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Pop-Out Without Awareness: Unseen Feature Singletons Capture Attention Only When Top-Down Attention Is Available

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Abstract

Visual pop-out occurs when a unique visual target (e.g., a feature singleton) is present in a set of homogeneous distractors. However, the role of visual awareness in this process remains unclear. In the experiments reported here, we showed that even though subjects were not aware of a suppressed pop-out display, their subsequent performance on an orientation-discrimination task was significantly better at the pop-out location than at a control location. These results indicate that conscious visual awareness of a feature singleton is not necessary for it to attract attention. Furthermore, the subliminal pop-out effect disappeared when subjects diverted their attention toward a rapid sequential visual presentation task while presented with the same subliminal pop-out display. These results suggest that top-down attention is necessary for the subliminal pop-out effect and that the cognitive processes underlying attention and awareness are somewhat independent.

Keywords
attention, consciousness, visual attention

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Visual pop-out refers to a phenomenon in which a unique visual target (e.g., a feature singleton) can be rapidly detected in a set of homogeneous distractors (Treisman, 1985; Wolfe, 1994). In the experiments reported here, we inquired about the roles of visual awareness and attention in this process. Specifically, what actually makes a feature singleton pop out? Is awareness of the feature singleton necessary for the stimulus to attract attention? Or can a feature singleton be processed and summon attention without the subject ever being aware of the stimulus?[1]

To answer these questions, we investigated (a) whether conscious visual awareness of a feature singleton is necessary for that stimulus to capture attention and, if not, (b) whether top-down attention is necessary to elicit such a subliminal response. Using continuous flash suppression (Tsuchiya & Koch, 2005), we subliminally presented a pop-out display (a feature singleton among several distractors) and demonstrated that, even though subjects were not aware of the display, their subsequent performance on an orientation-discrimination task was significantly better at the pop-out location than at a control location (Experiment 1). Furthermore, we showed that this effect disappeared when subjects diverted their attention toward a rapid sequential visual presentation (RSVP) task while viewing the same subliminal pop-out display (Experiment 2). Together, these findings suggest that (a) awareness of a feature singleton is not necessary for it to summon attention and that (b) top-down attention is necessary for this subliminal effect to occur.

Experiment 1: An Unseen Feature Singleton Attracts Attention

Method

Participants. Twelve, 16, and 9 healthy adult volunteers with normal depth perception and normal or corrected-to-normal visual acuity participated in Experiments 1a, 1b, and 1c, respectively. All subjects gave informed consent within a protocol approved by the Massachusetts Institute of Technology and were paid $5 for a session lasting approximately 30 min.

Stimuli and procedure. The stimulus configuration and experimental procedures used in Experiment 1a are shown in Figure 1. Participants viewed dichoptic images through a mirror stereoscope in a dark room. Throughout each trial, a white

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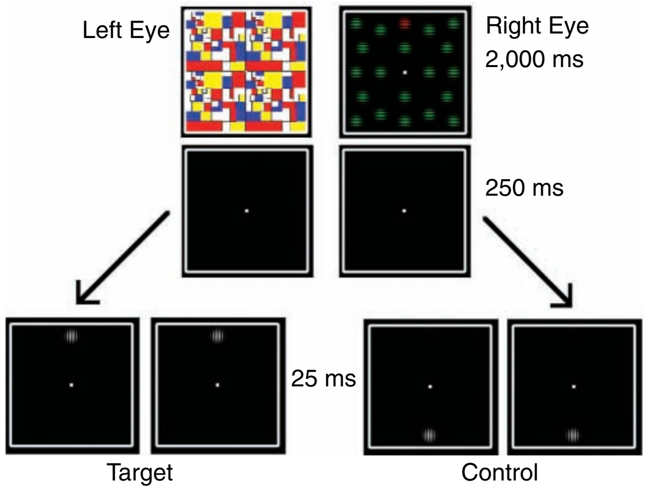

