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Biased Competition between Targets and Distractors Reduces Attentional Suppression: Evidence from the Positivity Posterior Contralateral and Distractor Positivity

Dirk Kerzel and Stanislas Huynh Cong

Abstract

■ The biased competition account claims that competition between two stimuli increases when they are close together compared with when they are far apart. The reason is that nearby stimuli are more likely to be represented in the same receptive fields, requiring top–down or bottom–up biases to resolve the ambiguity. Consistent with biased competition, previous research showed that an index of attentional enhancement, the N2pc component, was attenuated when two targets were close together. In contrast, it is unclear whether distractor processing would also be attenuated when the distractor is close to the target. To answer this question, we used the additional singleton paradigm where a target is sometimes accompanied by a more salient, but entirely irrelevant, distractor. In the conditions of interest, the distance between the target and the distractor was systematically manipulated whereas the eccentricity to central fixation was always the same. The results showed that two indices of attentional suppression, the positivity posterior contralateral and distractor positivity components, were attenuated when the distractor was close to the target. Consistent with biased competition, attentional suppression of distractors was inhibited when the distance between target and distractor was short. The reduced attentional suppression of distractors with nearby targets may contribute to the increased behavioral interference with close distractors. ■

INTRODUCTION

Our visual environment is populated by more objects than we could possibly process, requiring mechanisms to sort out nontarget in favor of target stimuli. At a neural level, an easy solution would be to increase the response rate of neurons representing target stimuli. However, visually sensitive cells in extrastriate cortex, such as V4, have large receptive fields that may contain both target and nontarget stimuli. According to the biased competition account, target and nontarget stimuli in the same receptive field compete for in-depth processing (Desimone & Duncan, 1995). The competition will be biased by bottom–up factors, such as the saliency of a stimulus, and top–down factors, such as the stored representation of a stimulus (Huynh Cong & Kerzel, 2021; Luck, Gaspelin, Folk, Remington, & Theeuwes, 2021; Eimer, 2014; Schneider, 2013; Carlisle, Arita, Pardo, & Woodman, 2011; Duncan & Humphreys, 1989).

In the current contribution, we focus on the distance between target and nontargets as the main determinant of competition. When target and nontargets are close together, competition is expected to increase because target and nontargets are more likely to be represented by the same receptive field. Whereas the biased competition account suggests that attention is the result of biased competition, the ambiguity resolution theory of Luck, Girelli, McDermott, and Ford (1997) considers attention as a resource that is needed to resolve the ambiguity between target and nontarget stimuli. In particular, ambiguity resolution theory suggests that more attention is necessary to process a target shown together with a competing nontarget than to process a target in isolation. As a measure for the allocation of attention, Luck et al. (1997) introduced the N2pc component of the ERP. The N2pc is a contralateral negativity from 200 to 300 msec after stimulus onset at posterior electrodes PO7/8 (Eimer, 1996; Luck & Hillyard, 1994). Consistent with ambiguity resolution theory, the N2pc was larger when a nontarget was shown close to the target than when it was presented in isolation (Luck et al., 1997). Note that there were always similar stimuli in the hemifield opposite to the target to guarantee balanced sensory processing. However, this early experiment compared a condition with a nontarget close to the target to a condition where the target was presented in isolation. Therefore, it is unclear whether the increase of the N2pc reflected the reduced distance between target and nontargets or an increase in the number of stimuli. Subsequent research found no effect of target–nontarget distance when the number of stimuli was fixed (Mazza, Turatto, & Caramazza, 2009), suggesting that the increase of the N2pc reported by Luck et al. (1997) was unrelated to the resolution of ambiguity in the receptive field of a neuron, but reflected a difference in numerosity.

