



Salience drives overt selection of two equally relevant visual targets

Gregory J. Christie¹ · Thomas M. Spalek¹ · John J. McDonald¹

Published online: 12 June 2018
© The Psychonomic Society, Inc. 2018

Abstract

In the present study, we investigated whether salience determines the sequence of selection when participants search for two equally relevant visual targets. To do this, attentional selection was tracked overtly as observers inspected two items of differing physical salience: one a highly salient color singleton, and the other a less salient shape singleton. Participants were instructed to make natural eye movements in order to determine whether two line segments contained within the two singletons were oriented in the same or in different directions. Because both singleton items were task-relevant, participants had no reason to inspect one item before the other. As expected, observers fixated both targets on the majority of trials. Critically, saccades to the color singleton preceded saccades to the less salient shape singleton on the majority of trials. This demonstrates that the order of attentional object selection is largely determined by stimulus salience when task relevance is equated.

Keywords Visual search · Salience · Pop-out · Capture · Overt attention

At any given moment, the locus of spatial selection is thought to be biased by two complementary control mechanisms: one driven by the features of the visual scene (stimulus-driven selection), and one driven by the intentions of the observer (goal-driven selection). In the laboratory, the ways in which these control mechanisms interact to affect the locus of selective attention can be studied using visual search tasks, which are designed to mimic the real-world task of finding a specific item of interest (a target) appearing among many irrelevant items (distractors).

An important finding from this work using visual search tasks is that salience differences between the items within the search display can greatly influence the time required to find the target. This effect is perhaps best demonstrated in tasks that utilize the *additional-singleton paradigm* (Theeuwes, 1991, 1992). In these tasks, observers are asked to find a target item defined by a unique feature (i.e., a singleton) that is presented alongside several homogeneous nontargets. For example, the target could be a green triangle and the other items green circles. On a subset of trials, the search array contains an

additional, nontarget singleton (a distractor). Although both the target and the distractor are salient, and thus appear to “pop out” from the other items, the time required to identify a subtle feature contained within the target singleton (e.g., the orientation of a line segment) can be impacted by the relative salience of the two singletons. If the distractor is less salient than the target—such as a yellowish-green circle among green circles—then response times (RTs) to the target are unaffected by the presence or absence of the distractor. In other words, observers appear to be able to ignore the distractor and orient attention to the target directly. However, if the distractor is more salient than the target—such as a red circle among green circles—then RTs to the target are longer. This salience-driven effect is largest when the properties of the target and the nontargets swap randomly from trial to trial (called *mixed-feature search*; Theeuwes, 1991), but it nevertheless persists even when the properties of all the items are fixed across trials (called *fixed-feature search*; Theeuwes, 1992).

The distractor interference effect observed in the additional-singleton paradigm is consistent with the *salience-driven selection hypothesis*, which states that the initial deployment of attention within a task-relevant region of space (sometimes called the “attentional window”) is determined entirely by stimulus salience (for a review, see Theeuwes, 2010). According to this hypothesis, observers automatically orient attention to the most salient item in the attentional window because salience-driven selection processes can be completed faster than goal-driven selection processes. If the most

✉ Gregory J. Christie
gchristi@sfu.ca

✉ John J. McDonald
jmcd@sfu.ca

¹ Department of Psychology, Simon Fraser University,
Burnaby, British Columbia, Canada

salient item happens to be the target then observers can select it without having attended the distractor, but if the most salient item happens to be the distractor, attention must then be redeployed to the next most salient item in the window. Furthermore, it is hypothesized that such salience-driven diversions of attention can be avoided only by reducing the size of the attentional window. It is assumed that salience computations are made only for items within this narrow attentional window, and thus that salient distractors falling outside the window can be ignored outright. Beyond the ability to alter the extent of the attentional window, however, selection is said to be under bottom-up control, and since the positions of the target and distractor are not typically known in advance, it is often not possible to position this narrow window to prevent capture.

