional circle with a radius of $1.3^\circ$. The search items were circles (1.2° diameter) drawn in red (18.6 cd/m$^2$, $x = .594$, $y = .333$), orange (18.5 cd/m$^2$, $x = .527$, $y = .414$), green (18.6 cd/m$^2$, $x = .322$, $y = .575$), blue (18.5 cd/m$^2$, $x = .181$, $y = .195$) or purple (18.6 cd/m$^2$, $x = .332$, $y = .185$). Each shape contained a black dot subtending 0.1° x 0.1° that was positioned 0.1° to the left or right edge of the shape. The onset cue was a white box (132.0 cd/m$^2$, 1.8° by 1.8°) that appeared around one of the circles. A fixation cross, which
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consisted of a black cross inside a gray circle (18.6 cd/m², 0.4° by 0.4°), was continuously visible except during the intertrial interval.

To prevent participants from adopting a displaywide attentional set for dynamic changes, the colors of the circles changed throughout the experimental block. Every 200 ms, at least one circle was randomly selected to change color. The search target was defined as a specific color circle, with a possibility of five possible colors: red, orange, green, blue, or purple. Each participant was randomly assigned to a target color condition, with the remaining items becoming distractor colors throughout the trials. The task was to report whether the black dot inside the target shape was located on the left or right of the shape (by pressing the L or R keys on the keyboard with their left hand). For each trial, target location was randomly selected as one of the four positions. The target could appear randomly with one of the color changes the between 1000 to 2000 ms. Participants were told to ignore the abrupt onset stimulus, which could appear for 100 ms at a stimulus onset asynchrony (SOA) with target stimulus of 600 ms, 300 ms, 200 ms, 100 ms, 0 ms, or -600 ms. All onset peripheral cues were nonpredictive of the target location, appearing at the target location on 25% of trials (a valid cue) and appearing at a distractor location on 75% of trials (an invalid cue).

Responses could be made any time after the appearance of a target circle. If participants took too long to respond (more than the 2000 ms), a timeout display appeared with the text “Too Slow”. If the response was incorrect, a 200 Hz tone sounded. If the response was correct, a rewarding chime sounded. Even during the intertrial interval, the circles remained on the screen and continued to change color. Participants first performed two practice blocks of 28 trials. The main experiment consisted of twenty-two blocks of 28 trials, yielding 616 total trials. Participants received block-by-block feedback on mean response time (RT) and accuracy.

Results

For all experiments in this paper, RTs less than 200 ms or greater than 1500 ms (less than 0.79% 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 cue validity effects. Figure 2 shows cue validity effects at each stimulus onset asynchrony.

As can be seen in Figure 2, cue validity effects from onset were large at short SOAs but small at long SOAs. To formally analyze this effect, we conducted a within-subject analysis of variance (ANOVA) with the factors stimulus onset asynchrony (600 ms, 300 ms, 200 ms, 100 ms, 0 ms, -600 ms) and cue validity (invalid, valid). This revealed a main effect of SOA, indicating that response times were generally faster at the 100 ms and 200 ms than other SOAs, F(5, 145) = 13.75, p < .001, η² = .322. Response times were also generally faster on valid trials than invalid trials, F(1, 29) = 22.60, p < .001, η² = .438. Critically, there was an interaction of SOA by cue validity, indicating that cue validity effects were large at 100 ms and 0 ms SOAs, but small at the longer SOAs, F(5, 145) = 17.29, p < .001, η² = .374. We conducted preplanned t tests comparing invalid and valid trials at each SOA. Cue validity effects were significant at the 100 ms (45 ms), t(29) = 8.12, p < .001, and 0 ms (30 ms), t(29) = 5.38, p < .001. This indicated that the onset cue captured attention and altered target detection when it appeared in close temporal proximity with the target. Cue validity effects were nonsignificant at all other SOAs, t(29) < 1. At the 300 ms SOA, there was a trend for response times to be faster on invalid trials than valid trials – a -8 ms cue validity effect, t(29) = -1.75, p = 0.09.

