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Proactive Suppression Can Be Applied to Multiple Salient Distractors in Visual Search

Brandi Lee Drisdelle[1, 2] and Martin Eimer[1]
[1] Department of Psychological Sciences, Birkbeck College, University of London
[2] School of Psychological Science, University of Bristol

There is a growing body of research demonstrating that the capture of attention by a single salient distractor can be prevented via proactive suppression. In real-world contexts, there are often several distracting events that compete for attention, but it is entirely unknown whether multiple objects can be suppressed concurrently. We used behavioral and electrophysiological measures to investigate the existence and time course of multiple-item suppression. We employed search displays that contained either one or two uniquely colored distractors that differed in their salience (S+ and S−), or no such distractors. Search performance improved with the number of salient distractors, indicating that the suppression of multiple items reduced the effective display set size. This was also the case when the target color was no longer fully predictable, ruling out an alternative explanation in terms of attentional guidance by target templates. In an experiment where S+ and S− always appeared together in the same display, the P_D component (a marker of proactive suppression) was triggered exclusively by the more salient distractor (S+), indicative of single-item suppression. However, when displays with one or both salient distractors were intermixed, a reliable P_D component was also triggered by S−, even when it was accompanied by S+ in the same display. These results show that multiple concurrent salient signals can be proactively inhibited. They demonstrate that signal suppression processes can be adaptively employed to counteract visual distraction at different locations, in order to facilitate the attentional selection of relevant objects in crowded visual environments.

Public Significance Statement

This study shows that humans are capable of suppressing multiple salient but irrelevant visual items simultaneously. This highlights the flexibility of inhibitory mechanisms in selective attention. We provide both behavioral and electrophysiological evidence of multiple distractor suppression.

Keywords: proactive suppression, selective attention, P_D component, signal suppression hypothesis, visual search

Supplemental materials: https://doi.org/10.1037/xge0001398.supp

Because our visual system is constantly bombarded with distractions, it is imperative that we mentally sort information critical to our current goals from irrelevant and potentially disruptive signals. Without this ability, maneuvering our visual environment would be slow and inefficient. For example, when driving down a main road, there are many critical pieces of visual information that must be attended such as street signs, pedestrian crossings, and other vehicles. Equally, there are a lot of distractions such as flashing advertising,

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Brandi Lee Drisdelle https://orcid.org/0000-0003-2794-6106

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All data have been made publicly available at on Figshare and can be accessed at https://doi.org/10.6084/m9.figshare.21976829. This study was not preregistered.

Brandi Lee Drisdelle served as lead for data curation, formal analysis, project administration, software, validation, visualization, and writing–original draft. Martin Eimer served as lead for resources and supervision and served in a supporting role for project administration and writing–original draft. Brandi Lee Drisdelle and Martin Eimer equally contributed to conceptualization, investigation, methodology, writing–review and editing, and funding acquisition.

Correspondence concerning this article should be addressed to Brandi Lee Drisdelle, Department of Psychological Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX, United Kingdom. Email: brandi.drisdelle@gmail.com

store fronts, and essentially anything that takes our eyes off the road. Such situations demonstrate not only the ubiquity of distraction, but also the significance of managing multiple sources of distracting information simultaneously: we must be able to ignore all of these objects and events to ensure that only the most relevant items in the visual field move on to more complex levels of processing.

Though consensus has not yet been reached regarding the exact mechanisms responsible for our ability to filter out visual distractions, it is generally assumed that inhibitory processes play a critical role (Chelazzi et al., 2019; Geng, 2014; Luck et al., 2021). Providing a comprehensive definition of inhibition remains challenging, as this function is likely to be implemented differently in different contexts (for attempts at defining visual information inhibition see Chelazzi et al., 2019; Geng, 2014; MacLeod, 2007). Investigating whether and how inhibitory mechanisms contribute to our ability to focus on currently task-relevant signals is clearly important for informing cognitive and neural models of selective attention, such as the biased competition account (e.g., Desimone & Duncan, 1995) or the normalization model of attention (Reynolds & Heeger, 2009). In addition, a better understanding of our ability to detect and suppress distracting information is also essential to develop better strategies to interact with modern information technology, where user interfaces are explicitly designed to attract attention away from its intentional focus toward irrelevant but highly salient events at other locations. Here, we focus on the mechanisms that enable us to suppress the processing of perceptually salient but irrelevant visual signals, in order to counteract their capacity to attract attention. More specifically, we investigate the important question of whether it is possible to apply this suppression simultaneously to multiple signals at different locations in the visual field.

It has been suggested that suppression can be either proactive or reactive (Meyer & Bucci, 2016). Reactive suppression refers to the inhibition of processing that commences after, and in response to, the initial rapid capture of attention by a salient distractor. Proactive suppression is guided by a preparatory control state, and operates early, thereby preventing any distractor-induced attentional capture. Returning to the driving scenario, the salience of a new flashing advert may initially capture our attention, causing us to momentarily attend to it, before applying reactive inhibition and returning our attentional focus to the road. After having passed the same advert several times, we may be able to apply proactive inhibition in order to prevent any attentional capture in the first place. Both forms of inhibition allow us to effectively adapt to and learn from our environment.

The question of whether proactive suppression exists has been at the center of a longstanding debate about the role of salience signals in the attentional control of visual processing. According to stimulus-driven theories (e.g., Theeuwes, 2010), highly salient distractor objects cannot be proactively suppressed but will always capture attention automatically. Thus, any form of distractor suppression can only be triggered reactively. According to goal-driven theories (e.g., Gaspelin et al., 2015), proactive suppression can be applied to prevent salience-driven attentional capture by distractors. Initial evidence for the stimulus-driven account came from visual search tasks where a shape singleton target was accompanied by multiple distractors. On a subset of trials, one of these distractors was a salient color singleton (additional singleton paradigm). Even though the color was task-irrelevant, response times (RTs) were slower when this additional singleton was present than when it was absent, indicating that the singleton had captured attention automatically (Theeuwes, 1992; see also Yantis & Jonides, 1984). However, subsequent work (Bacon & Egeth, 1994) showed that these singleton costs were no longer present when a shape-defined target was presented among distractors with multiple different shapes, and observers could therefore no longer adopt a singleton detection mode to find the target (Pashler, 1988). This observation shows that salience-driven attentional capture is not always triggered automatically, but can be prevented under certain circumstances, possibly through the rapid suppression of salient distractors. Although the debate about the boundary conditions for attentional capture versus proactive suppression continues (e.g., Stilwell & Gaspelin, 2021; Wang & Theeuwes, 2020), some progress toward the resolution of this debate has been made in recent years (Luck et al., 2021). The signal suppression account (Gaspelin et al., 2015; Sawaki & Luck, 2010) integrates important aspects of stimulus-driven and goal-driven theories. According to this account, perceptually salient visual stimuli automatically generate a priority signal. In the absence of appropriate attentional control settings, this will result in attentional capture, as proposed by stimulus-driven theories. However, and in line with goal-driven theories, the capture of attention by salient objects can be prevented if control settings are appropriately configured (Folk et al., 1992).

Robust and replicable evidence for this signal suppression hypothesis has been obtained with the capture-probe task where an additional singleton search task is interleaved with a probe task (Gaspelin et al., 2015). In the majority of trials, participants search for a shape-defined target among other nontarget shapes and a unique color singleton distractor. On infrequent probe trials, letters are briefly superimposed on all visual objects in the search display, and participants have to report as many of these letters as possible. Critically, letters that appeared at the singleton distractor location were reported less frequently than letters at the locations of the nonsingleton distractors (Gaspelin et al., 2015). This probe suppression effect at the location of color singletons indicates that this location was proactively suppressed (see also Gaspelin et al., 2017 for corresponding suppression effects observed for oculomotor responses). Additional behavioral evidence for proactive distractor suppression was found with the additional singleton paradigm in experiments with small display set sizes (Gaspelin & Luck, 2018a; Drisdelle & Eimer, 2021). Here, the presence of a salient color singleton actually decreased RTs relative to trials where this singleton was absent. Such singleton benefits were interpreted as the result of proactive distractor suppression, which eliminates the color singleton as a potential target, thereby reducing the effective set size for visual search.

Further neural evidence for proactive suppression comes from event-related potential (ERP) studies investigating the time course of two ERP components; the N2pc, associated with attentional capture (Eimer, 1996; Luck & Hillyard, 1994a, 1994b), and the P_D, associated with inhibition (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018a; Hickey et al., 2009; Jannati et al., 2013; Drisdelle & Eimer, 2021; Sawaki & Luck, 2010; van Moorselaar et al., 2021). The N2pc is an electrophysiological marker of attentional deployment and is characterized by a negativity contralateral to an attended item which occurs around 200–300 ms after display onset (Eimer, 1996; Luck & Hillyard, 1994a, 1994b). The P_D, on the other hand, is considered a marker of the suppression of salient singletons, and is characterized by a positivity contralateral to an inhibited item (Hickey et al., 2009). Support for links between the P_D and proactive suppression comes from observations that the amplitude of P_D components is associated with the size of probe suppression effects (i.e., the decreased probability of reporting probes at color singleton locations; Gaspelin & Luck, 2018a). Further evidence for a link between the P_D component and proactive suppression was obtained in a study of individual differences (Gaspar et al., 2016). Individuals with good attentional control ability (as indexed by their working memory capacity) showed large P_D components to additional color singletons. In contrast, these singletons triggered an N2pc in participants with poor control, indicative of attentional capture resulting from a failure of proactive suppression.