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Another problem for ambiguity resolution theory is that the N2pc also occurred in sparse displays without nontargets in the vicinity of the target (Eimer, 1996), suggesting that the N2pc was associated with target enhancement, not the resolution of spatial ambiguities. If the N2pc reflects target enhancement, then biased competition predicts a reduced N2pc when two target stimuli are presented close together. The reason is that mutual inhibition between two target stimuli decreases neural enhancement of each target. To test this prediction, Hilimire, Mounts, Parks, and Corballis (2010) asked their participants to attend to two colored targets in an array of otherwise gray nontargets and to indicate whether the targets were the same or different. Behavioral performance was worse when the distance between the colored targets was short. Similarly, the N2pc was smaller when the colored targets were close than when they were far, suggesting that spatial competition between the two targets degraded neural enhancement and resulted in poor behavioral performance. Whereas the smaller N2pc with close targets is consistent with the biased competition account, the results are at odds with ambiguity resolution theory. Because ambiguity is larger with close than far targets, the N2pc should be larger with close than far targets, but the opposite was observed.

Predictions of the biased competition account were not only tested in displays with two targets, but also in displays with a target and a salient nontarget, referred to as distractor. Interference between target and distractor stimuli was investigated in variants of the additional singleton paradigm developed by Theeuwes (1991a). In the most common variant, a salient distractor competes with a less salient target stimulus, resulting in longer RTs on distractor-present than -absent trials. To investigate spatial interactions between target and distractor processing, Gaspar and McDonald (2014) varied the position of the distractor relative to the target in three conditions. The distractor was either in the same hemifield, resulting in short distances, or it was on the vertical midline while the target was lateral, resulting in intermediate distances, or it was in the opposite hemifield, resulting in large distances. Gaspar and McDonald (2014) found the N2pc to the target to be smaller as distractors got closer (but see the work of Jannati, Gaspar, & McDonald, 2013). This pattern of results is consistent with the work of Hilimire et al. (2010) and corroborates the idea of biased competition because target enhancement, as indexed by the N2pc, was reduced when competition between target and distractor was large.

However, Gaspar and McDonald (2014) explained the results differently. They separated the N2pc into two complementary components, the distractor positivity (P_D) and target negativity (N_T), which occur in the same time interval and at the same electrodes, but have opposite polarity. The N_T is a negativity contralateral to the target and was thought to reflect target enhancement. The P_D is a positivity contralateral to the distractor and was hypothesized to reflect attentional suppression (Hickey, Di Lollo, & McDonald, 2009). If target and distractor are placed in the same hemifield, the contralateral negativity to the target and the contralateral positivity to the distractor cancel out and result in an overall reduced N2pc. If the distractor is placed in the hemifield opposite the target, the positivity and negativity add up and result in an increased N2pc. Thus, the N2pc to lateral targets with distractors in the same or opposite hemifield shows that target- and distractor-elicited components are additive (see also the work of Liesefeld, Liesefeld, Töllner, & Müller, 2017). This interpretation is not consistent with the biased competition account because the smaller N2pc at short distances was explained by the summation of two independent components, the P_D and N_T, and not by reduced target enhancement or reduced distractor suppression.

Furthermore, target–distractor distance in the electrophysiological measures of Gaspar and McDonald (2014) was only manipulated at the level of hemispheres. Therefore, Feldmann-Wustefeld, Weinberger, and Awh (2021) provided a more fine-grained analysis of distance effects. Importantly, Feldmann-Wustefeld et al. (2021) isolated target and distractor processing by placing one of the two stimuli on the vertical midline and the other on a lateral position. Only the stimulus on the lateral position elicits lateralized components whereas the stimulus on the vertical midline does not because it is represented equally in both hemispheres (Woodman & Luck, 2003). In the displays of Feldmann-Wustefeld et al. (2021), there were six possible positions. One position was above fixation, and another was below fixation. In addition, there were two lateral positions per hemifield, allowing for target–distractor distances of one (close) or two (far). When they focused on the target-elicited N2pc, Feldmann-Wustefeld et al. (2021) found a smaller N2pc with close than far distractors. The reduced target-elicited N2pc with short target–distractor distance is consistent with biased competition. However, when they focused on the distractor-elicited P_D, Feldmann-Wustefeld et al. (2021) found a larger P_D with close than far targets, which is inconsistent with biased competition. The interpretation of the authors was that more suppression was applied to close than far distractors (reflected in the larger P_D for close distractors) at the expense of target enhancement (reflected in the smaller N2pc for close targets).