Fig. 1. Stimuli and procedure used in Experiment 1a. During the initial phase (top row), a pop-out display of 20 horizontally oriented Gabor patches (with a white central fixation point) was presented to one eye, while dynamic Mondrian patterns were presented to the other eye to suppress the pop-out display (the eye to which the display was presented alternated with every trial). One of the Gabor patches in the pop-out display was colored red, and the rest were colored green. The pop-out display gradually increased in contrast for 2,000 ms, and then the stimuli presented to both eyes were replaced by a blank screen for 250 ms (middle row). After this interstimulus interval, a test Gabor patch with a nearly vertical orientation was presented for 25 ms to both eyes (bottom row). This white Gabor patch was presented at either the target location (i.e., the location of the red Gabor patch in the pop-out display) or the diametrically opposed control location. The test Gabor patch was rotated 1.5° clockwise or counterclockwise, and the observer was required to press one of two buttons to indicate which orientation he or she perceived. At the end of every trial, subjects also reported whether or not the Mondrian patterns effectively masked the colored Gabor patches.

central fixation spot subtending 0.27° × 0.27° of visual angle remained on-screen. At the start of each trial, one eye was presented with 20 colored, horizontally oriented Gabor patches. Each Gabor patch subtended a visual angle of 1.1° × 1.1° and had a spatial frequency of 5.5 cycles per degree. Twelve of the Gabor patches were arranged around the fixation point in a circle with a radius of 4.2°. Four Gabor patches formed the corners of a square that was centered at the fixation point and had sides of 8.9° in length. The remaining four Gabor patches were located 2.1° above, below, and to the left and right of the fixation point, respectively. The default color for all of these Gabor patches was green. In each trial, one of the 12 radial Gabor patches was randomly selected to be red (as a feature singleton). The luminance levels of red and green were subjectively matched before the experiments (Anstis & Cavanagh, 1983). Four identical dynamic Mondrian patterns with a refresh rate of 10 Hz were presented to the other eye in four separate quadrants that collectively masked the stimulus area (each side of the stimulus area was 10.6° in length). Ten distinct Mondrian patterns consisting of randomly generated red, blue, yellow, and white rectangles were created before the experiment.

The initial phase of each trial lasted 2,000 ms, during which the contrast of all 20 Gabor patches increased linearly from 0% to 25%. A blank interstimulus interval (ISI) of 250 ms followed the initial phase. After the ISI, a nearly vertical white Gabor patch with 100% contrast was presented to the two eyes against a blank display for 25 ms. This test Gabor patch appeared at either the target location (i.e., the location of the unique red Gabor patch) or a diametrically opposed control location, and it was rotated 1.5° clockwise or counterclockwise. The observer was required to press one of two buttons to indicate the Gabor patch's orientation. At the end of every trial, subjects also indirectly indicated whether or not the Mondrian patterns effectively masked the colored Gabor patches by reporting whether any of the four quadrants appeared different. Data for subjects in whom suppression was interrupted in five or more trials were excluded from the analysis. This was done as a conservative measure: When subjects saw the "subliminal" stimulus too often, there might not have been enough trials left to analyze, and we were less confident that the remaining trials were pure. (This occurred for 5 subjects in Experiment 1a, 4 subjects in Experiment 1b, and 2 subjects in Experiment 1c.) For the remaining subjects, fewer than five trials with broken suppression were removed when calculating each subject's performance.

The eye to which the suppressed Gabor patches were presented alternated with every trial. The possible locations in which a red Gabor patch could be assigned (1 of 12 locations), the orientation of the test Gabor patch (left or right tilt), and the location in which the test Gabor patch appeared (target or control) were all randomized and counterbalanced across the 48 trials in each block. Each participant completed one block.

To view the experiment, subjects placed their chins on a chin rest for visual stabilization. The visual stimulator was a Dell workstation running Windows XP. The stimuli were generated with Vision Egg software (Straw, 2008) and presented on a 20-in. Sony CRT gamma-corrected monitor with a resolution of 1,024 × 768 pixels and a refresh rate of 100 Hz.