The presence of probe suppression effects, singleton benefits, and reliable P_D components provides strong evidence that salient distractors in the additional singleton paradigm can be proactively suppressed. However, because search displays in these paradigms only contained one unique irrelevant color singleton, this suppression was always only applied to a single object. This exclusive focus on single-object suppression contrasts with real-world environments that often contain multiple salient distractors that compete with task-relevant objects for attentional priority, and thus need to be suppressed. The goal of the present study was to investigate the important question of whether proactive suppression can also be applied to multiple simultaneously present distractor objects.

The possibility of multiple-object proactive suppression is also relevant to the more general question about the relationship between facilitatory and inhibitory mechanisms in selective attention. Based on early work with monkeys demonstrating competitive interactions among neurons representing different stimuli within the same receptive field (e.g., Moran & Desimone, 1985), it has been suggested that these interactions can result in the suppression of neuronal activity associated with irrelevant stimuli (Desimone, 1998; Desimone & Duncan, 1995; Moran & Desimone, 1985). According to the biased competition model, top-down attentional guidance toward some visual objects and the suppression of other objects produce competitive biases that favor the sensory processing and encoding of currently task-relevant objects. However, this type of suppression is only activated once sensory representations interact in a competitive fashion, and is therefore reactive rather than proactive. Thus, it remains unclear whether multiple-item suppression at the neural level can be based on proactive mechanisms. In contrast, there is clear evidence that proactive attentional guidance can operate for several objects simultaneously. For example, it has been shown that preparatory task sets for target features (attentional templates) can be activated in parallel for multiple features (Cavanagh & Alvarez, 2005; Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016; Irons et al., 2012; Jenkins et al., 2018). Attention can be guided independently to two target objects at different spatial locations, and this is reflected by two N2pc components with distinct time courses, indicative of parallel independent foci of attention (Eimer & Grubert, 2014; Jenkins et al., 2018). If facilitation and inhibition in selective attention act in parallel and in a functionally equivalent fashion, this ability for multiple-target attentional facilitation should be mirrored by the capacity to simultaneously suppress multiple distractors.

Alternatively, it is possible that facilitation and suppression are based on functionally distinct mechanisms. For example, the normalization model of attention (Reynolds & Heeger, 2009), assumes the existence of a suppressive field which represents the object features and locations that contribute to the suppression of neural activity. In contrast to the attentional field, which modulates the activity of neurons that are tuned to particular task-relevant features or locations, the suppressive field is assumed to be largely nonspecific and independent of current task goals, allowing suppression to spread to neurons that are tuned to multiple different stimulus attributes. In this model, facilitation and suppression are qualitatively distinct, as only facilitation can be flexibly activated based on task goals. Recent research has found evidence for such an asymmetry by demonstrating that our ability to activate distractor templates (or negative search templates) following task instructions is severely limited. Prior knowledge about distractor features does not facilitate target selection immediately (Beck et al., 2018; Moher & Egeth, 2012), and extensive training is required before such facilitation can be observed (Berggren & Eimer, 2021). Thus, while both facilitation and suppression can contribute to attentional selectivity, the underlying mechanisms may be quite different (see Chelazzi et al., 2019). In this case, the existence of simultaneous multiple-item facilitation has no implications for proactive suppression, which may be strictly limited to a single object at a time.

In the present study, we investigated the question of whether multiple sources of salient distractor information can be suppressed simultaneously, or whether suppression can only be applied to one of these sources. We employed a version of the additional singleton paradigm. Across four experiments, participants searched for a target shape among nonsalient and salient distractors in search displays that contained six items in total. As usual, some search displays contained either a single salient distractor (a color singleton) or no such distractor. The critical new feature was that other search displays now contained two different color singleton distractors. We used this procedure to obtain new insights into the mechanisms involved in proactive suppression. First, and most importantly, we wanted to determine whether this type of suppression is only ever applied to the most salient item in a search display (single-item suppression) or whether it is more flexible and can be allocated to two simultaneously present salient items (multiple-item suppression). To answer this question, we also varied the relative salience of the salient distractors by manipulating the color contrast between these items and the majority of items in the search display (the target and the nonsalient distractors). For example, in displays where the target and nonsalient distractors were green, the more salient distractor (S+) was red, while the less salient distractor (S−) was yellow.

We employed both behavioral and ERP markers of proactive suppression. Based on previous observations that the presence of a salient color singleton in a search display can result in faster target RTs relative to singleton-absent displays, we tested whether such singleton benefits would increase when a second salient item is added. If multiple-item suppression is possible, these benefits should be larger for displays where both S+ and S− are present relative to displays that include only one of these salient items, reflecting the bigger reduction of effective set size in the former search displays. If proactive suppression was only applied to the most salient item in a display, singleton benefits should not differ between these displays. In addition, we also measured P_D components in response to search displays with one versus two salient items. Because the P_D is a lateralized component, it is difficult to isolate the relative contributions of suppression applied to S+ and S− in displays where both these items are presented laterally. However, when one of these items appears on the vertical midline and the other laterally, only the lateral item will elicit a P_D. We applied this logic in the ERP studies reported below to measure P_D components that exclusively reflect the suppression of either S+ or S−. To obtain a P_D that is associated with the suppression of S+, we recorded in ERPs in response to search displays where S+ appeared on the left or right side and S− above or below fixation. Conversely, to measure P_D components to S− items, we employed search displays were S− was presented laterally and S+ on the vertical midline.

Multiple-item suppression should in principle be reflected by two separate P_D components elicited in response to both S+ and S−, whereas single-item suppression applied to the most salient item in a search display should result in a single P_D, regardless of whether displays include one or two salient items. For example, for search displays that contain both S+ and S−, only S+ should be able to elicit a P_D component.

If multiple-item suppression is possible, a second question arises, regarding the order in which salient items are inhibited. One possibility is that color salient distractors are suppressed sequentially according to priority, with S+ suppressed before S−, which would result in sequential nonoverlapping P_D components. Alternatively, suppression might be triggered in parallel, as reflected by fully overlapping P_D components to S+ and S−. An intermediate possibility is that the suppression of S+ is triggered faster than the suppression of S−, but both processes co-occur in time. This should result in onset latency differences and a partial overlap between the two corresponding P_D components.

Experiment 1

The goal of Experiment 1 was to provide behavioral evidence for multiple-item suppression in search displays with six items. Participants searched for shape-defined targets in displays that contained one or two salient items that differed in color from the target and the other distractor item(s). One of these color singletons (S+) was more salient than the other (S−). In displays with two salient items, both S+ and S− were present. There were also singleton-absent search displays. The search display shapes were heterogeneous, so that participants had to adopt feature search (rather than singleton search mode; Bacon & Egeth, 1994) to find the target. We measured singleton benefits by comparing performance in response to search displays with or without salient distractor singletons. Successful distractor suppression will be indicated by faster RTs for search displays that contain a color singleton, reflecting a reduction in effective display set size. If multiple-item suppression can be applied these benefits should be larger for displays that contain both S + and S− relative to displays that include only one of these items.

Method

Participants

Twenty-five participants were recruited for Experiment 1. One participant was removed due to having accuracy at chance level (proportion correct: 0.48), leaving 24 participants in the final sample (age: $M = 27.75$ years, $SD = 11.16$ years; 19 female and five male[1], six left-handed and 18 right-handed). All participants reported having a normal or corrected-to-normal vision. Sample size selection was based on previous work that has showed a singleton benefit in an additional singleton paradigm (24 participants: Gaspelin et al., 2015; 20 participants: Gaspelin & Luck, 2018a; 22 participants in Experiment 2: Kerzel & Burra, 2020). Kerzel and Burra (2020) obtained a Cohen's d of 0.84 in the critical t-test showing faster RTs for singleton-present as compared to singleton-absent trials. To replicate this effect with a power of 0.95 at an alpha of 0.05, a minimum sample of 21 would be necessary (determined using G*power; Faul et al., 2007). Similarly, a sample size of 19 participants would be required to replicate this effect reported by Gaspelin and Luck (2018a), with a Cohen's d of 0.90. The departmental ethics committee at Birkbeck College, University of London, approved the method and procedure for this experiment and all subsequent experiments reported.

Stimuli and Procedure

Stimuli were presented using a 24-in. BenQ monitor (1,920 × 1,080 screen resolution) attached to a SilverStone PC. Participants' viewing distance was approximately 80 cm. The experiment (and all subsequent experiments) was programed using E-prime 3.0 software (Psychology Software Tools, Pittsburgh, PA, United States). Participants had to identify and report the location of a dot (left or right) within a predefined target shape. They responded by using the "x" or "n" keys on a computer keyboard to indicate that the dot was located on the left or right side of the target shape. Each trial began with a fixation cross, which was presented for 500 ms (± 100 ms jitter). Search displays were then presented for 200 ms. Once the display disappeared, participants had 4 s to respond. A blank intertrial interval of 500 ms was included after a response was registered, followed by the next trial (which began automatically).

All search displays contained six items, with two items presented to the left of fixation, two items presented to the right of fixation, one item above fixation, and one item below fixation (see Figure 1). The target was placed in the up, down, left (either upper or lower) and right (either upper or lower) locations with equal probability. When placed laterally, the location of the target, S+, and S− in the upper or lower positions of the visual field were determined randomly, and these items were always accompanied by a target-color distractor on the same side. Thus, these three critical items never appeared together on the same lateral side. Items were presented on a black background, with a gray fixation at the center of the screen. The center of each shape was presented at a distance of 2° from fixation. The main manipulation was the number of salient distractor items present in the display (none: 20% of trials; one: 40% of trials; two: 40% of trials). Figure 1 illustrates the time course of a trial, the possible targets, and displays with one, two, or no salient distractors.