We ran the same ANOVA on mean error rates. Mean accuracy was above 94% in all conditions. All main effects and the interaction were nonsignificant.
Discussion

In this study, we made abrupt onsets entirely task-irrelevant and discouraged participants from creating an attentional set for abrupt onsets. Even when we did this, we still found a large capture effect from abrupt onsets when they were presented in close temporal proximity with the target (45 ms at the 100 ms SOA). This finding provides evidence that the onsets captured spatial attention, even when participants were discouraged from establishing a displaywide attentional set for changes. This is consistent with the stimulus-driven account of attentional capture.

Experiment 2

Experiment 2 tested an alternative explanation of the capture effects observed in Experiment 1. In Experiment 1, the onset cues appeared at six SOAs relative to the target stimulus, and four out of the six SOAs resulted in the onset cue appearing just momentarily before the target. In other words, the temporal location of the onset cue in the stream was predictive of when the target would appear. Thus, it is possible that the cues provided useful information about the timing of targets, motivating participants to develop an attentional set for onsets, which then caused them to capture attention. In Experiment 2, we ruled out this account by making onsets nonpredictive of the temporal location of the target. Here, an onset cue appeared every 400 ms. Thus, participants could not use the temporal location of the onset to predict the temporal location of the target. If onsets capture spatial attention, we should observe a cue validity effect at the short SOAs, just like in Experiment 1.

Methods

The methods used in Experiment 2 were identical to those used in Experiment 1, with the following exceptions. A new sample of 54 students participated (39 females, 15 males; mean age = 20.5 years). The abrupt onset stimulus now appeared every 400 ms and lasted for 100 ms. The jitter of the cues with the target was random – that is, the shortest SOA with target stimulus was randomly chosen as 300 ms, 200 ms, 100 ms, or 0 ms. The location of the onset cue in the temporal stream was uncorrelated with the temporal location of the target (r = .00004). All onset cue locations were chosen at random and occurred with replacement, so the cue could consecutively appear in the same location.

Results

To reduce the problem of multiple comparisons and ensure a reasonable number of trials per condition, we constrained analysis to SOAs between 1400 ms and -400 ms SOAs (see Figure 3). We conducted a within-subject analysis of variance (ANOVA) with the factors cue SOA and cue validity. This revealed a main effect of SOA, indicating faster response times at 100 ms and 0 ms than other SOAs, $F(1, 49) = 28.68, p < .001, \eta^2_p = 0.369$. This also revealed a main effect of cue validity, indicating faster times for valid cues than invalid cues, $F(1, 49) = 3.616, p > .001, \eta^2_p = .06873$. Finally, the ANOVA revealed an interaction of cue SOA and cue validity, $F(1, 49) = 6.708, p > .001, \eta^2_p = .12041$. To formally analyze this interaction, we then conducted preplanned t tests comparing invalid and valid trials at each SOA, which can be found in Table 1. To correct for multiple comparisons, critical p values were adjusted with a Bonferroni correction, resulting in a critical $p = 0.0026$. At 1400 ms to 600 ms, or the long SOAs, there were no reliable cue validity effects. From 500 to 300 ms, participants showed small-but-significant reversed cue validity effects ($p$’s < .001). This indicates that response
times were faster when the cue was invalid at these SOAs because spatial attention went to the location of the onset and then subsequently suppressed that location, making response times slower if the target appeared in the same location (an inhibition of return effect). Critically, at 100 and 0 SOA, abrupt onsets produced substantial cue validity effects at the 100 ms (M = 24.736 ms, t(100) = 7.094, p < .000000005) and 0 ms SOAs (M = 18.440 ms, t(0) = 5.317, p < .000003). This provides key evidence that the onset cues can capture attention in this study.

**Discussion**

In this experiment, we further encouraged participants to avoid an attentional set for onsets by making the onsets nonpredictive of both the temporal and spatial location of the target. We still observed large capture effects when the abrupt onsets appeared in close temporal proximity to the target (e.g., 24 ms at 100 ms SOA). This provides evidence that the onsets captured spatial attention, even when participants were discouraged from creating an attentional set for the onsets themselves. This is consistent with the stimulus-driven account of attentional capture.