The stimulus configuration and experimental procedures for Experiments 1b and 1c were identical to those of Experiment 1a, except as follows. To investigate whether the presence of red in the Mondrian patterns might affect the pop-out effect for a red singleton, the Mondrian patterns used in Experiment 1b contained only blue, yellow, and white rectangles. After indicating the orientation of the test Gabor patch at the end of every trial, subjects also indirectly indicated whether the masking was effective by reporting whether or not they perceived any colors other than those appearing in the Mondrian patterns.

To provide a more stringent test of awareness of the pop-out display, we doubled the number of trials (to 96) in Experiment 1c and removed the pop-out display in half of them, such that one eye still received Mondrian patterns and the other eye received no visual stimulus. In addition to indicating the orientation of the test Gabor patch and whether they perceived any colors other than those appearing in the Mondrian patterns, subjects were required to guess whether a pop-out display had been presented during the initial phase, even if they reported that they did not perceive any colors other than those appearing in the Mondrian patterns.

Results

We computed the percentage of trials in which subjects correctly identified the orientation of the test Gabor patch. For each experiment, a paired *t* test was performed to compare these percentages for the two conditions (feature singleton location vs. control location) across subjects. As Figure 2a shows, subjects on average correctly identified the orientation of the test Gabor patch in Experiment 1a significantly more often when the Gabor patch was in the target location than when it was in the control location (mean effect size = 5.34%), paired $t(6) = 4.51$, $p = .004$. This was also the case in Experiment 1b (mean effect size = 6.31%), paired $t(11) = 2.25$, $p = .046$ (Fig. 2b).

In Experiment 1c, the percentage of correct responses subjects made when asked to indicate whether they saw the pop-out display was not significantly different from chance, paired $t(6) = 0.827$, $p = .440$ (Fig. 3a). However, as in Experiments 1a and 1b, subjects in Experiment 1c correctly identified the orientation of the test Gabor patch significantly more often when the Gabor patch was in the target location than when it was in the control location (mean effect size = 10.20%), paired $t(6) = 3.15$, $p = .020$ (Fig. 3b).

Experiment 2: Top-Down Attention Is Necessary for the Subliminal Pop-Out Effect

Method

Participants. Eleven and 5 healthy adults with normal depth perception and normal or corrected-to-normal visual acuity participated in Experiments 2a and 2b, respectively. All subjects gave informed consent within a protocol approved by the Massachusetts Institute of Technology and were paid $5 for a session lasting approximately 30 min (Experiment 2a) or $40 for a session lasting approximately 4 hr (Experiment 2b).

Stimuli and procedure. The stimulus configuration, experimental procedures, and data analysis for Experiment 2a were identical to those of Experiment 1a, except as follows. The initial phase of each trial (i.e., presentation of the dichoptic images) lasted 9,000 ms instead of 2,000 ms, but the contrast of the suppressed Gabor patches still reached its peak of 25% by 2,000 ms and remained at 25% thereafter. During this initial phase, observers were also given an RSVP task, in which 10 numerical digits were superimposed monocularly on top of the Mondrian patterns at the central fixation point. This random sequence was looped six times, so that it spanned the entire 9,000-ms length of the initial phase, with a refresh rate of 6.67 Hz. The digits were black and subtended up to 1.5° × 2.3° of visual angle. The observer was required to press a button every time a probe (the digit “5”) appeared, which occurred three times per trial.

In Experiment 2b, there were different intervals (100 ms, 150 ms, 200 ms, 250 ms, and 300 ms) between the offset of suppression and the onset of the test Gabor patch. In addition, there were two types of trial block: attention-available blocks and no-attention blocks. The stimulus configuration and experimental procedures utilized for the attention-available blocks were similar to those of Experiment 1c, except as follows. The duration of the test Gabor patch was increased from