A target was always present and could be a diamond (1.6° × 1.6°), a circle (0.7° in radius), or a hexagon (1.5° × 1.5°; counterbalanced between-subjects; see Figure 1B). The other distractor items in the display could be a square (1.13° × 1.13°) and/or a gate stimulus (1.2° × 1.2°), as well as the other target shapes that did not serve as the target for that subject (i.e., if the target was a hexagon, the diamond and circle were distractor items for this

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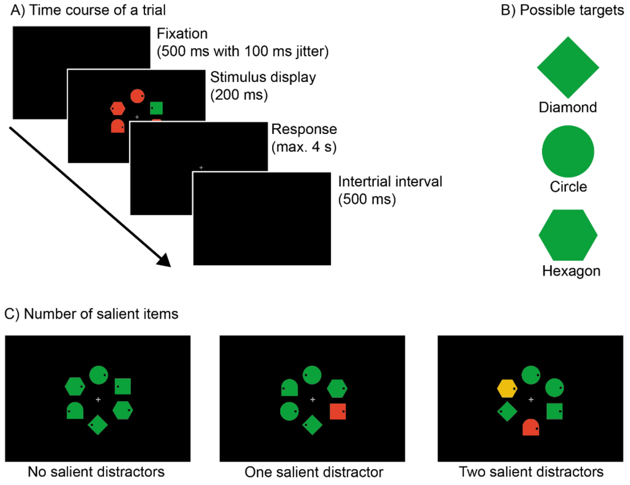
[1] Participants were asked for their gender but also given the option of "none of the above" and "prefer not to say." In this experiment and all subsequent experiments, these options were not selected. No information regarding race and ethnicity were collected.

Figure 1

Illustration of Experimental Procedures for Experiment 1



Note. (A) The time course of a trial. (B) The possible target stimuli, which remained constant for each participant. (C) Search displays without a salient distractor item, or with one or two of these items. In (C), the target was a green diamond, S+ was red and S− yellow. For half of all participants, the color assignment was changed, with red targets, a green S+, and a yellow S− (A). See the online article for the color version of this figure.

subject). The locations of the target-colored distractors were randomly selected. Target-colored distractors could not have the same shape as a salient distractor within the same display, and no more than two target-colored distractors could have the same shape. Moreover, salient distractors could never be the same shape. All search display items contained a dot (size: $0.1° \times 0.1°$) on the left or right side at a horizontal distance of 0.2° from its outer edge. The location of each dot was randomly assigned for each display item. For half of the participants, the target and target-colored distractor(s) were green (CIE coordinates: 0.304/0.612, luminance: 45.5 cd/m^2), one possible salient distractor was red (S+; 0.672/0.336, 45.4 cd/m^2) and the other yellow (S−; 0.467/0.485, 45.9 cd/m^2). For the other half of participants, the target and target-colored distractor(s) were red, one possible salient distractor was green (S+) and the other yellow (S−). The counterbalancing of colors was chosen to ensure that any effect particular to S+ was not due to its specific color. For displays with a single salient distractor, S+ and S− were equally probable (each was presented in 20% of all trials). All possible spatial configurations of target and salient distractor locations were equally probable in displays with one or two salient distractors. All different types of search displays were presented in random order.

There was a total of 600 experimental trials, separated into 15 blocks of 40 trials each. The experiment began with one block of 15 practice trials. To begin the experimental blocks, participants needed an accuracy of 70% and an average RT of 1,500 ms during the practice block. The practice block restarted until this level of performance was achieved. For incorrect trials in the practice block, a red fixation cross was presented after response execution. In experimental trials, no trial-by-trial feedback was provided. Participants received block-by-block feedback on accuracy at the end of all experimental blocks and the practice block.

Analysis

For both accuracy and RTs, data were analyzed using a 2 (color scheme: S+ red with S− yellow vs. S+ green with S− yellow) × 3 (number of salient distractors: 0, 1, or 2) mixed-model ANOVA. Greenhouse–Geisser corrections were applied to *p*-values when sphericity was violated. To understand the effect of distractor salience on RT, a 2 (salient color: S+ vs. S−) × 2 (color scheme) mixed ANOVA for trials with only one salient distractor was also conducted. Reported effect sizes for ANOVA results were determined using partial eta squared (η_p^2; Keppel, 1991) and for *t*-test results were determined using Cohen's *d* (M_1–M_2/SD_{pooled}) for this experiment and all subsequent experiments.

Overall accuracy for all participants was within three *SD*s of the mean. Trials with RTs above or below 2.5 *SD*s of the mean for each level of the number of salient distractors were considered outliers and removed. For RT analyses, only accurate trials were kept for final analysis.

Transparency and Openness

We have provided a repository link in the authors' note as well as a data citation in our reference list that directs to all data to comply with the TOP guidelines. This study was not preregistered.

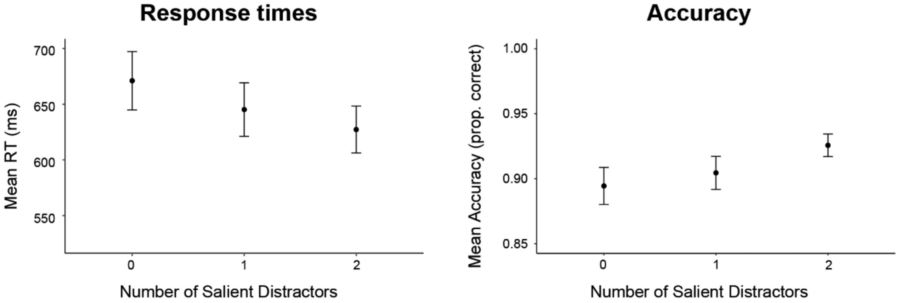
Results

As predicted, there was a singleton benefit, as RTs decreased with an increase in the number of salient distractors, $F(2, 44) = 35.94$, $p < .0001$, $\eta_p^2 = 0.62$; no salient distractors: $M = 671$ ms, $SE = 26$ ms; one salient distractor: $M = 645$ ms, $SE = 24$ ms; two salient distractors: $M = 627$ ms, $SE = 21$ ms; see Figure 2. Paired *t*-tests (with Bonferroni corrections for multiple comparisons) show a significant RT difference between displays with no salient items versus one salient item, $t(23) = 6.19$, $p < .0001$, $d = 0.21$, as well as between displays with one versus two salient items, $t(23) = 4.13$, $p = .0008$, $d = 0.16$). There was no main effect of color scheme, $F < 1$, nor did color scheme interact with the number of salient distractors, $F(2, 44) = 1.00$, $p = .38$. The relative salience of the color singleton in displays with one salient item (S+ or S−) had no effect on RTs (S+ vs. S−; $F(1, 22) = 1.94$, $p = .18$). In this second analysis, there was also no main effect of color scheme ($F < 1$), and no interaction between both factors, $F(1, 22) = 2.06$, $p = .17$.

Accuracy was generally high (see right panel of Figure 2), but clear singleton benefits were still present, as accuracy increased with the number of salient distractors, $F(2, 44) = 7.18$, $p = .002$, $\eta_p^2 = 0.25$ (see Figure 2). Paired *t*-tests show a significant increase in accuracy between displays with one ($M = 0.90$, $SE = 0.01$) versus two salient distractors ($M = 0.93$, $SE = 0.009$; $t(23) = 3.14$, $p = .01$, $d = 0.40$). There was no accuracy difference between displays with no salient items ($M = 0.89$, $SE = 0.01$) and displays with one salient distractor, $t(23) = 1.27$, $p = .43$. Similar to RTs, accuracy for displays with one salient distractor was not reliably affected by distractor color (S+ vs. S−), $F(1, 22) = 3.77$, $p = .07$ (main effect of color scheme and interaction, both $F < 1$).

Figure 2

Effect of the Number of Salient Distractors for Experiment 1



Note. Results showed a decrease in RTs with an increase in the number of salient distractors, with corresponding results for accuracy. Error bars represent the standard error of the mean for each condition. RT = response time.

Interim Discussion

Experiment 1 obtained behavioral evidence for multiple-item suppression. Clear singleton benefits were found, as RTs were faster for displays that contained one salient singleton relative to displays where no such singleton was included. These benefits were not modulated by the relative salience (S+ vs. S−) of this singleton. The critical new finding was that the singleton benefits for RTs further increased for displays with two salient distractor items. This suggests that in these displays, both of these items were suppressed, thereby further reducing the effective set size (see also Stilwell & Vecera, 2019).[2] For accuracy, there was an analogous tendency toward increased singleton benefits for displays with two salient distractors.

To investigate whether an analogous increase of singleton benefits for search displays with two salient distractors would also be obtained even with four-item displays (which were employed in previous studies reporting such a benefit; Gaspelin & Luck, 2018a; Drisdelle & Eimer, 2021), we conducted another experiment that was identical to Experiment 1 except that display set size was reduced to four items. A reliably larger singleton benefit for search displays containing both S+ and S− was indeed observed in this experiment (for details, see Supplementary Material, Experiment 1S), suggesting that multiple-item suppression does not depend on display set size, and is even triggered in four-item search displays.