This salience-driven selection account has faced stiff opposition from many attention researchers, and a longstanding debate has considered whether salient stimuli automatically capture attention or whether top-down control processes can prevent capture. At least four lines of evidence argue against salience-driven selection. First, the RT interference penalty is not typically evident when observers use a feature-based visual search strategy rather than a singleton-based strategy (Bacon & Egeth, 1994). Second, event-related potential (ERP) studies have shown that salient distractors do not typically capture attention. Such distractors sometimes elicit an N2pc—a well-known ERP index of attentional selection—when the features of the target and distractor swap unpredictably across trials (Hickey, McDonald, & Theeuwes, 2006; McDonald, Green, Jannati, & Di Lollo, 2013), but they do not elicit the N2pc when target and distractor features remain fixed (Gaspar & McDonald, 2014; Jannati, Gaspar, & McDonald, 2013). Third, under fixed-feature search conditions, salient distractors often elicit a contralateral positivity called the P_D , which is believed to reflect suppression processes that minimize salience-driven distraction (Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016; Gaspar & McDonald, 2014; Sawaki & Luck, 2010). Finally, under fixed-feature search conditions, human observers as well as monkeys make fewer eye movements to salient distractors than to targets (Gaspelin, Leonard, & Luck, 2017; Ipata, Gee, Goldberg, & Bisley, 2006).

Taken together, these studies demonstrate that when salience-driven selection mechanisms are pitted against goal-driven selection mechanisms (as well as other processes, such as selection history; see Awh, Belopolsky, & Theeuwes, 2012), goal-driven selection mechanisms appear to prevail. The presence of the P_D and the absence of a distractor-elicited N2pc rule out the idea that the most salient item in the attentional window is invariably selected first. Notably, these electrophysiological results are observed even when conditions closely mirror those of the conventional additional-singleton paradigm, in which the attentional

window must be kept wide in order to rapidly respond to targets appearing around the display (McDonald et al., 2013).

However, one additional tenet of the salience-driven selection hypothesis may still hold: that salience-driven selection processes are completed faster than goal-driven selection processes, thus allowing salient items to be selected more rapidly. Several studies have attempted to determine whether this is the case by measuring saccadic RTs in the additional-singleton paradigm, typically with the finding that the fastest saccades are made toward the location of the distractor (Godijn & Theeuwes, 2002; Van Zoest & Donk, 2008). Similar results were also noted in tasks that did not require the suppression of a salient distractor, but rather the inspection of several potentially task-relevant stimuli that differed in salience (e.g., Godijn & Theeuwes, 2003). In these tasks, the fastest saccades were directed typically to the location of the most salient item in the display. However, this salience-driven selection advantage was eliminated for longer-latency saccades, suggesting that although salience determines fast saccades, top-down control of slower saccades is possible (Donk & van Zoest, 2008; Siebold, van Zoest, & Donk, 2011).

Here, we investigated whether salience-driven selection would prevail when two singletons of differing salience were equally relevant to the task at hand. Because both singletons were equally relevant, goal-directed selection mechanisms would be equally biased toward both stimuli. This leads to two potential experimental outcomes. On the one hand, if observers rely exclusively on goal-directed mechanisms to guide their attention, they may disregard the salience difference between the two items and inspect the two singletons in random sequence. This outcome would be consistent with the fact that neither bottom-up nor top-down control mechanisms are strategically beneficial in this task. On the other hand, observers may, in addition to any goal-directed factors, implement a salience-based selection mechanism to bias the order of selection, even though doing so conferred no strategic benefit. Given that goal-directed factors would not bias search toward either target, only the salience-based mechanism would bias eye movements, and thus first fixations would be expected to be more likely to the salient color singleton. This would be consistent with the idea that stimulus-driven salience always plays a role in visual search, but that its influence on object selection can be offset by top-down control parameters (Lamy, Leber, & Egeth, 2004).

To ensure that goal-driven selection processes were equated across the two items, both singletons were present on all trials, and participants were asked to report whether line segments contained within each item were similar or dissimilar in orientation. Participants were instructed to move their eyes freely in performing this task, and the locus of attentional selection was measured directly using an eye tracker. Notably, discrete fixations at each singleton would be consistent with the serial selection and inspection of each item.

According to the salience-driven selection hypothesis, salience should impart a speed of processing advantage, and the more salient singleton should therefore be selected initially for inspection, even though doing so would confer no benefit for completing the task. Alternatively, if salience does not confer a processing advantage, then neither item should be consistently selected before the other, and the initial saccade will be made randomly between the two singletons.

Method

The Office of Research Ethics at Simon Fraser University approved all experimental procedures.

Participants

Nineteen observers (mean age = 20.4 years; 11 female, eight male, three left-handed) participated after providing informed consent. All participants reported normal or corrected-to-normal vision and were screened for colorblindness using Ishihara color plates.

Apparatus

The experiment was conducted in a dimly lit, acoustically isolated room. Participants sat 57 cm from a computer monitor operating at a resolution of 800 × 600 pixels and an 85-Hz vertical refresh. Stimulus presentation was controlled by Presentation (Neurobehavioral Systems Inc, Albany, CA) from a Windows-based computer. Ocular data were recorded from the right eye using a desk-mounted, high-resolution eye tracking system operating at a 1,000-Hz sampling rate (EyeLink 1000, SR Research, Ottawa, ON).