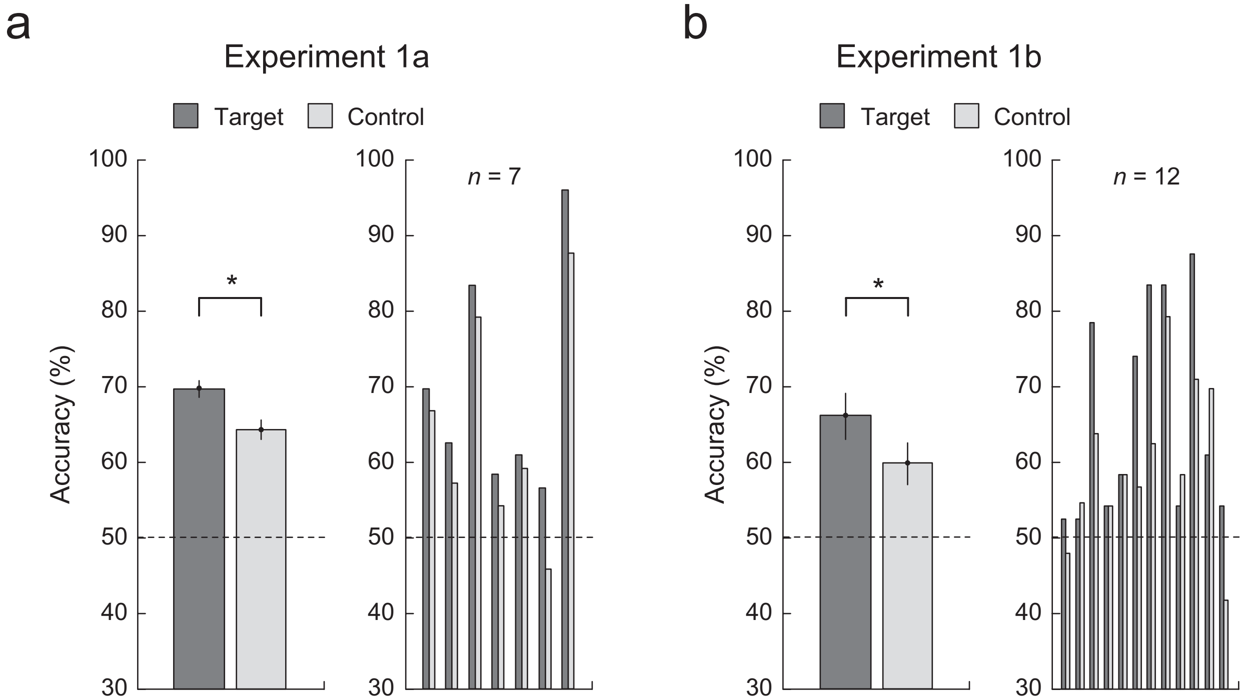

Fig. 2. Results of (a) Experiment 1a and (b) Experiment 1b: percentage of trials in which subjects correctly identified the orientation of a test Gabor patch that appeared in either a target or a control location. Graphs on the left of each panel show mean results, and graphs on the right of each panel show individual results. The asterisks indicate a significant difference between accuracies for target and control locations ($p = .004$ and $p = .046$ for Experiments 1a and 1b, respectively). Dotted lines indicate chance levels, and error bars show standard errors.