However, this observation, as well as the results of Experiment 1S, do not provide indisputable evidence for multiple-item suppression, as an alternative explanation in terms of color-based attentional guidance remains possible. As targets were defined by a specific shape, participants will have activated a corresponding shape-selective search template (e.g., "circle") to guide attention to the location of the target in each search display. However, due to the fact that the color of the target item remained constant throughout, this target template may also have included the target color (e.g., "green circle"), and this may have resulted in some attentional guidance toward all items that matched this color. This type of attentional guidance could have reduced effective set size and thus produced performance benefits for displays with two salient singletons, without involving any singleton suppression. Experiment 2 was conducted to test and rule out this alternative explanation.

Experiment 2

If the additional performance benefits observed in Experiment 1 for displays with two salient singletons were a result of participants employing a combined shape/color search template, such benefits should no longer be present under conditions where the target color is no longer constant, but changes unpredictably across trials. To test this possibility, Experiment 2 used the same procedures as Experiment 1, except that the target color now randomly repeated or changed to a different color on each trial. For one group of participants, the possible target colors were blue or yellow, and the two distractor colors were red and green. This assignment was reversed for the other group. Because it was no longer possible for participants to search for a specific constant color/shape combination, search should now be guided exclusively by a template for the target shape. If the additional two-singleton benefits remain present under these conditions, they cannot be due to color-based attentional guidance reducing effective set size, thereby providing further evidence for the alternative multiple-item suppression account. Because of the variability of target and distractor colors in Experiment 2, there was no longer an explicit manipulation of the relative salience of a specific singleton distractor (i.e., S+ vs. S−), in contrast to Experiment 1.

Method

Twenty-five participants were recruited for Experiment 2. One participant was removed due to having accuracy at chance level (proportion correct: 0.51), leaving 24 participants in the final sample (age: $M = 33.13$ years, $SE = 7.85$ years; 14 female and 10 male; 4 left-handed and 20 right-handed). All participants reported having a normal or corrected-to-normal vision. The methodology was the same as in Experiment 1 except for the following changes.

The task-relevant color for each trial (i.e., the color of the target shape and remaining target-colored shapes) was randomly selected

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[2] To test whether these increased singleton benefits remained present even when the additional second salient distractor was relatively less salient (S−), we compared RTs on trials where displays contained S+ only to trials where they included both S+ and S−. There was still a significant additional singleton benefit (643 ms vs. 627 ms; $t[23] = 3.55$, $p = .002$, $d = 0.14$).

from two possible colors. For half of the participants, the target color could be blue (CIE coordinates: 0.167/0.105, luminance: 58.0 cd/m^2) or yellow (CIE: 0.402/0.530; 57.9 cd/m^2) and salient distractors could be red (CIE: 0.621/0.330; 58.0 cd/m^2) and green (CIE: 0.306/0.608; 58.0 cd/m^2). For the other half, the color scheme was inversed (red and green target-defining colors with blue and yellow salient distractors). The proportion of trials with none, one or two salient distractors remained identical to Experiment 1. The same statistical analyses as Experiment 1 were conducted for Experiment 2, except for comparisons of S+ and S− and this manipulation was not present in Experiment 2.

Results

As in Experiment 1, there were clear singleton benefits that were modulated by the number of salient distractors (see Figure 3). The addition of salient colored distractors decreased RTs, $F(2, 44) = 7.64$, $p = .001$, $\eta_p^2 = 0.26$, relative to no-singleton displays, and this effect was stronger for displays with two salient items (no salient items: $M = 614$ ms, $SE = 24$ ms; one salient item: $M = 605$ ms, $SE = 21$ ms; two salient items: 597 ms, $SE = 20$ ms). Planned paired t-tests showed a significant RT difference between displays with no salient items versus one salient item, $t(23) = 2.31$, $p = .03$, $d = 0.08$, as well as between displays with one salient item and two salient items, $t(23) = 2.62$, $p = .02$, $d = 0.08$. There was no main effect of color scheme (red/green target color scheme vs. blue/yellow target color scheme), nor did the target scheme and the number of salient items interact (both Fs < 1).

As in Experiment 1, accuracy was high ($M = 0.90$, $SD = 0.07$), but there were no significant singleton benefits or any other effects for accuracy (all Fs < 1).

Comparison of RT Effects in Experiments 1 and 2

While we observed an RT benefit associated with the presence of a second salient item in Experiment 2, the size of the singleton benefits was generally smaller than in Experiment 1. This was confirmed in an additional ANOVA for the RT data across Experiments 1 and 2, with Experiment (2 levels: 1 vs. 2) as an additional level. As expected, there was a significant interaction between the Experiment and the number of salient distractors, $F(2, 92) = 8.68$, $p = .002$, $\eta_p^2 = 0.16$, demonstrating that singleton benefits for RT were indeed smaller in Experiment 2.

Interim Discussion

The results of Experiment 2 demonstrated that the benefits associated with the presence of a second salient distractor observed in Experiment 1 were not entirely due to the fact that the target color remained constant in this experiment. Thus, these additional singleton benefits cannot exclusively be the result of color-based attentional guidance reducing effective set size. Their presence in Experiment 2, where target color was no longer constant and predictable, and search should therefore have been guided exclusively by a template for the target shape, thus providing clear evidence for multiple-item suppression. It is also unclear why participants should have chosen to employ a combined shape/color template in Experiment 1, as such a template would have made search guidance less effective (by also including distractor objects in the search display) than a purely shape-specific search template. However, it is notable that the singleton benefits on RTs were smaller in Experiment 2 relative to Experiment 1, and that there were no longer any such benefits for accuracy. This suggests that factors other than multiple-item suppression (such as some residual color-based attentional guidance) may have contributed to the effects observed in Experiment 1.

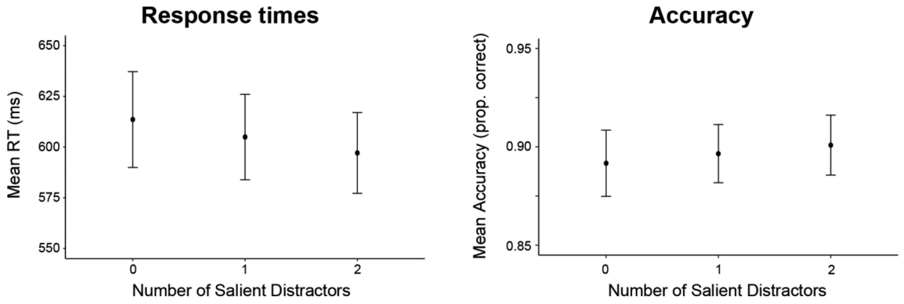
Overall, Experiments 1 and 2 have provided new behavioral evidence for multiple-item suppression in visual search. The goal of Experiments 3 and 4 was to investigate whether these behavioral effects would be mirrored by corresponding electrophysiological evidence from P_D components.

Experiment 3

Experiment 3 was designed to provide electrophysiological evidence of multiple-item suppression by measuring P_D components in response to search displays that always included two items with a unique color (S+ and S−). In some displays, one of these appeared on the vertical midline, and the other on the left or right side, so that only the lateral item would elicit a P_D. In other displays, S+ and S− were both lateral, and appeared on opposite sides. If proactive suppression is only triggered by the single most salient distractor in a

Figure 3

Effect of the Number of Salient Distractors for Experiment 2



Note. Similar to Experiment 1, results showed a decrease in RTs with an increase in the number of salient distractors. No-singleton benefits were found for accuracy. Error bars represent the standard error of the mean for each condition. RT = response time.

search display, a P_D should be observed for S+ but not S−. If suppression can be applied to two salient distractors in the same search display, both items should trigger P_D components. If salient items are suppressed according to priority, then sequential nonoverlapping P_D components should be observed. Parallel multiple-item suppression predicts similar P_D onset latencies for both S+ and S−, while an intermediate possibility is that the suppression of S+ is triggered faster than the suppression of S−, but that both processes co-occur in time, resulting in onset latency differences and a partial overlap between both P_D components.

To maximize the number of visual search displays available for computing ERPs, a multiple frame procedure was used, where several consecutive search displays are presented on the same trial (e.g., Aubin & Jolicoeur, 2016; Fortier-Gauthier & Jolicoeur, 2018; Drisdelle & Eimer, 2021; Drisdelle et al., 2017; Drisdelle & Jolicoeur, 2018; Maheux & Jolicœur, 2017). Participants had to monitor four successive search displays, in order to report the number of displays that included a target after all displays have been presented.

Method

Participants

Eighteen participants were recruited for Experiment 3 (age: $M =$ 29.78 years, $SD = 6.8$ years, 13 female and five male; one left-handed; and 17 right-handed). Two participants from Experiment 3 also took part in Experiment 4. All participants reported having a normal or corrected-to-normal vision. Sample size calculation was based on Experiment 1 of Gaspelin and Luck (2018a; 20 participants) and on Experiment 2 of Kerzel and Burra (2020; 22 participants). For Kerzel and Burra (2020), the critical t-test showing the existence of a P_D component for lateral distractors (with a midline target) had a Cohen's d_z of 1.39. To replicate this effect with a power of 0.95 at an alpha of .05, a minimum sample of nine participants was necessary (Faul et al., 2007). Because we included two salient distractors (S+ and S−), we decided to double the minimum sample and include a sample similar to Gaspelin and Luck (2018a) and Kerzel and Burra (2020).