Stimuli and procedure

Prior to the commencement of the main task, participants, under supervision, were asked to subjectively match the brightness of the color red to the color green, until the participant was satisfied that the two were isoluminant. The process was repeated four times, and the average red value used subsequently (Jannati et al., 2013). The stimuli in the visual search task were presented against a black background, and a fixation dot measuring 0.5° visual angle was presented at all times during the experiment. Each trial consisted of two screens: a blank intertrial display containing only the fixation dot and the search display. The search display consisted of six stimuli 2.3° in diameter and arranged equidistant along an invisible circle with a radius of 5°. Each search display contained four task-irrelevant distractor circles (e.g., green), a single shape target singleton (e.g., green diamond), and a single color target singleton (e.g., red circle). Within each

stimulus there was a vertical or a horizontal line segment measuring 1.1°, and participants had to respond via a button response whether the lines contained within the two targets were pointed in the same or in different directions. The search array was presented for 4,000 ms or until participants responded, and participants were asked to respond “as quickly as possible while minimizing errors.” Colors were consistent across all trials for each participant, and were counterbalanced across participants. Participants were encouraged to move their eyes naturally in order to complete the task, but they were not encouraged to follow any particular pattern of eye movements or fixations (e.g., they were not encouraged to initially inspect either singleton).

Each block of 32 trials contained equal numbers of trials in which the color target was presented in a lateral visual hemifield and the shape target on the vertical visual meridian (lateral color, midline shape), in which the shape target was presented in a lateral visual hemifield and the color target on the vertical visual meridian (lateral shape, midline color), in which both the color and shape targets were presented in the same lateral visual hemifield (fully ipsilateral), and in which the color and shape targets were in opposing visual hemifields (fully contralateral). Trials were randomly shuffled by the experimental computer, and participants completed 15 blocks of 32 trials.

Drift and offset were corrected by having participants complete a nine-point calibration routine at the beginning of every new block of trials. A new trial would not commence until participants had returned their gaze to the fixation cross and maintained it there for a random duration of 800–1,200 ms.

Data analysis

Saccadic RTs, the duration of gaze fixation, and the order of target inspection were computed from blink-free, correct-response trials. Saccades were identified using a detection algorithm as the point at which an eye movement’s velocity exceeded 30°/s and its acceleration exceeded 8,000°/s²; fixations were defined as the point at which an eye movement dropped below these thresholds.

For each trial, two circular regions of interest with a radius of 4.5° were defined around each of the two singletons. Saccadic RTs were computed as the time at which participants had ceased fixation and started to saccade toward a region of interest, time-locked to the appearance of the search display. Dwell times were computed for each singleton as the duration of the first fixation at the item.

Results

On average, 3.1% of trials were rejected from the analysis due to an incorrect response, and a further 4.7% of trials were

rejected due to blinking or tracking error. Across all trials, the median response speed was 1,271 ms ($SEM = 66$ ms), which is notably slower than in one-target additional-singleton search tasks (cf. Theeuwes, 1992). Participants responded faster when the line segments matched (1,294 ms) than when they did not match (1,350 ms), $t(18) = 2.97, p = .008$. There was no difference in accuracy rates between the two target types (97.0% vs. 97.2%, respectively), $t(18) = 0.55, p = .59$.

In the standard additional-singleton paradigm, response speeds are computed as a function of the presence or absence of a highly salient distractor. Such an analysis was not possible here, because each singleton was task-relevant. However, the distance between these two items did vary unpredictably from one trial to another, so an additional behavioral analysis was conducted to determine whether RT varied as a function of target–target distance. RTs were therefore recomputed for trials in which the two targets were adjacent to each other (Distance 1: 1,320 ms), were separated by one nontarget (Distance 2: 1,343 ms), or were separated by two nontargets (Distance 3: 1,304 ms). RTs were found to differ significantly across the three target–target distances, $F(2, 36) = 4.12, p = .025$, but the effect was not linear (only the Distance 2 vs. Distance 3 difference was significant by pairwise comparison after Bonferroni correction). Error rates were statistically indistinguishable across the three target–target distances, $F(2, 36) = 2.22, p = .12$, suggesting that there was no speed–accuracy trade-off in this task.

The primary goal of this study was to determine whether the order of overt inspection was biased by salience. This research question is predicated on the assumption that observers made two discrete fixations, one at each singleton. Therefore, it was necessary to first rule out two alternative accounts of attentional object selection: (1) that participants completed the task by fixating just one of the two singletons, or (2) that participants completed the task without fixating either singleton.