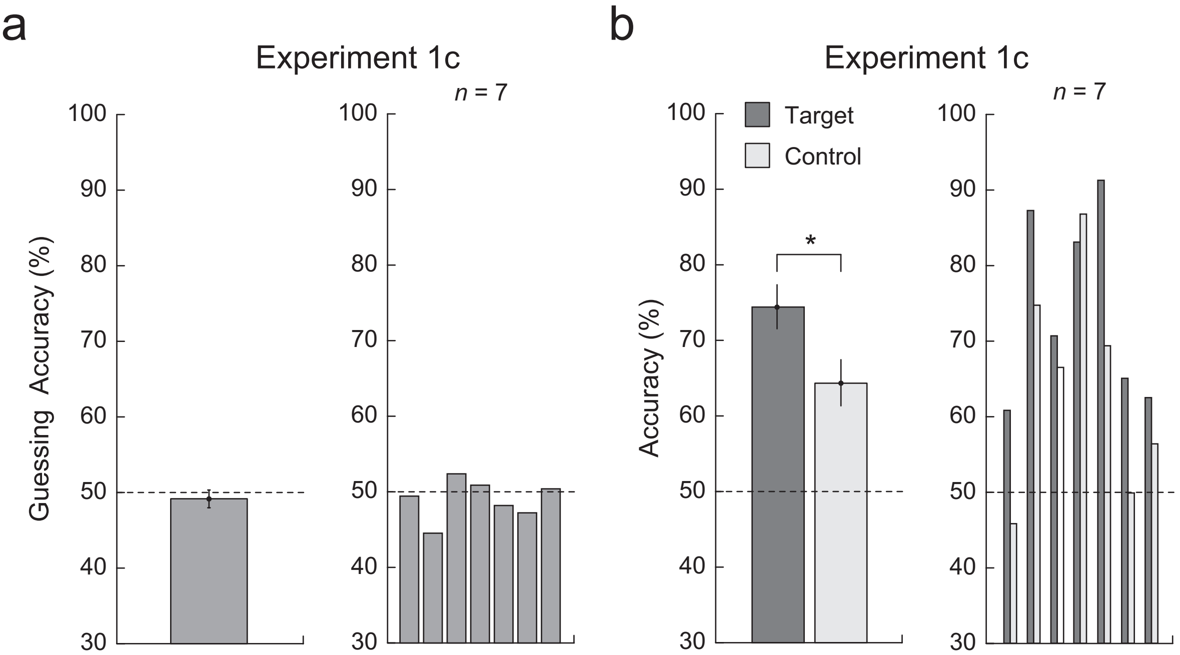

Fig. 3. Results of Experiment 1c: percentage of trials in which subjects (a) correctly guessed that the pop-out display was present and (b) correctly identified the orientation of a test Gabor patch that appeared in either a target or a control location. Graphs on the left of each panel show mean results, and graphs on the right of each panel show individual results. The asterisk indicates a significant difference between accuracies for target and control locations (p = .020). Dashed lines indicate chance levels, and error bars show standard errors.

25 ms to 50 ms. In the beginning of each block, the maximum contrast of the suppressed Gabor patches was still assigned to 25%. However, after each trial, the contrast was adjusted dynamically according to whether or not suppression was broken, decreasing by 2% when suppression was broken or increasing by 1% otherwise. Such adjustment was made to make sure the contrast of the "subliminal" Gabor patch was around the breaking threshold so that it was strong enough to be effective. The stimulus configuration and experimental procedures utilized for the no-attention blocks were similar to those of Experiment 2a, but the initial suppression phase of each trial lasted only 2,000 ms to parallel that of the attention-available blocks. Additionally, the RSVP sequence was looped twice instead of six times, with a refresh rate of 10 Hz. To control for the generation of a motor response, we asked subjects to report whether or not the RSVP probe appeared after the trial ended. Each subject completed two blocks of each condition (attention available and no attention), each of which included 480 trials.

Data analysis. Data from 4 of the subjects in Experiment 2a were excluded from analysis because the subjects saw the "subliminal" stimulus too often. For the remaining subjects, fewer than five trials with broken suppression were removed when calculating each subject's performance.

Results

We computed the percentage of trials in which subjects correctly identified the orientation of the test Gabor patch. In Experiment 2a, a paired t test was performed to compare these percentages for the two conditions (feature singleton location vs. control location) across subjects. In Experiment 2b, a two-way repeated measures analysis of variance (ANOVA) on the interaction between Gabor-patch location and ISI was performed within both the attention-available blocks and the no-attention blocks to test for significant main effects of location (i.e., target vs. control). An omnibus ANOVA was performed to test for a three-way interaction of block, location, and ISI. Finally, post hoc paired t tests between the effect sizes (target location – control location) of the two blocks were conducted for each of the five ISIs. We thus tested whether top-down attention is necessary for such a subliminal pop-out effect.