Stimuli and Procedures

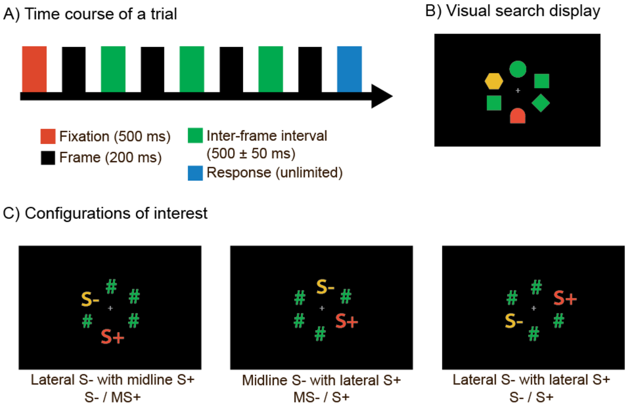
On each trial, four visual search displays (i.e., frames) were presented sequentially (multiple frame procedure). Participants' task was to count and report the number of frames that contained a predefined target shape among heterogeneous distractor shapes. The stimulus shapes, colors, and locations were identical to those in Experiment 1, except that no lateral dots were present, target-absent displays were included, and all displays contained both salient distractors (S+ and S−). When a target was present, the five nontarget shapes were the four remaining possible items and one that was randomly selected again among these four items. For example, if the target was a diamond, the remaining shapes were a hexagon, a square, a gate, a circle, plus one other of these four nontarget shapes. For target-absent trials, two of the four nontarget shapes appeared twice, again selected at random. For all participants, S+ was red, S− was yellow, and the target and the other nontarget distractor(s) were green. Target-absent displays contained four green nontarget distractors. Target location probabilities were the same as Experiment 1, with the target being equally likely to appear in the up, down, left (either upper or lower), and right (either upper or lower) locations. Figure 4 shows (A) the time course of a trial, (B) an example of a display frame, and (C) the different S+/S− configurations of interest.

Before the experiment began, participants were informed about the color and shape of the target and instructed to ignore the salient distractors and to respond as quickly and as accurately as possible. Trials began with a fixation cross that remained presented until participants were prompted for a response after all four frames were presented. After 500 ms, the first search display (frame) appeared. Each frame was presented for 200 ms, with an inter-frame interval of 500 ms (±50 ms jitter). Once the last frame was presented, including a final 500 ms (±50 ms jitter), participants were prompted to respond. Their task was to report the number of frames with a target (possible responses: 1, 2, 3, or 4 frames with a target) by pressing "z," "x," "n," or "m" keys on a computer keyboard with their left/right middle/index finger. The next trial was initiated once a response was registered. For incorrect trials in the practice block, a red fixation cross was presented after response execution. In experimental trials, no trial-by-trial feedback was provided, and the gray fixation cross disappeared momentarily to indicate that a response was registered. Participants received block-by-block feedback on accuracy at the end of all experimental blocks and the practice block.

There were 16 experimental blocks (25 four-frame trials in each block), resulting in 400 experimental trials (each with four frames, 1,600 frames in total). A practice block (10 trials; 40 frames) was completed by all participants prior to the first experimental block. A target was present in 62.5% of all frames and absent in the remaining 37.5% of frames. Frames were randomly sorted into trials, with the restriction that there was an equal overall number of trials with 1, 2, 3, or 4 target frames. These four types of trials were then presented in random order.

Figure 4

Illustration of Experimental Design for Experiment 3



Lateral S- with midline S+
S- / MS+

Midline S- with lateral S+
MS- / S+

Lateral S- with lateral S+
S- / S+

Note. (A) The time course of a trial. Every trial consisted of four visual displays (frames) separated by an interframe interval. (B) A visual display with six items, which were presented for 200 ms. (C) The configurations of interest for the EEG analysis. We compared displays that elicited lateralized EEG activity associated with S− only (left panel), S+ only (middle panel), and both S− and S+ (right panel). The hash symbols represent placeholders for nonsalient distractors and/or targets (when present). Possible target shapes were the same as in Experiment 1 (see Figure 1B). See the online article for the color version of this figure.

EEG Recording and Analysis

Preprocessing. The electroencephalogram (EEG) was DC-recorded from 27 scalp electrodes mounted on an elastic cap at the following sites according to the international 10/20 system: Fpz, F7, F8, F3, F4, Fz, FC5, FC6, T7, T8, C3, C4, Cz, CP5, CP6, P9, P10, P7, P8, P3, P4, Pz, PO7, PO8, PO9, PO10, and Oz (Sharbrough, 1991). Data were recorded using Brain Products software and sampled at 500 Hz with an online low-pass filter of 40 Hz and an online notch filter of 50 Hz. Channels were referenced online to an electrode placed on the left earlobe and re-referenced offline to the average of both earlobes. The horizontal electrooculogram (HEOG), used to measure horizontal eye movements, was calculated offline as the voltage difference between electrodes lateral to the external canthi of both eyes (placed using the elastic cap). Frames were segmented from 100 pre-stimulus to 500 ms poststimulus (600 ms epochs). Segmentations were baseline corrected by subtracting the average voltage of the 100 ms pre-stimulus period from the entire epoch. Frames with activity considered blinks or vertical eye movements (exceeding ±60 μV at Fpz) or horizontal eye movements (exceeding ±35 μV in the HEOG channel) were automatically rejected. To detect any systematic residual eye movements toward lateral salient distractors that remained after automated artifact rejection, lateralized HEOG differences for frames with left versus right salient distractors were examined for each participant (averaged across all other conditions). Averaged lateralized HEOG deflections remained below 3 μV for all participants included in the final sample, indicating that they maintained reasonable fixation. Other artifacts, such as movement-related artifacts, were identified and automatically rejected using a cut-off of ±80 μV for all other channels. Data were analyzed using BrainVision Analyzer 2 (Brain Products GmbH, Gilching, Germany). Trials with incorrect responses were included in the EEG analysis, given the overall high accuracy (93%) and because responses were provided only after four visual search frames. A correct response to a trial in this multiple-frame procedure indicates that participants had detected the presence or absence of a target in all four successive frames. In contrast, an incorrect response does not indicate a failure to discriminate target presence or absence in all frames (i.e., participants could have made a correct decision for three of four frames). Assuming independence of response choice across frames, the approximate accuracy of a participant is proportional to the fourth root of the overall accuracy (assuming the probability of canceling errors is low). Thus, an overall trial accuracy rate of 0.80 would correspond to 0.95 accuracy rate for individual frames. For this reason, all trials were kept for final analyses, irrespective of response accuracy.

ERPs. Averaged ERP waveforms for the main analysis were computed for individual frames, separately as a function of whether the salient distractor (S− and S+) was presented laterally or on the vertical midline (M). Only frames where the target was presented on the midline (TM) or was absent (T0) were included. ERPs were separately averaged for six different frame types ((a) S−/MS+–T0, (b) S−/MS+–TM, (c) MS−/S+–T0, (d) MS−/S+–TM, (e) S−/S+–T0, and (f) S−/S+–TM). When both salient distractors were lateral (frame types 5 and 6), laterality was defined relative to the position of S+ (so that any lateralized activity associated with S− will be polarity-inverted). To isolate lateralized activity associated with salient distractors, ERPs recorded at electrode pair PO7/PO8 ipsilateral to the salient distractor were subtracted from contralateral ERPs at the same electrode pair.

Statistical Analysis. Analyses of variance (ANOVA) and *t*-tests were used to evaluate ERP results statistically. Because our study focused on lateralized components, only effects containing the laterality factor are reported. Lateralized ERP effects were quantified as contralateral minus ipsilateral differences (C–I Δ). The time windows for effects on these components were quantified using the collapsed localizer method, as described by Luck and Gaspelin (2017). For the P_D component, frames containing a lateral salient distractor were averaged (collapsed over all other conditions), and the P_D time window was determined as ranging between 110 and 160 ms.[3]

Results

Overall accuracy of reporting the correct number of target-present frames on a trial was high (proportion correct: 0.93). ERP waveforms elicited at electrodes PO7/PO8 contralateral and ipsilateral to a salient distractor, and the corresponding contralateral–ipsilateral difference waves are shown in Figure 5 (collapsed across displays where the target appeared on the midline or was absent). An initial contralateral positivity (P_D component) was present for displays that included a lateral S+, regardless of whether S− appeared on the vertical midline or on the opposite side. No such P_D was present for displays with a lateral S− and a midline S+. There was also a second contralateral positivity starting around 200 ms after display onset that was more pronounced for displays with one lateral salient distractor (either S+ or S−).