To investigate these two possibilities, and to assess the primary research question, trials were sorted into one of five categories: (1) No saccade was made to either singleton; (2) one saccade was made to the color singleton only; (3) one saccade was made to the shape singleton only; (4) a saccade was made first to the color singleton and then to the shape singleton; or (5) a saccade was made first to the shape singleton and then to the color singleton. The percentage of trials corresponding to each of these five categories is depicted in Table 1. A repeated measures analysis of variance confirmed significant differences in the percentages of these trials, $F(4, 72) = 31.68, p < .001$, and Bonferroni-corrected pairwise comparisons confirmed that observers made saccades to the color singleton and then the shape singleton significantly more often than each of the other outcomes. These findings disconfirmed the two alternative accounts of attentional object selection outlined previously and confirmed that observers

fixated each of the two targets on the majority (71.6%) of trials. More importantly, the results showed that when faced with a task that requires careful inspection of two target objects, observers have a natural tendency to fixate the more salient item before the less salient item.

The next analysis was conducted to determine whether salience determined not only the order of selection but also the speed of initial selection. For this, saccadic RTs were computed separately for trials on which the first saccade was directed to the more-salient color singleton (63.8% of all trials) or to the less salient shape singleton (29.0% of all trials). The median saccadic RT to the color singleton (266 ms) was significantly shorter than that for the shape singleton (419 ms), $t(18) = 7.06, p < .001$. This finding shows that initial saccades to the more-salient target were faster than initial saccades to the less salient target.

Next, we computed the median fixation times at the color singleton and at the shape singleton, again from trials on which each respective item was selected first. Interestingly, the fixation times at the two target locations were identical (both 211 ms), $t(18) = 0.02, p = .99$, which suggests that the attentional dwell time at each item was unaffected by object salience. Although the conclusion is speculative, this suggests that the process of identifying the target line segment within each singleton was unaffected by the salience of the singleton surrounding it.

Discussion

Observers located two singletons, one a highly salient color singleton and the other a less salient shape singleton, and made an evaluative comparison of the two items. Critically, the design of this experiment equated the task relevance of the two singletons in order to better assess the effects of bottom-up control factors, without pitting them against top-down control factors. Because both singletons were relevant to the task at hand, if goal-directed selection was the only controlling factor then the order of attentional object selection would have been random—that is, on a trial-by-trial basis, observers would initially (and unpredictably) select either the color or the shape singleton first (cf. Christie, Livingstone, & McDonald, 2015). Instead, the results revealed that selection was consistently and predictably biased by salience. Namely, observers selected the color singleton before the less salient shape singleton on most trials, as was evidenced by saccadic RTs that were markedly faster to the color singleton than to the shape singleton. On the basis of these effects, it is clear that salience biases the priority for attentional selection, at least in those cases in which the most salient item is relevant and thus cannot be ignored.

Although similar results have been shown previously, past studies have argued that this influence of salience on

Table 1 Median percentages of trial types, correct response times (RTs), median saccadic RTs, and fixation times

	Percentage of Total Trials (<i>SEM</i>)	Behavioral RT, ms (<i>SEM</i>)	Color Singleton		Shape Singleton	
			Saccadic RT, ms (<i>SEM</i>)	Fixation Time, ms (<i>SEM</i>)	Saccadic RT, ms (<i>SEM</i>)	Fixation Time, ms (<i>SEM</i>)
No saccade	7.1 (2.2)	1,092 (68)	/	/	/	/
Saccade color only	11.6 (2.2)	1,134 (66)	316 (21.3)	241 (15.7)	/	/
Saccade shape only	9.6 (1.9)	1,213 (87)	/	/	539 (46.2)	266 (25.9)
Saccade color, then shape	52.2 (5.0)	1,312 (60)	258 (5.1)	203 (7.7)	643 (31.1)	264 (16.3)
Saccade shape, then color	19.4 (2.3)	1,338 (71)	729 (34.4)	247 (14.5)	413 (24.1)	194 (8.6)

attentional selection is relatively brief. For example, a study by Siebold et al. (2011) reported that salience determined the order of selection only when the first saccade was initiated within 200 ms of stimulus onset. Saccades initiated after 200 ms were equally likely to land on the most salient singleton or on one of several salient singletons. In contrast, the more salient of the two singletons was reliably selected first in the present study, even though the initial saccade was usually initiated well beyond Siebold et al.'s 200-ms threshold.