As Figure 4a shows, data averaged across subjects in Experiment 2a indicated that, unlike in Experiments 1a, 1b, and 1c, there was no significant difference in the number of correct responses when the test Gabor patch was in the target location than when it was in the control location, paired $t(6)$ = 0.770, p = .471. Moreover, the magnitude of the effect size between the two conditions was significantly greater for Experiment 1 than for Experiment 2a (mean effect size = 9.74%), two-sample $t(31)$ = 2.76, p = .009.

One might argue that the subliminal pop-out effect disappeared in Experiment 2a not because top-down attention was unavailable when engaged with the RSVP task, but simply because the presentation duration was too long (9,000 ms) for the pop-out effect to be maintained. To test this possibility, we fixed the duration of the initial suppression phase (2,000 ms) in Experiment 2b for the two attentional conditions and explored the influence of different ISIs (between the offset of suppression and the onset of the test Gabor patch) on the subliminal pop-out effect. Figure 4b shows the mean percentage

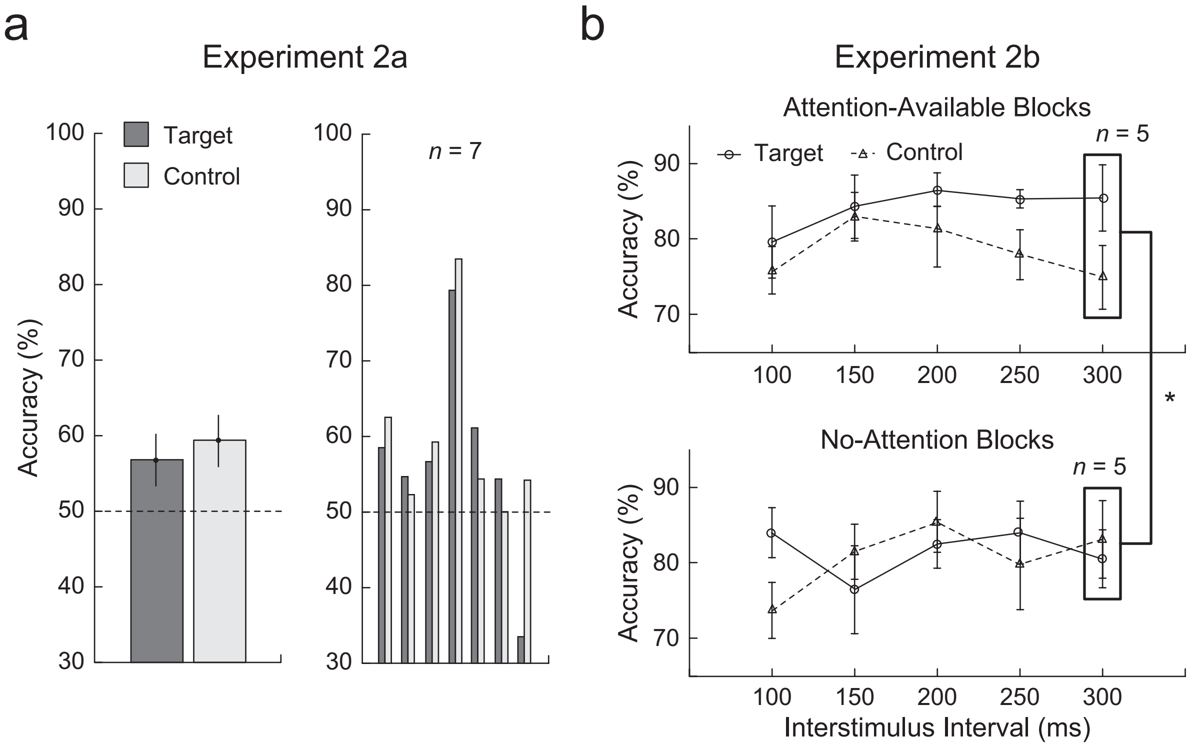

Fig. 4. Percentage of trials in (a) Experiment 2a and (b) Experiment 2b in which subjects correctly identified the orientation of a test Gabor patch. Results for Experiment 2a are shown as a function of whether the Gabor patch appeared in the target or the control location. The graph on the left shows mean results, and the graph on the right shows individual results. Dashed lines indicate chance levels. Mean results for Experiment 2b are shown for both the target location and the control location as a function of the interval between the offset of suppression and the onset of the test Gabor patch, separately for the attention-available trial blocks (upper graph) and the no-attention trial blocks (lower graph). The asterisk indicates a significant interaction between block and location (p = .034). In all graphs, error bars show standard errors.