These results are surprising on empirical and theoretical grounds. First, Gaspar and McDonald (2014) suggested that that the P_D and N_T were not affected by target–distractor distance, whereas Feldmann-Wustefeld et al. (2021) found a larger P_D with close than far distractors. Second, the idea of biased competition holds that there is more competition between stimuli when distances are short, which is expected to inhibit target- and distractor-related processing alike. Consistently, the study by Hilimire et al. (2010) found that target–target inhibition reduced an index of target enhancement, the N2pc. It is therefore surprising that more competition would increase distractor-related suppression as indexed by the P_D while reducing target-related enhancement as indexed by the N2pc.

Possibly, these contradictions result from different experimental protocols. In Feldmann-Wustefeld et al. (2021), the target was shown with the same probability on the location of the distractor as on any other stimulus location. In the work of Gaspar and McDonald (2014), however, the target was never shown on the distractor location, which made the distractor completely response-irrelevant, consistent with the additional singleton paradigm (Luck et al., 2021; Theeuwes, 2019). Although longer RTs on distractor-present trials were confirmed in both protocols, the increase may be more pronounced if the target occurs on the distractor location on some trials (Hodsoll, Mevorach, & Humphreys, 2009; Becker, 2007; Yantis & Egeth, 1999). Consistent with the idea that there is more attentional capture if the distractor is not completely response-irrelevant, the distractor-elicited P_D was preceded by a distractor-elicited N2pc in the work of Feldmann-Wustefeld et al. (2021), but not in the work of Gaspar and McDonald (2014). Furthermore, the visual characteristics of the distractor stimuli differed between Gaspar and McDonald (2014) and Feldmann-Wustefeld et al. (2021). Whereas most electrophysiological research on the additional singleton paradigm rendered the color distractor as a geometrical shape with the same dimensions and luminance as the other stimuli in the array (e.g., Feldmann-Wustefeld, Busch, & Schubö, 2020; Liesefeld et al., 2017; Barras & Kerzel, 2016; Gaspar & McDonald, 2014; Hickey, McDonald, & Theeuwes, 2006), Feldmann-Wustefeld et al. (2021) rendered the distractor as a colored circle around one shape of the search array, which is likely to result in large differences in luminance. Consistently, Feldmann-Wustefeld et al. (2021) observed a large positivity contralateral to the distractor between 100 and 150 msec after stimulus onset, which may reflect a sensory imbalance between the hemifield containing the distractor and the opposite hemifield.

The positivity between 100 and 150 msec after stimulus onset is referred to as positivity posterior contralateral (Ppc). In some studies, the Ppc has been ascribed to imbalanced saliency unrelated to attentional processing. The main evidence for this view was that the Ppc was unchanged whether the salient stimulus was a target or distractor (Jannati et al., 2013) or whether the stimulus was attended or not (Schönhammer, Becker, & Kerzel, 2020; Schönhammer, Grubert, Kerzel, & Becker, 2016; Sawaki & Luck, 2010). On the other hand, the Ppc was found to indicate successful suppression of distractors as reflected in goal-directed saccades (Weaver, van Zoest, & Hickey, 2017). The Ppc was also restricted to search tasks where the distractor was unlikely to be attentionally selected and suppression was therefore promoted (Barras & Kerzel, 2017). Furthermore, the Ppc can be elicited in memory (Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012), suggesting that it reflects a representation of interest, rather than bottom–up stimulus saliency. Overall, however, the functional significance of the Ppc awaits clarification. Nonetheless, there may be some evidence that it reflects an early stage of saliency detection related to distractor suppression, as suggested by Sawaki and Luck (2010).

METHODS

The goal of the present investigation was to reexamine effects of target–distractor distance on distractor suppression. The prediction derived from the biased competition account is that mutual inhibition increases when the target is close to the distractor. As a result, target-related processing (as indexed by the N2pc component) is expected to decline. The predicted decline has been confirmed by some previous research (Feldmann-Wustefeld et al., 2021; Hilimire et al., 2010; but see Jannati et al., 2013; Mazza et al., 2009). Similarly, distractor-related processing (as indexed by the P_D component) is also expected to decline, but the previous study by Feldmann-Wustefeld et al. (2021) found the opposite result. Instead of a smaller P_D component with close distractors, they found a larger P_D. However, this study deviated in important ways from typical studies on distractor suppression. Notably, the distractor was not completely irrelevant and there may have been a strong sensory imbalance related to the distractor.