$\mathrm{P_D}$ *Component*

Data were submitted to a 2 (laterality: ipsilateral vs. contralateral) × 3 (configuration: S−/MS+, MS−/S+, S−/S+) repeated-measures ANOVA.[4] A main effect of laterality was observed, $F(1, 17) = 43.65$, $p < .0001$, $\eta_p^2 = 0.72$, demonstrating the existence of an overall P_D. Laterality interacted with configuration, $F(2, 34) = 28.31$, $p < .0001$, $\eta_p^2 = 0.63$. As can be seen in Figure 5, a P_D was elicited by displays with a lateral S+ item (MS−/S+ and S−/S+), but not by displays with a lateral S− item (S−/MS+). Paired *t*-tests (with a Bonferroni correction for three comparisons applied to the *p*-values) comparing contralateral and ipsilateral ERPs confirmed the presence of a P_D for MS−/S+ displays, $t(17) = 7.32$, $p < .0001$, $d = 0.29$, and for S−/S+ displays, $t(17) = 5.55$, $p = .0001$, $d = 0.29$, but not for S−/MS+ displays, $t(17) = 1.08$, $p = .88$, showing that a P_D was only elicited by the more salient red item (S+). To test whether the

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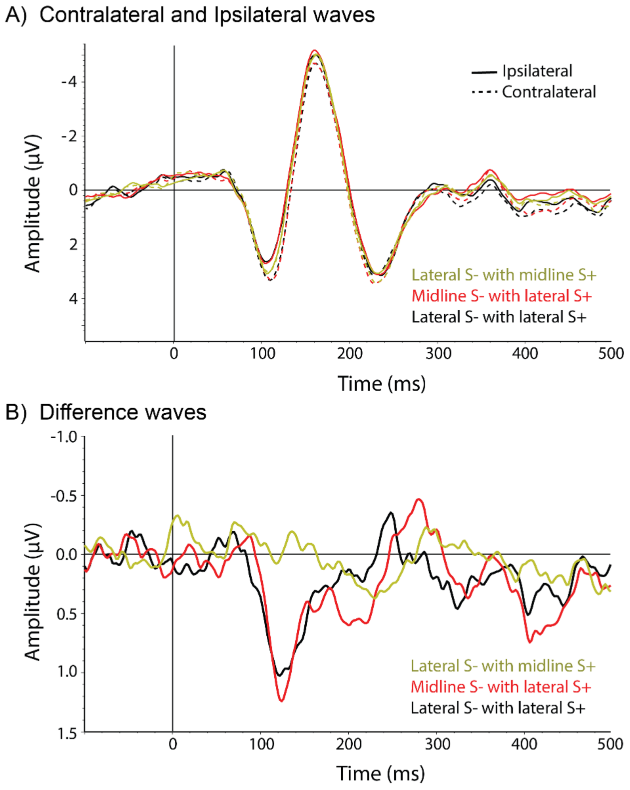
[3] The P_D component is known to vary over a broad range (100–400 ms) based on task and stimulus saliency (Sawaki et al., 2012). The P_D components observed in this study appear to have an earlier offset compared with previous research (e.g., Drisdelle & Eimer, 2021; Gaspelin & Luck, 2018a; Sawaki & Luck, 2010; Sawaki et al., 2012). This may be due to the use of a multiple frames paradigm that produces a larger number of search displays, leading to more robust ERP components and reducing any average smearing due to trial-by-trial variations in component timing. In addition, collapsing across different salient distractor colors, as is common in previous studies, may also result in a more temporally extended P_D.

[4] Data were first analyzed with target presence (absent vs. present) as a factor. There was no significant interaction between target presence and laterality in either of the two analysis windows (P_D and the second contralateral positivity; all *F*s < 1.10, *p*s > .34), so data were collapsed over this condition for both components to improve power.

Figure 5

Waveforms for Electrode Sites PO7 and PO8 of Experiment 3 Associated With Lateral Salient Distractors



Note. (A) The contralateral and ipsilateral activity associated with lateral salient distractors. (B) The corresponding difference wave. The first positivity is a P_D component to lateral S+ items. For displays where both S+ and S− were lateral (black lines), contra/ipsilateral were defined relative to the side of S+. See the online article for the color version of this figure.

location of S− affected the P_D elicited by lateral S+ items, we compared displays where a lateral S+ was presented together with a midline S− or with an S− on the opposite side. No difference in P_D amplitude was found between these displays ($t < 1$).

Second Contralateral Positivity

The presence of a second contralateral positivity following the P_D component was unexpected. As shown in Figure 5B, this positivity appears to be elicited by displays that contained one lateral salient item. Its overall presence was confirmed when mean amplitudes measured between 200 and 250 ms poststimulus were submitted to a 2 (laterality: ipsilateral vs. contralateral) × 3 (configuration: S−/MS+, MS−/S+, S−/S+) repeated-measures ANOVA. There was a main effect of laterality, $F(1, 17) = 15.21$, $p = .001$, $\eta_p^2 = 0.47$, which interacted with configuration, $F(1, 17) = 3.85$, $p = .031$, $\eta_p^2 = 0.19$. Paired *t*-tests (with Bonferroni corrections for multiple comparisons) comparing contralateral and ipsilateral waveforms showed that this second contralateral positivity was significantly present for MS−/S+ displays, $t(17) = 4.41$, $p = .01$, $d = 0.14$, marginally significantly present for S−/MS+ displays, $t(17) = 2.57$, $p = .06$, $d = 0.11$, and not present for S−/S+ displays, $t < 1$.

Interim Discussion

The central finding of Experiment 3 was the absence of any evidence for a P_D triggered by S−. In contrast, a clear P_D component was triggered by S+. This suggests that suppression was only applied to the most salient item in a search display (S+), in line with the single-item suppression hypothesis. There was also an unexpected second positive component, which was only observed for displays that contained only one lateral salient item. One possibility is that participants attended to a lateral target-colored distractor opposite to S+ or S− on some trials, resulting in a small but reliable N2pc component (i.e., a negativity contralateral to this distractor that would appear as a contralateral positivity when plotted relative to the location of S+ or S−).

We also investigated whether a similar pattern of ERP results would be observed with four-item displays (as used by Gaspelin & Luck, 2018a; Drisdelle & Eimer, 2021), by running another experiment that was identical to Experiment 3 apart from display set size being reduced to four items. Results were very similar to Experiment 3 (see Supplementary Material, Experiment 2S), replicating the presence of a P_D for S+ items only but not S− items for four-item search displays. These data provide further support for the hypothesis that the P_D component reflects single-item suppression that is exclusively applied to the most salient distractor in a search display. However, these results appear inconsistent with the behavioral results of Experiments 1 and 2, which provided clear evidence for multiple-item suppression. One possibility is that the yellow S− items used in Experiment 3 were not sufficiently salient, and therefore unable to activate suppression processes that were strong enough to generate P_D components. To test this possibility, we conducted a second ERP experiment that was similar to Experiment 3, except that displays with only a single salient item (either S+ or S−) were now also included.

Experiment 4

In Experiment 4, we tested the possibility that S− was insufficiently salient to generate a P_D when presented alongside a more salient item (S+), by including search displays that only contained one singleton item (either S+ or S−) among five target-color items. If the P_D reflects suppression of the most salient distractor item, then a P_D should be observed when S− is presented without S+, as it is now the most salient object in the display. If the onset of suppression was sensitive to the absolute salience of a distractor, the P_D component to S− items might emerge later than the P_D triggered by S+ items. Alternatively, S− items might not be able to elicit a P_D component at all, even when presented alone. This would suggest that the salience of a singleton distractor has to be high in order for their suppression to be reflected by a P_D.

Method

Eighteen subjects participated in Experiment 4 (age: $M =$ 29.22 years, $SE = 8.08$ years, 11 female and seven male; five left-handed and 13 right-handed). Two participants from Experiment 4 also participated in Experiment 3. All experimental details, including stimulus setup, analyses, and statistics, were the same as Experiment 3, except for the following changes.

The number of salient distractors in the search displays was manipulated. Half of all displays included one salient item (either S− or S+, with equal probability) and the other half included both salient items (S− and S+; see Figure 6). For displays that included a single salient item (S+ or S−) and the target, all possible combinations of target and salient distractor locations were presented with equal probability. In target-absent displays with a single salient distractor, this salient distractor was only presented laterally (on the right or left of fixation). When both salient distractors (S+ and S−) were included, one of them always appeared on the midline and the other laterally (both for target-present and target-absent displays).

Statistical analyses and EEG preprocessing were the same as in Experiment 3. ERP data were collapsed over upper versus lower lateral salient distractor position (for left and right separately; MS−/S+, S−/MS+, S− only, and S+ only). Data were submitted to a 2 (laterality: ipsilateral vs. contralateral) × 2 (number of salient distractors: one vs. two) repeated-measures ANOVA separately for displays that included either a lateral S+ or a lateral S− item.[5]

Results

Accuracy in Experiment 4 was again high (proportion correct: 0.93). The waveforms in Figure 6A show a clear P_D component for lateral S+ items regardless of S− presence. For lateral S− items (Figure 6B), a smaller and delayed P_D component appears to be present in response to displays without a midline S+ item.

P_D *Component*

The P_D to S+ was quantified within the same 110–160 ms poststimulus time window used in Experiment 3. A significant main effect of laterality was observed, $F(1,\ 17) = 28.83$, $p > .0001$, $\eta_p^2 = 0.63$, reflecting the presence of a P_D in response to a lateral S + item. Bonferroni-corrected *t*-tests against baseline (two comparisons; 0 μV) showed that this P_D was significant regardless of whether a lateral S+ appeared with or without a midline S−, $t(17) = 7.2$, $p < .0001$, $d = 0.24$, and $t(17) = 3.74$, $p = .003$, $d = 0.24$, respectively. Accordingly, there was no interaction between laterality and the number of salient items (one vs. two), $F < 1$. Because the P_D component for S− emerged later than the P_D for S+ (see Figure 6), it was analyzed within a different mean amplitude time window (150–200 ms poststimulus). Importantly, there was a significant effect of laterality during this time window, $F(1,\ 17) = 11.06$, $p = .004$, $\eta_p^2 = 0.39$, indicating the presence of a reliable P_D for S−. Follow-up Bonferroni-corrected *t*-tests against baseline confirmed the presence of a significant P_D component for displays where S− was the only salient item, $t(17) = 3.0$, $p = .02$, $d = 0.14$. In contrast, no significant P_D was observed for displays where S− was accompanied by a midline S+ for this time window, $t(17) = 1.37$, $p = .38$. However, the interaction between laterality and the number of salient items was not reliable, $F(1,\ 17) = 1.67$, $p = .21$.