Similar “persistent” effects of salience have been observed in free-viewing tasks with complex scenes containing natural or artificial objects (Itti, 2005; Parkhurst, Law, & Niebur, 2002; Peters, Iyer, Itti, & Koch, 2005). Siebold et al. (2011) conjectured that the persistent biasing observed in these types of tasks reflected an object advantage rather than a bona fide salience advantage. In particular, it was hypothesized that participants preferentially moved their eyes to objects because those objects tended to be located near the center of the image or were particularly interesting (Siebold et al., 2011). No central-object bias was possible in the present study because all of the stimuli were equidistant from fixation. The interesting-object bias is more difficult to rule out conclusively because of the difficulty in determining how interested our participants were in our two singletons. However, given that the features of the two singletons were fixed across 480 trials, it is unlikely that either singleton was perceived to be very interesting in the present study. Thus, it is more likely that the saccadic bias observed in the present study was driven by stimulus salience rather than some intrinsic difference in object “interestingness.” An important upshot of this conclusion is that stimulus salience may help to guide visual search beyond the first 200 ms of stimulus processing.

Because the features of the two singletons were fixed across all trials of the experiment, it could be argued that the bias to first fixate the more salient target was due not to a purely salience-driven bias but to a top-down strategy to select the salient item first. Although varying the features of the singletons could eliminate some strategies (e.g., to fixate the red item first), it is probably not possible to rule out the

possibility of a salience-based strategy. However, it is interesting to note that if such a strategy did contribute to the present results, it would indicate that the majority of participants shared the very same top-down strategy to prioritize selection of the more salient color singleton over selection of the less salient shape singleton. Regardless of whether the selection bias observed here is purely bottom up or under top-down control (cf. Folk, Remington, & Johnston, 1992), we conclude that when faced with a task of comparing two visual-search targets, human participants have a natural tendency to select the more salient item first.

Successive fixations were observed to each of the two targets, demonstrating that attention was overtly and serially deployed to each target. Moreover, attentional dwell time was found to be approximately 200–250 ms, a value broadly consistent with that observed in several other studies (Moore, Egeth, Berglan, & Luck, 1996; Theeuwes, Godijn, & Pratt, 2004; Woodman & Luck, 1999, 2003). Although not a primary goal of this experiment, this finding relates to the longstanding debate about whether fine visual perception is possible for multiple items at multiple locations (parallel selection) or is restricted to a single item at a single location (serial selection; Townsend, 1990). In the additional-singleton paradigm, observers often make saccades to a location between the two singletons (called a global effect; see Van der Stigchel, Meeter, & Theeuwes, 2006). These interstitial selections could occur because the salient distractor biased the eye movement, such that the programmed saccade landed outside the to-be-inspected object. Alternatively, this could occur because the salient distractor was partially (and covertly) selected for additional scrutiny by observers. In the standard additional-singleton paradigm, it is not possible to disentangle these two accounts. Here, however, the results clearly support the conclusion that observers made discrete fixations at each object's location on most trials, a finding that is arguably more consistent with serial object selection.

However, eye movements cannot unambiguously reveal “purely serial” deployments of attention from partially overlapping object selection. This issue is far from academic:

Many real-world estimates of object processing estimate that the visual system can process about 30 items per second (Wolfe, 1998), but attentional dwell time experiments suggest that attention can only be redeployed about five times per second (Moore et al., 1996; Theeuwes et al., 2004; Woodman & Luck, 1999). To account for this, it has been proposed that visual processing can be accomplished through a hybrid of serial and parallel item selection (Wolfe, 2007), but oculomotor data cannot unambiguously disentangle serial selection from hybrid serial/parallel selection in most visual search tasks. Using an online measure of attentional selection, the N2pc component of the time-locked ERP, several recent studies collectively suggest that such hybrid serial/parallel selection may be possible (Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016). Additional studies will be required in order to determine the extent to which salience influences this putative ability to select multiple items in parallel.

On salience-driven capture

The present study confirmed that the order of attentional object selection is profoundly biased by salience—the most salient item within the field of view is selected first when there is no reason to override this salience-driven processing advantage. At first pass, this is conceptually consistent with the theory of automatic, salience-driven capture of attention. According to this theory, object salience is computed rapidly and early, and biases subsequent object selection. Top-down control cannot override this initial, salience-driven selection (Theeuwes, 2010). However, many real-world search conditions involve an interplay between stimulus- and goal-driven selection, and it does not necessarily follow that top-down control can occur only after initial salience-driven selection.