We therefore investigated effects of target–distractor distance in two experiments that were closely modeled on previous studies by Gaspar and colleagues (Gaspar & McDonald, 2014, 2018; Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016). As shown in Figure 1, the search display contained green circles as nontargets and participants either searched for a yellow circle (color target, Experiment 1) or a green diamond (shape target, Experiment 2). Both targets were less salient than the red distractor. To provide evidence for differences in saliency, previous studies examined RTs to each target stimulus separately. Consistent with the assumed differences in saliency, responses to yellow targets were slower than responses to red targets (Gaspar & McDonald, 2014) and responses to shape targets were slower than responses to color targets (Jannati et al., 2013; Kerzel & Schonhammer, 2013; Theeuwes, 1992). Furthermore, the distractor never coincided with the target and could therefore be fully ignored. We focused on the distractor-elicited Ppc and P_D components as both have been associated with distractor suppression. In the condition of interest, the target was on the vertical midline and the distractor on a lateral position, which isolated lateralized components to the distractor. We manipulated the target–distractor distance in two conditions. In the close condition, the distractor was adjacent to the target, which corresponds to a distance of one. In the far condition, the distractor was at a distance of four, but on the same positions of the search array as with a distance of one (see Figure 1). In both conditions, the eccentricity of the distractor with respect to central fixation was the same.

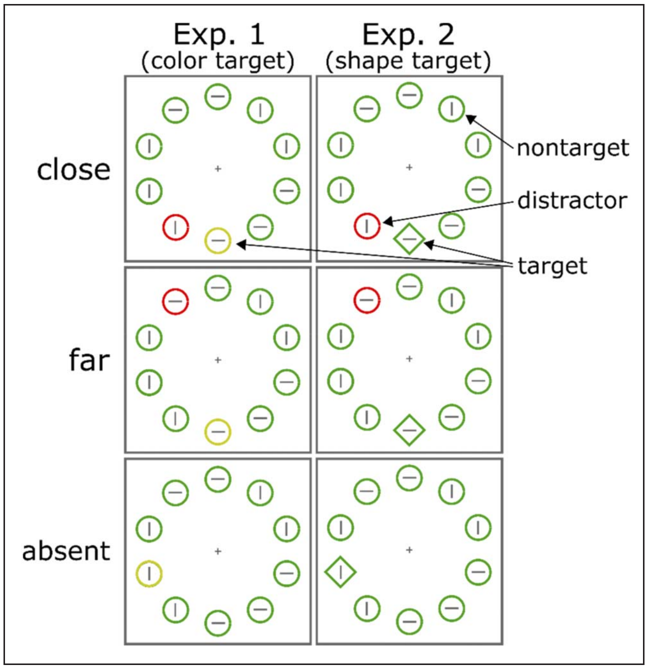

Figure 1. Illustration of experimental stimuli. A color target (yellow circle) was used in Experiment 1 and a shape target (green diamond) in Experiment 2. On half of the trials, a red color distractor was shown. The three trial types providing data for the analysis of ERPs are shown, but other trial types occurred randomly. To measure distractor-elicited ERPs, the target was placed on the vertical midline and a distractor was shown on the adjacent lateral position (close) or on the corresponding position on the opposite side (far). The target–distractor distance was 1 or 4, respectively. To measure target-elicited ERPs, the target was on a lateral position and the distractor was absent.

This is important because the N2pc has been shown to vary with eccentricity (Papaioannou & Luck, 2020) and we cannot rule out similar effects for the P_D or Ppc.

Participants

Sample size was based on the study by Gaspar and McDonald (2014) with 16 participants per experiment. We had 18 data sets in Experiment 1 (five men, age: $M = 21$ years, $SD = 3$ years) and 18 in Experiment 2 (six men, age: $M = 20$ years, $SD = 2$ years) after replacing 11 data sets because of missing trials (see below). With 18 participants, we were able to detect P_D or Ppc components with an effect size of $d_z = 0.7$ in a one-sample t test against zero (alpha = .05, power = .8). The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences of the University of Geneva and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before each experiment.