of trials in which subjects correctly identified the orientation of the test Gabor patch in Experiment 2b as a function of the ISI for both the target location and the control location in the two attentional conditions.

For the attention-available blocks, a two-way repeated measures ANOVA investigating the interaction of location and ISI revealed a main effect of location—i.e., subjects on average made a significantly greater number of correct responses when the test Gabor patch was in the target location than when it was in the control location, $F(1, 4) = 8.241$, $p = .045$. Neither the main effect of ISI, $F(4, 16) = 2.867$, $p = .058$, nor the interaction between ISI and location, $F(4, 16) = 1.872$, $p = .165$, reached significance. For the no-attention blocks, we found neither a significant main effect of location, $F(1, 4) = 0.257$, $p = .639$, nor a significant main effect of ISI, $F(4, 16) = 2.240$, $p = .110$, and there was no significant interaction between these two variables, $F(4, 16) = 2.765$, $p = .064$.

Given that our analyses suggested that an effect of location was present for the attention-available block but not for the no-attention block (i.e., the subliminal pop-out effect was present only in the attention-available blocks), we proceeded to further test this possibility by performing a three-way omnibus ANOVA on the interaction of block, location, and ISI over all data. This ANOVA revealed a significant three-way interaction of block, location, and ISI, $F(4, 16) = 3.985$, $p = .020$, and indicated an interaction of block and location over some ISIs more than others. Therefore, we conducted additional post hoc analyses at each ISI. These analyses consisted of paired t tests over the effect sizes (target location – control location) between the two blocks at each ISI, and the results revealed a significant difference between the two blocks for the 300-ms ISI, $t(4) = 3.162$, $p = .034$, but not for the other ISIs, $t(4) < 1.908$, $p > .129$. Thus, for the 300-ms ISI, there was a key interaction of block and location, indicating that visual awareness of a feature singleton is not necessary for it to attract attention and that the availability of top-down attention is necessary for such subliminal pop-out effects to occur.

General Discussion

In the experiments reported here, we demonstrated that a subliminal feature singleton enhances subjects' performance on a subsequent orientation-discrimination task presented at the location of the original stimulus. This finding indicates that the feature singleton attracted attention even though observers were unaware of both the singleton itself and its distractors. This result is consistent with prior findings that stimuli that are not perceived consciously can nonetheless be perceptually analyzed (for review, see Kouider & Dehaene, 2007, and Z. Lin & He, 2009) and can affect spatial attention (Astle, Nobre, & Scerif, 2010; Jiang, Costello, Fang, Huang, & He, 2006; J. Y. Lin, Murray, & Boynton, 2009; McCormick, 1997). Our finding goes beyond these prior results insofar as we have established that a feature singleton can be processed and summon attention even when it is not perceived consciously. Many theories of visual search posit the existence of a preattentive processing stage that extracts featural contrasts from the visual scene (Itti & Koch, 2001; Wolfe, 1994) and integrates them into a saliency map that guides spatial attention to the location on the map with the highest value. Consistent with these models, the results of Experiment 1 demonstrate that attention can be shifted to the location of a feature singleton and induce increased orientation sensitivity even if the feature singleton is presented subliminally.

This subliminal pop-out effect is in line with a previous finding (Zhaoping, 2008), which established that attention can be captured by a supraliminal ocular singleton (e.g., an item presented to the right eye when all other items are presented to the left eye) even when observers are unaware of which eye received the visual inputs. Our findings differ insofar as we demonstrated that, even when an observer was completely prevented from consciously perceiving a feature singleton (as opposed to perceiving a stimulus without awareness of its eye of origin), this suppressed feature singleton could nonetheless attract attention. In other words, our findings further suggest that one eye can still construct a saliency map even when the stimuli presented to that eye are completely suppressed from consciousness.