Second Contralateral Positivity

For lateral S+ items, there was no main effect of laterality in the 200–250 ms poststimulus time window ($F < 1$), indicating that the second contralateral positivity observed in Experiment 3 was now absent. There was also no interaction between laterality and the number of salient items in the display, $F(1,\ 17) = 1.65$, $p = .22$. For S− items, a significant effect of laterality was observed within this time window, $F(1,\ 17) = 11.41$, $p = .004$, $\eta_p^2 = 0.40$ (see Figure 6B), with no interaction between laterality and number of salient distractors ($F < 1$).

Interim Discussion

Overall, the P_D results observed for S+ items in Experiment 4 were essentially the same as those in Experiment 3. Critically, and in contrast to the previous experiment, a reliable P_D was now also found for S−. Although this component was smaller and delayed relative to the P_D in response to S+, its presence during the 150–200 ms poststimulus time window shows that S− items were sufficiently salient to trigger a P_D, especially in displays where S− was the only salient item. The second contralateral positivity observed in Experiment 3 was no longer reliably present in displays with a lateral S+ item. This indicates that the design of Experiment 4 where displays with one or two salient distractors were randomly intermixed might have further reduced any tendency to selectively attend to target-color items that appear opposite to a salient distractor (see below for further discussion). However, a contralateral positivity between 200 and 250 ms poststimulus was reliably present for displays with a lateral S− item (see Figure 6B). It is possible that this positivity reflects the continuation of a suppression-related P_D which was already reliably present between 150 and 200 ms. We therefore conducted another analysis of ERPs in response to displays with a lateral S− item across the entire 150–250 ms poststimulus interval, with the factors laterality and number of salient items (one: S− only; two: S− with midline S+). There was a significant main effect of laterality, $F(1,\ 17) = 18.41$, $p = .0005$, $\eta_p^2 = 0.52$, demonstrating the existence of a contralateral positivity triggered during this time window by lateral S− items. To specifically assess whether this positivity was reliably present even for displays where S− was accompanied by a midline S+ item, as predicted by the multiple-item suppression hypothesis, we conducted a final *t*-test against baseline for difference amplitudes obtained during the 150–250 ms interval. This test did indeed reveal a reliable contralateral positivity, $t(17) = 2.19$, $p = .043$, $d = 0.09$, suggesting that a small suppression-related P_D component might indeed have been elicited in response to S− in displays where the more salient S+ distractor was also present.

Discussion

The question of whether salient distractors attract attention automatically or only when they possess task-relevant features has remained controversial for three decades. More recently, the signal suppression account has offered a potential resolution to this longstanding debate (Gaspelin et al., 2015; Luck et al., 2021). According to this account, all salient objects automatically generate a priority signal, but this signal can be suppressed in order to prevent attentional capture by task-irrelevant objects. This type of proactive

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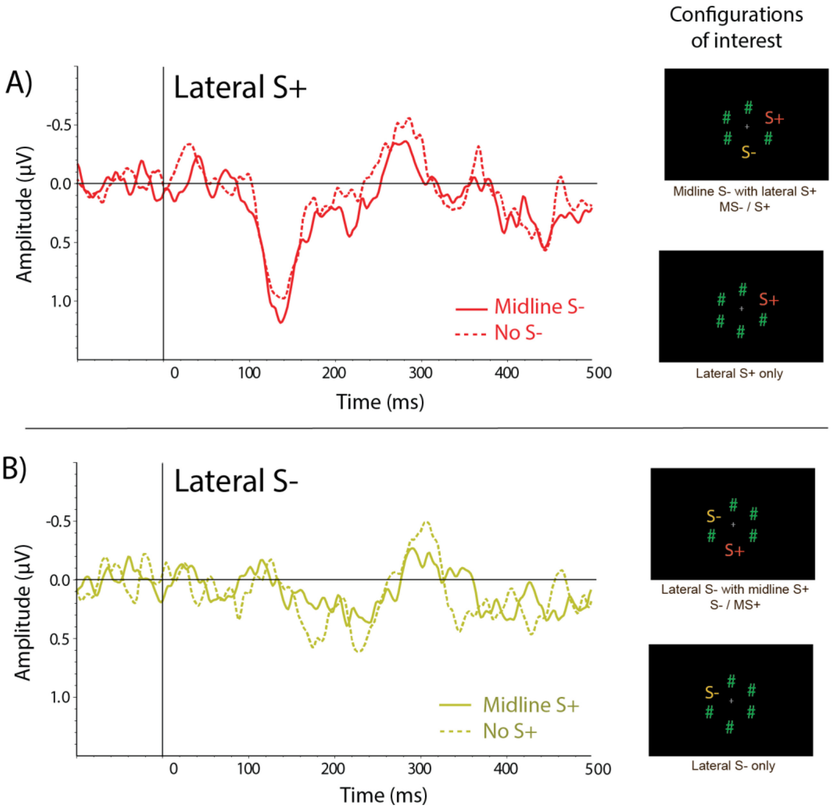
[5] Target presence did not interact with laterality for the P_D or second contralateral positivity in Experiment 4 for S+ or S− (*F*s < 3.72, *p*s > .07), so data were collapsed over this condition to improve power.

Figure 6

Illustration of Display Configurations of Interest and Electrophysiological Results for Experiment 4



Note. (A) Results (contralateral–ipsilateral difference waveforms) for displays with a lateral S+, and examples of both configurations of interest (S+ with a midline S− and S+ only; right panel). (B) The same comparison and configurations of interest for lateral S− items. For the configurations, the hash symbols represent placeholders for nonsalient distractors and targets (when present). For both difference waveform panels, the first positivity is a P_D component to lateral salient distractors. See the online article for the color version of this figure.

suppression would obviously be highly adaptive in real-world environments which often contain multiple salient objects that have to be ignored. However, research on distractor suppression has typically employed displays which only contain a single salient distractor item. Thus, the question of whether multiple-item suppression is possible and whether it is as effective as the suppression of a single salient visual object has not yet been investigated. Here, we manipulated the number of salient distractors in a search display (none, one, or two), and also varied the relative salience of these distractors. In two behavioral experiments, we measured performance improvements associated with the presence of one or two salient distractors (singleton benefits) as markers of successful distractor suppression. We also conducted two ERP experiments where we used the P_D component to track the presence and time course of suppression. Overall, we found clear-cut behavioral evidence for multiple-item suppression. The corresponding results for the P_D component were more complex and suggest important constraints for the concurrent suppression of multiple salient distractors.

We provide robust behavioral evidence showing that proactive suppression can prevent salience-driven attentional capture of multiple salient distractors during visual search. Confirming previous observations (Gaspelin & Luck, 2018a; Drisdelle & Eimer, 2021), we demonstrated that the inclusion of a salient color singleton distractor in search displays resulted in faster RTs as compared to displays that did not contain a singleton. Such singleton benefits were previously interpreted as evidence for proactive suppression, reducing the effective set size of search displays, thereby making visual search more efficient (see also Stilwell & Vecera, 2019). The critical new finding from Experiments 1 and 2 was that these benefits were reliably larger when search displays contained two compared to just a single salient distractor. This strongly suggests that suppression can be applied to at least two objects in the same search display. These effects were also not modulated by differences in the color contrast between these distractors and other search display items (S+ vs. S−; Experiment 1). In Experiment 2, target color was no longer constant but unpredictably varied between trials, in order to rule out the possibility that the singleton benefits observed in Experiment 1 were not linked to suppression, but instead the result of attentional guidance by a combined shape/color search template. Reliable (albeit smaller) singleton benefits remained present, and these benefits were again larger for displays containing two salient distractors, in line with the hypothesis that these benefits are at least partially produced by suppression that can be applied to multiple items in the same search display. The fact that singleton benefits were smaller than in Experiment 1 indicates that in addition to multiple-item suppression, color-based attentional guidance may also contribute to these benefits when the target color is fully predictable. The link between the number of salient distractors and the size of singleton benefits and the fact that these benefits were also observed with four-item displays (Supplementary Material, Experiment 1S) not only provides evidence for multiple-item suppression, but also suggest that this suppression is not strongly affected by the absolute salience of distractors (as determined by display set size), or by their relative salience levels within a given search display.

If both salient distractors were effectively suppressed, as suggested by these behavioral data, this should also be reflected by P_D components, which are electrophysiological markers of distractor suppression (i.e., Eimer & Kiss, 2008; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018a; Jannati et al., 2013; Drisdelle & Eimer, 2021; Sawaki & Luck, 2010, 2011). In Experiments 3 and 4, we measured the P_D during task performance, to track the presence and time course of suppression, separately for the most salient distractor in a search display (S+) and the other less salient distractor (S−). Given the robust behavioral evidence for multiple-item suppression, we anticipated that both S+ and S− would elicit reliable P_D components. However, a P_D was only elicited by S+ in Experiment 3, and there was no indication of a P_D in response to S−. This is puzzling since the behavioral results showed that the additional presence of S− in a search display resulted in reliably larger singleton benefits relative to displays that only included S+. One possibility is that S− was not actively suppressed, but was simply ignored. Another possibility is that S− was not sufficiently salient to generate a P_D component. Experiment 4 therefore tested whether S− items would trigger a P_D component in search displays where no S+ item was present, so that S− was now the most salient object in these displays. A reliable P_D was indeed elicited by S− distractors under these conditions, demonstrating that its absence in Experiment 3 was not due to the insufficient absolute salience of S− items.