**General Discussion**

For decades, researchers have debated whether abrupt onset stimuli can involuntarily capture attention. According to stimulus-driven theorists, abrupt onsets will automatically capture attention, regardless of one’s goals. According to goal-driven theorists, in contrast, task-irrelevant abrupt onsets will never be able to automatically capture attention because they are not in accordance with one’s goals. Much debate has occurred over which theory can explain attentional capture. In the current study, we attempted to provide evidence of stimulus-driven capture by onsets by testing whether abrupt onsets could involuntarily capture attention when they are orthogonal to one’s goals.

Experiment 1 provided key evidence for truly stimulus-driven attentional capture by abrupt onsets. Even when displaywide orienting was discouraged, task-irrelevant onset cues produced large capture effects. The search display discouraged participants from creating an attentional set for change, so the capture by abrupt onsets that occurred was due to the saliency of the onsets themselves. Note that because the cue validity effects are a spatial index of attentional capture, they cannot be attributed to mere filtering costs (Folk & Remington, 1998; Becker, 2007).

Experiment 2 provided further evidence that abrupt onsets involuntarily capture attention by testing an alternative explanation of the capture effects observed in Experiment 1. Even when the onsets were nonpredictive of the temporal and spatial location target, onset cues still produced significant capture effects. Participants were discouraged from creating attentional sets for change and the onsets themselves, so the saliency of the onsets alone resulted in capture by abrupt onsets.

Displaywide orienting accounts highlight a key problem in the attentional capture literature: We currently have no independent measure of the attentional set. Instead, the attentional set is inferred based upon intuitions about the experimental design and data about what captures attention (e.g., Folk et al., 1992). This becomes particularly problematic when the target is defined by multiple visual features, as it becomes unclear which feature participants used to locate the target. In other words, because we have no independent measure of whether the attentional set exists, any apparent evidence of stimulus-driven attentional capture can be criticized as a result of an attentional set for a non-target defining feature, which we call goal
contamination. Future research should work to discourage any possible displaywide orienting within the search display to ensure that goal contamination does not occur and that any possible attentional capture is not due to one’s attentional set.

It is worth briefly mentioning that displaywide orienting models are a bad fit for pre-existing studies of attentional capture by abrupt onsets. Although such models can explain most instances of apparent stimulus-driven capture (as noted by Burnham, 2007), displaywide models massively over-predict capture (as reviewed by Gaspelin, Ruthruff, & Lien, 2016). For example, in spatial cuing studies, where no premasks are used to deter displaywide attentional sets for onsets, task-irrelevant onset cues produce no capture effects. Yet, in irrelevant feature paradigms, where premasks are used to deter displaywide sets for onsets, capture is observed by abrupt onsets. Thus, the displaywide model massively over-predicts capture.

One plausible alternative explanation of our observed findings are filtering costs. With filtering costs, the cue never actually draws spatial attention, but, rather, alters a decision about where to move attention (Folk & Remington, 1998; Becker, 2007). On invalid trials, the onset and target appear at different locations, causing confusion about where to move attention. On valid trials, the onset and target appear at the same location, causing no confusion about where to move attention. This filtering cost has never been formally advocated, but should be ruled out in future studies.

In summary, the results of the current study, in which task-irrelevant abrupt onsets involuntarily captured attention, are inconsistent with a displaywide account. Participants were discouraged from taking an attentional set for dynamic changes, so the involuntary attentional capture by abrupt onsets was the result of the saliency of the onsets. These findings provide evidence to stimulus-driven attentional capture.
References


Figure 1. The stimulus display from Experiments 1 and 2. The target color was assigned randomly and the abrupt onset cue appeared randomly at one location. In this example, the target color is red and the onset cue appears as the white box surrounding one of the circles. For animations of a single trial, go to: https://sites.google.com/site/nickgaspelin/cristina_gif.
Figure 2. For Experiment 1, response times (ms) for invalid and valid trials by stimulus onset asynchrony (ms). Error bars are based upon the within-subject confidence interval (Masson & Loftus, 1994).

Figure 3. For Experiment 2, response times (ms) for invalid and valid trials by stimulus onset asynchrony (ms). Error bars are based upon the within-subject confidence interval (Masson & Loftus, 1994).
Table 1

*Mean Response Time (ms), Cue Validity, T-Values, and P-Values by SOA for Experiment 2.*

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*Note.* P-values were not adjusted for multiple comparisons.