There is little question that salience can affect initial stimulus processing, or that top-down modulation can be slow to influence stimulus processing. For example, a study by Ogawa and Komatsu (2004) investigated the underlying neural mechanisms of object selection in monkeys trained in the additional-singleton paradigm. Neurons in area V4 responded more robustly to a color singleton than to a shape singleton within the first 175 ms of stimulus presentation. Moreover, the rate of neuronal activity was identical whether the monkey was searching for the color singleton (and ignoring the shape singleton) or vice versa. In other words, for the first 175 ms following stimulus delivery, neuronal activity was identical regardless of whether the stimulus matched the search goal or did not match the search goal. Similarly, salient items can modulate neuronal responses in subcortical regions, most notably in the superior colliculus (SC), a region strongly associated with the generation of saccadic eye movements (Boehnke & Munoz, 2008; Krauzlis, Lovejoy, & Zénon, 2013). Activity within the SC is sensitive to both stimulus-driven and top-down parameters. For example, when a peripheral cue is

flashed just before onset of a visual target, saccadic latency to the target is reduced and the corresponding neuronal response in SC is larger. Importantly, this cueing benefit is larger when the cue is predictive of the target location, which suggests that the SC is not simply responsive to low-level feature differences within a scene (Fecteau, Bell, & Munoz, 2004).

The early influence of salience bears an electrophysiological marker, as well. A physically salient stimulus can lead to a lateralized positivity in the interval of the visual P1 and N1, known as the positivity, posterior contralateral (Ppc). The Ppc is elicited by both target and nontarget singletons, and is hypothesized to reflect a salience-driven signal that may bias subsequent selection (Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012; Jannati et al., 2013). That the Ppc is elicited by both task relevant and task irrelevant stimuli further supports the idea that salience affects visual processing prior to the application of top-down attentional control.

The crux of the issue though is whether these salience-biased processes lead to the automatic selection of the most salient item. This process of object selection and enhancement is instantiated by an attentional control area, the frontal eye fields (Purcell, Schall, & Woodman, 2012), which contributes to the subsequent generation of the N2pc during search. Using the N2pc as a measure of attentional selection, some evidence exists for the erroneous capture of attention by a salient but irrelevant distractor. For example, a study by Hickey, McDonald, and Theeuwes (2006) tracked the locus of selection in a mixed-feature variant of the additional-singleton paradigm, in which the colors and forms of the target and nontargets changed unpredictably from one trial to the next. In that study, there was evidence for the early selection of a highly salient color singleton distractor prior to the subsequent selection of the less salient shape singleton target. Similar results were observed in Hickey, Olivers, Meeter, and Theeuwes, (2011), which showed an earlier N2pc to a salient but irrelevant item. To further investigate this, a reanalysis of the data published in Hickey et al. (2006) divided trials into quartiles by response speed, with the idea that slow-response trials likely involved the initial selection of the distractor (Hickey, van Zoest, & Theeuwes, 2009). Confirming this, on slow trials the N2pc was elicited initially by the distractor, and then by the target. Moreover, there was no evidence that the target was selected before the distractor on fast-response trials, and across all trials the fastest selection was for the distractor on slow-response trials. From this, the authors concluded that the fastest shifts of attention are driven exogenously by item salience.

In other studies, the evidence for stimulus-driven capture is either ambiguous or absent outright. For example, a reanalysis of Hickey et al. (2006) revealed that the distractor-elicited N2pc—a critical piece of evidence supporting capture and central to the results from Hickey et al. (2009)—was absent when the sample size was increased (McDonald et al., 2013).

Similarly, there was no evidence for capture by the salient distractor in two variants of a fixed-feature search task, in which the properties of the target and the distractor remained static across all trials (Gaspar & McDonald, 2014; Jannati et al., 2013). However, an important detail emerges from these studies: Whereas distractor capture is prevented on the fastest trials, on slow-response trials observers initially inspect the most salient (but irrelevant) item. Although these findings are technically inconsistent with the idea of capture—which posits that the most salient item will always be selected—they do reveal that salience-driven selection is probably nuanced.

A solution to these disparate results may lie in a recent study conducted by Gaspar and colleagues (Gaspar et al., 2016). In that study, observers searched for a color singleton target while ignoring an even more salient color singleton distractor. Measures of visual short-term memory capacity (VSTM) were obtained from all participants and ERP waveforms were computed on the basis of a tertile split of VSTM score. The results were striking: Whereas high-capacity observers effectively implemented a suppressive mechanism to prevent capture by the distractor, low-capacity observers showed a distractor-elicited N2pc, consistent with capture. In other words, some (but not all) observers can implement top-down guidance to prevent salience-driven automatic selection.