These P_D results seem to suggest that P_D is only elicited by the most salient object in a search display, in line with the single-item suppression hypothesis. This would explain why a P_D was not triggered by S− distractors under conditions where they were always accompanied by S+ distractors (Experiment 3), but was present in displays where S+ was absent (S− only displays of Experiment 4). However, in Experiment 4, where displays with one and two salient distractors were intermixed, lateral S− distractors generated a small but reliable contralateral positivity even when they were accompanied by a midline S+. This suggests that there was some proactive suppression of S− in these displays, in line with the multiple-item suppression hypothesis. It is important to note that the intermixed presentation of displays with one and two salient distractors in Experiment 4 was analogous to the two behavioral experiments, which also included S+ only, S− only, and S+/S− displays. This suggests that the dissociation between behavioral and electrophysiological markers of multiple-item suppression may be more apparent than real. The absence of a P_D in Experiment 3 could be due to the fact that participants were never exposed to search displays that included only an S− distractor. Under these conditions, they may have adopted a search strategy that involved the suppression of only the most salient item (S+). In Experiments 1, 2, and 4, the presence of S− only displays could have encouraged a different and more flexible strategy, with suppression applied both to S+ and S− distractors, even when these appeared in the same search display. This would explain the increased behavioral singleton benefits for displays with S+ and S− relative to S+ only displays in Experiments 1 and 2, and the presence of a small but reliable P_D to S− in S−/MS+ displays in Experiment 4. Thus, our results suggest that multiple-item suppression may not be an obligatory or default mechanism, but that is activated only when it is strategically useful to facilitate efficient visual search. An interesting avenue for future research would be to test more systematically whether and in what way expectations about the presence of different types of salient distractors modulate the type of suppression that is applied to these distractors.

While Experiment 4 provided evidence for a P_D in response to S− distractors, even in displays that also included S+, this component was smaller and emerged later than the P_D to S+ distractors. This suggests that the suppression mechanisms reflected by this component are sensitive to differences in salience, with more salient distractors triggering suppression more rapidly and more strongly than distractors that are less salient (see also Failing & Theeuwes, 2018 for a similar conclusion). There was little temporal overlap between the P_D components elicited by S+ and S− distractors (see Figure 6), which suggests that at least for the relative salience manipulation employed in the present study, the two suppression processes were activated sequentially. It is an open question whether multiple-item suppression might be activated in parallel when distractors that are equally salient are present in the same search display. This will need to be investigated in future experiments. Interestingly, the difference in the speed and intensity of the suppression processes triggered by S+ and S− distractors reflected by P_D latencies and amplitudes was not reflected by corresponding behavioral differences in Experiment 1. Here, singleton benefits for target RTs were equal in size for displays that included S+ or S− distractors, indicating that salience-related differences in the efficiency of distractor suppression had no impact on task performance. If singleton benefits are due to a reduction of effective display set size, this result suggests that although delayed relative to S+, the proactive inhibition of S− distractors was sufficient to prevent attentional shifts to these items. Along similar lines, Lien et al., (2022) recently found equivalent probe suppression effects at the location of salient singleton distractors and less salient color distractor triplets, indicative of a dissociation between behavioral suppression effects and the saliency of distractor objects. More generally, the current results suggest that behavioral and ERP markers of distractor suppression reflect different aspects of attentional selectivity: while the P_D can inform us about the speed and amount of salience-based distractor suppression, performance measures indicate the efficiency of target selection that is mediated by these suppression processes.

In Experiment 3, a second contralateral positivity was observed for search displays that contained a lateral S+ distractor. This unexpected effect, which started around 200 ms after the search display onset and followed the P_D component, may indicate that participants sometimes allocated attention to the distractor on the opposite side, which was the same color as the target. Such an attention shift should result in an enhanced negativity (N2pc component) contralateral to this distractor. This effect was eliminated in Experiment 4, where half of all search displays included one lateral salient color singleton and five target-color objects. This should have reduced the probability of attention being strategically allocated to a particular lateral target-color item on the opposite side. The absence of a second contralateral positivity for S+ distractors in Experiment 4 is also inconsistent with the assumption that this positivity reflects the genuine inhibition-related P_D component, whereas the earlier and larger positivity triggered only by S+ distractors represents the initial salience signal which subsequently leads to either capture or suppression. S+ distractors were the prime target for suppression and should therefore have elicited a clear P_D, which was only reliably present before 200 ms poststimulus.

Our behavioral and electrophysiological results not only provide further support for the hypothesis that proactive suppression can prevent attentional capture by salient distractors, but also strongly suggest that this suppression can be applied to more than one object in a search display. This is inconsistent with stimulus-driven accounts, which assume that the most salient item in a search display will capture attention automatically, irrespective of its task relevance. Recently, Wang and Theeuwes (2020) have argued that goal-driven suppression of singleton distractors may only be possible with small display set sizes (i.e., four items), where these singletons are not particularly salient. In the present study, we obtained behavioral singleton benefits and P_D components with six-item search displays (similar to Gaspelin & Luck, 2018b; see also Stilwell et al., 2022 for an example of proactive suppression at 16 items). These observations, together with the new evidence for multiple-item suppression in these displays, provide clear supporting evidence for the signal suppression hypothesis by demonstrating that inhibitory mechanisms can be flexibly employed to prevent the capture of attention by distracting visual signals.

Our findings also have wider implications for general questions regarding the relationship between facilitatory and inhibitory mechanisms in selective attention. Research has shown that it is possible to simultaneously maintain multiple attentional search templates for different target features (Irons et al., 2012; Moore & Weissman, 2010), and that attention can be allocated in parallel to multiple objects in the same display (e.g., Cavanagh & Alvarez, 2005; Eimer & Grubert, 2014). The results of Experiments 1, 2, and 4 suggest that similar to attentional facilitation, suppression can also be applied to multiple objects. However, this does not necessarily imply that multiple attentional “templates for rejection” can be activated simultaneously. Although there is evidence that such templates can affect search performance after extensive practice by guiding attention away from distractors (Arita et al., 2012; Beck et al., 2018; Beck & Hollingworth, 2015; Moher & Egeth, 2012), it is unclear whether these templates are functionally equivalent to facilitatory target templates (Berggren & Eimer, 2021; Rajsic et al., 2020; Reeder et al., 2018). One possibility is that instead of operating in a feature-based fashion, suppression may be applied more generally to all salient items that do not possess target attributes, regardless of their specific features. This interpretation would be in line with the differences between facilitation and suppression postulated by the normalization model of attention (Reynolds & Heeger, 2009). According to this model, the facilitatory attentional field is sensitive to particular task-relevant features and locations, whereas the suppressive field shows no feature selectivity and is less tuned to current task goals. Our observation that S+ and S− distractors produced virtually identical behavioral singleton benefits provides some evidence for this hypothesis. If templates for rejection were feature-based, one would expect that the presence of the more distinctive distractor feature (S+) would produce stronger suppression-related effects. In this context, the fact that S+ distractors triggered larger and earlier P_D components relative to S− distractors reflects the absolute salience difference between these items (i.e., the strength of the priority signal), rather than any feature selectivity of the suppression mechanism. Future work could also explore the impact of target presence on the processing of single and multiple salient distractors. Previous work has shown that the presence of a singleton distractor impacts search differently when a target is present or absent (Lawrence & Pratt, 2022; Moher, 2020), and we previously observed overall enhanced P_D components when a target was present in the same search display (Drisdelle & Eimer, 2021). Although there were no interactions between target presence and distractor suppression effects in the present work, it will be important to further investigate the impact of this factor on the processing of salient distractors.

In summary, the current study has provided novel and converging behavioral and electrophysiological evidence for the existence and the time course of multiple-item suppression in visual search. In line with the signal suppression account, our results show that the capture of attention by salient distractors can be prevented if control settings are appropriately configured. While the default setting may be to only suppress the most salient item in a search display, multiple distractor suppression is possible when each distractor also appears as the only salient object in some displays. Future research will need to elucidate the limitations of multiple-item suppression, such as the number of items that can be suppressed concurrently, and the relative and absolute salience levels required to trigger suppression. It will also be important to determine whether this type of suppression always operates within a single feature dimension such as color, or can also be observed across dimensions.

Constraints on Generality

The results from our electrophysiological and behavioral studies converge with prior evidence that salient signals can be suppressed during visual search (e.g., Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018a; Drisdelle & Eimer, 2021). We sampled from a subject pool at Birkbeck, University of London, that includes both students and other members of the academic community. Some individuals in the subject pool have participated in prior visual search experiments (both behavioral and EEG), which may have improved their task efficiency, but should not impact the generalizability of our findings. We excluded individuals above the age of 50 (to reduce temporal variation in electrophysiological components), or who are color blind (our task required color discrimination). We believe the results will be reproducible with adults from similar subject pools serving as participants. Our results should generalize to experiments set in a similar environment, using materials like what is described in the method section of Experiment 1 for behavioral findings and Experiment 3 for electrophysiological findings. We have no reason to believe that the results depend on any other characteristics of the participants, materials, or context.

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