Moreover, our data from Experiment 2 also show that unseen feature singletons did not recruit attention when subjects were distracted by an RSVP task while viewing the subliminal pop-out display. This finding suggests that top-down attention might be necessary for preattentive calculation of featural contrasts. This interpretation is consistent with prior findings showing that perceptual processing (e.g., cuing of spatial attention, the supraliminal pop-out effect, perceptual grouping, texture-based analysis, flicker perception, subliminal orientation processing) can be diminished when cognitive load is high (Bahrami, Carmel, Walsh, Rees, & Lavie, 2008; Ben-Av, Sagi, & Braun, 1992; Carmel, Rees, & Lavie, 2007; Joseph, Chun, & Nakayama, 1997; Lee, Lee, & Boyle, 2009; Moore & Egeth, 1997; Santangelo, Finoia, Raffone, Belardinelli, & Spence, 2008; but see Braun & Sagi, 1990, 1991; Egeth, Leonard, & Palomares, 2008). This interpretation is also in line with studies showing that top-down, feature-based attention can modulate the processing of invisible stimuli (Bahrami, Lavie, & Rees, 2007; Kanai, Tsuchiya, & Verstraten, 2006; Wyart & Tallon-Baudry, 2008). Together, these findings challenge the view that pop-out for visual attributes such as orientation, color, or size differences are processed preattentively (Treisman, 1985) and instead suggest that top-down attention can be critical for the detection of some of these purportedly preattentive features.

Alternatively, it might be the case that the calculation of featural contrast and the resulting saliency map were identical in both Experiments 1 and 2, but in Experiment 2, spatial attention was engaged so strongly at the center of the visual field that the weak saliency signal was not sufficient to capture attention. Bacon and Egeth's (1994) proposal that, in order for a salient singleton to automatically attract attention, observers have to engage a *singleton detection mode*, is consistent with this notion. It is possible that observers were in such a search mode in Experiment 1, but not in Experiment 2, because they were completely engaged in the RSVP task in the latter case. Additionally, Belopolsky, Zwaan, Theeuwes, and Kramer (2007) introduced the concept of "size of an attentional window" (similar to a zoom-lens model of spatial attention) and concluded that, in order for salient singletons to attract attention, the attentional window has to be distributed over the whole visual field, which is not the case in Experiment 2. Although these possibilities need to be distinguished more finely in future studies, our findings nevertheless challenge the notion that attention and awareness are inextricably coupled (Mack & Rock, 1998; Merikle & Joordens, 1997; O'Regan & Noe, 2001).

To conclude, the dissociation of attention and awareness that we demonstrated supports the view that these two processes are related but distinct phenomena that need not occur together and that entail distinct functions and neural mechanisms (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Kentridge, Heywood, & Weiskrantz, 2004; Kentridge, Nijboer, & Heywood, 2008; Koch & Tsuchiya, 2006; Lamme, 2003; Naccache, Blandin, & Dehaene, 2002). This dissociation of attentional cuing and awareness also suggests that the neural substrates for bottom-up saliency reside at an early stage in the visual pathway before visual processing has reached sufficient awareness. This finding is consistent with the theory (Li, 2002) that preattentive computation in primary visual cortex creates a saliency map, a finding that challenges other theories that imply that the saliency map results from summing various visual-feature maps and therefore must reside in a higher brain region where neurons are no longer tuned to any low-level visual features (Koch & Ullman, 1985).

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Note

1. In this article, awareness is operationalized as reportability (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). Top-down attention has been related to spatial, featural, temporal, and object-based variants of attention behaviorally, and neuronal versions of top-down attention also include shrinking receptive fields (Bundesen, Habekost, & Kyllingsbaek, 2005). For our purposes, top-down attention refers only to the spatial and featural variants of attention.

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