When these findings are taken together with the present results, two main conclusions can be drawn. First, in the absence of a top-down bias toward or away from a singleton, relative differences in the perceived salience of each stimulus are sufficient to consistently bias the order of selection. This is consistent with both the theory that the item with the highest priority—defined as the combination of both salience and task relevance—wins the initial competition for selection. Second, top-down attentional parameters can vary the weightings attached to each item's salience, to promote the selection of one stimulus relative to another (Desimone & Duncan, 1995). One's ability to implement this mechanism likely varies with both stimulus-level parameters (e.g., fixed- vs. mixed-feature search) and innate differences in VSTM capacity.

Author note This study was supported by grants from the Natural Sciences and Research Council of Canada, the Canadian Foundation for Innovation, and the Canada Research Chairs program. The authors thank Ashley Livingstone for assistance with data collection.

References

- Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*, 437–443. doi:<https://doi.org/10.1016/j.tics.2012.06.010>
- Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*, 485–496.
- Boehnke, S. E., & Munoz, D. P. (2008). On the importance of the transient visual response in the superior colliculus. *Current Opinion in Neurobiology*, *18*, 544–551. doi:<https://doi.org/10.1016/j.conb.2008.11.004>
- Christie, G. J., Livingstone, A. C., & McDonald, J. J. (2015). Searching for inefficiency in visual search. *Journal of Cognitive Neuroscience*, *27*, 46–56. doi:https://doi.org/10.1162/jocn_a_00716
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. doi:<https://doi.org/10.1146/annurev.ne.18.030195.001205>
- Donk, M., & van Zoest, W. (2008). Effects of salience are short-lived. *Psychological Science*, *19*, 733–739. doi:<https://doi.org/10.1111/j.1467-9280.2008.02149.x>
- Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*, 193–198. doi:<https://doi.org/10.1016/j.cub.2013.12.001>
- Fecteau, J. H., Bell, A. H., & Munoz, D. P. (2004). Neural correlates of the automatic and goal-driven biases in orienting spatial attention. *Journal of Neurophysiology*, *92*, 1728–1737. doi:<https://doi.org/10.1152/jn.00184.2004>
- Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030–1044. doi:<https://doi.org/10.1037/0096-1523.18.4.1030>
- Fortier-Gauthier, U., Moffat, N., Dell'Acqua, R., McDonald, J. J., & Jolicœur, P. (2012). Contralateral cortical organisation of information in visual short-term memory: Evidence from lateralized brain activity during retrieval. *Neuropsychologia*, *50*, 1748–1758. doi:<https://doi.org/10.1016/j.neuropsychologia.2012.03.032>
- Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences*, *113*, 3693–3698. doi:<https://doi.org/10.1073/pnas.1523471113>
- Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *Journal of Neuroscience*, *34*, 5658–5666. doi:<https://doi.org/10.1523/JNEUROSCI.4161-13.2014>
- Gaspelin, N., Leonard, C. J., & Luck, S. J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception, & Psychophysics*, *79*, 45–62. doi:<https://doi.org/10.3758/s13414-016-1209-1>
- Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 1039–1054.
- Godijn, R., & Theeuwes, J. (2003). Parallel allocation of attention prior to the execution of saccade sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 882–896. doi:<https://doi.org/10.1037/0096-1523.29.5.882>
- Grubert, A., & Eimer, M. (2015). The speed of serial attention shifts in visual search: Evidence from the N2pc component. *Journal of Cognitive Neuroscience*, *28*, 319–332. doi:https://doi.org/10.1162/jocn_a_00898
- Grubert, A., & Eimer, M. (2016). All set, indeed! N2pc components reveal simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance*. doi:<https://doi.org/10.1037/xhp0000221>
- Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience*, *18*, 604–613. doi:<https://doi.org/10.1162/jocn.2006.18.4.604>
- Hickey, C., Olivers, C., Meeter, M., & Theeuwes, J. (2011). Feature priming and the capture of visual attention: Linking two ambiguity

- resolution hypotheses. *Brain Research*, 1370, 175–184. doi:<https://doi.org/10.1016/j.brainres.2010.11.025>
- Hickey, C., van Zoest, W., & Theeuwes, J. (2009). The time course of exogenous and endogenous control of covert attention. *Experimental Brain Research*, 201, 789–796. doi:<https://doi.org/10.1007/s00221-009-2094-9>
- Ipata, A. E., Gee, A. L., Goldberg, M. E., & Bisley, J. W. (2006). Activity in the lateral intraparietal area predicts the goal and latency of saccades in a free-viewing visual search task. *Journal of Neuroscience*, 26, 3656–3661. doi:<https://doi.org/10.1523/JNEUROSCI.5074-05.2006>
- Itti, L. (2005). Quantifying the contribution of low-level saliency to human eye movements in dynamic scenes. *Visual Cognition*, 12, 1093–1123. doi:<https://doi.org/10.1080/1350628044000661>
- Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, 39, 1713–1730. doi:<https://doi.org/10.1037/a0032251>
- Krauzlis, R. J., Lovejoy, L. P., & Zénon, A. (2013). Superior colliculus and visual spatial attention. *Annual Review of Neuroscience*, 36, 165–182. doi:<https://doi.org/10.1146/annurev-neuro-062012-170249>
- Lamy, D., Leber, A., & Egeth, H. E. (2004). Effects of task relevance and stimulus-driven saliency in feature-search mode. *Journal of Experimental Psychology: Human Perception and Performance*, 30, 1019–1031. doi:<https://doi.org/10.1037/0096-1523.30.6.1019>
- McDonald, J. J., Green, J. J., Jannati, A., & Di Lollo, V. (2013). On the electrophysiological evidence for the capture of visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, 39, 849–860. doi:<https://doi.org/10.1037/a0030510>
- Moore, C. M., Egeth, H., Berglan, L. R., & Luck, S. J. (1996). Are attentional dwell times inconsistent with serial visual search? *Psychonomic Bulletin & Review*, 3, 360–365. doi:<https://doi.org/10.3758/BF03210761>
- Ogawa, T., & Komatsu, H. (2004). Target selection in area V4 during a multidimensional visual search task. *Journal of Neuroscience*, 24, 6371–6382. doi:<https://doi.org/10.1523/JNEUROSCI.0569-04.2004>
- Parkhurst, D., Law, K., & Niebur, E. (2002). Modeling the role of saliency in the allocation of overt visual attention. *Vision Research*, 42, 107–123. doi:<https://doi.org/10.1016/S0042-698900250-4>
- Peters, R. J., Iyer, A., Itti, L., & Koch, C. (2005). Components of bottom-up gaze allocation in natural images. *Vision Research*, 45, 2397–2416. doi:<https://doi.org/10.1016/j.visres.2005.03.019>
- Purcell, B. A., Schall, J. D., & Woodman, G. F. (2012). On the origin of event-related potentials indexing covert attentional selection during visual search: Timing of selection by macaque frontal eye field and event-related potentials during pop-out search. *Journal of Neurophysiology*, 109, 557–569. doi:<https://doi.org/10.1152/jn.00549.2012>
- Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics*, 72, 1455–1470. doi:<https://doi.org/10.3758/APP.72.6.1455>
- Siebold, A., van Zoest, W., & Donk, M. (2011). Oculomotor evidence for top-down control following the initial saccade. *PLoS ONE*, 6, e23552. doi:<https://doi.org/10.1371/journal.pone.0023552>
- Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, 50, 184–93.
- Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, 51, 599–606. doi:<https://doi.org/10.3758/BF03211656>
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, 135, 77–99. doi:<https://doi.org/10.1016/j.actpsy.2010.02.006>
- Theeuwes, J., Godijn, R., & Pratt, J. (2004). A new estimation of the duration of attentional dwell time. *Psychonomic Bulletin & Review*, 11, 60–64. doi:<https://doi.org/10.3758/BF03206461>
- Townsend, J. T. (1990). Serial vs. parallel processing: Sometimes they look like Tweedledum and Tweedledee but they can (and should) be distinguished. *Psychological Science*, 1, 46–54. doi:<https://doi.org/10.1111/j.1467-9280.1990.tb00067.x>
- Van der Stigchel, S., Meeter, M., & Theeuwes, J. (2006). Eye movement trajectories and what they tell us. *Neuroscience & Biobehavioral Reviews*, 30, 666–679. doi:<https://doi.org/10.1016/j.neubiorev.2005.12.001>
- Van Zoest, W., & Donk, M. (2008). Goal-driven modulation as a function of time in saccadic target selection. *Quarterly Journal of Experimental Psychology*, 61, 1553–1572. doi:<https://doi.org/10.1080/17470210701595555>
- Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, 9, 33–39. doi:<https://doi.org/10.1111/1467-9280.00006>
- Wolfe, J. M. (2007). Guided Search 4.0: Current progress with a model of visual search. In W. D. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99–119). New York, NY: Oxford University Press.
- Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, 400, 867–869. doi:<https://doi.org/10.1038/23698>
- Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 29, 121–138. doi:<https://doi.org/10.1037/0096-1523.29.1.121>