Apparatus and Stimuli

To display the stimuli, we used a 22.5-in. LCD monitor running at 100 Hz and a resolution of 1920 × 1200 pixels (VIEWPixx Light, VPixx Technologies Inc.). Responses were collected by a RESPONSEPixx Handheld five-button response box (VPixx Technologies Inc.). The response box had four keys arranged in a cross shape and one central key. We used the left and top keys in the experiments, which participants pressed with their left and right index fingers, respectively. Stimulus presentation and response collection were controlled by the Psychtoolbox (Kleiner et al., 2007; Brainard, 1997).

The stimulus sizes, locations, and colors were based on Gaspar and McDonald (2014). The stimuli were shown on a black background, but a white background was used in the illustration of the stimuli in Figure 1 to increase visibility. Throughout the experiment, a gray fixation cross was shown in the center of the display (diameter of 0.5, line width 0.04°). The search display consisted of 10 outline shapes shown on an imaginary circle around fixation. The distance from the center of the fixation cross to the center of the outline shapes was 9°. The shapes were equally spaced and arranged so that one shape was directly above and below fixation. For brevity, these positions on the vertical midline are also referred to as "vertical positions." The shapes were circles or diamonds (diameters of 3.3° and 3.7°, respectively, line width 0.3°). Inside each shape, a vertical or horizontal line was drawn in gray (length of 0.9°, line width of 0.2°).

The shapes in the search array were green circles except for the target and distractor. In Experiment 1, the target was a yellow circle. In Experiment 2, the target was a green diamond. In both experiments, the distractor was a red circle. The CIE1931 *xy*-coordinates of the colors were as follows: red = (0.66, 0.31), green = (0.1, 0.72), yellow = (0.39, 0.51), gray = (0.27, 0.35). The luminance of all stimuli was 8 cd/m^2. A ColorCAL MKII colorimeter (Cambridge Research Systems) was used to measure color coordinates and luminance.

Procedure

A trial started with the presentation of the fixation cross for a randomly selected duration between 0.85 and 1.15 sec. Then, the search display was presented for 200 msec. The task was to find the target shape and report the orientation of the line inside the shape. The target shape was the yellow circle in Experiment 1 and the green diamond in Experiment 2. Participants pressed the left button on the response box for a horizontal line and the top button for a vertical line. They were asked to maintain fixation on the central fixation cross, to ignore the red circle, and to respond as rapidly as possible while keeping the error rate below 10%. Choice errors and RTs outside the response window of 2 sec were reported to the participant by visual feedback immediately after the response. After blocks of 32 trials, mean RT and the error rate were shown during a self-determined break of at least 2 sec. At the beginning of the experiment, participants practiced the experimental task until they felt comfortable with it, but at least for 64 trials. On average, participants performed 96 practice trials (*SD* = 34) in Experiment 1 and 108 practice trials (*SD* = 63) in Experiment 2.

Design

There were 1152 experimental trials with an equal number of distractor-present and -absent trials. In order to test our experimental hypothesis, we were interested in distractor-present trials where the target was on the vertical midline and the distractor on the lateral position next to the vertical midline (see Figure 1). On trials with close distractors, the distractor was adjacent to the target at a target–distractor distance of 1. On trials with far distractors, it was on the opposite side at a distance of 4. Because many trials are needed for reliable measurements of the N2pc and P_D components, we tweaked the frequencies of the remaining spatial configurations to avoid the expectation that the target occurred more frequently on the vertical midline (see Table 1). Focusing attention on a more frequent target location may reduce attentional capture by irrelevant distractors at unattended locations (Burnham, 2018; Ruthruff & Gaspelin, 2018; Theeuwes, 1991b; Yantis & Jonides, 1990). As shown in Table 1, the target was shown on one of the two vertical positions on 16.7% of all trials, which is close to the 20% expected with random placement on any of the 10 positions. The distribution of trials with vertical targets differed between distractor-absent and -present trials. On distractor-absent trials, the target was never shown on vertical, but only on lateral positions. On distractor-present trials, the target was either shown on vertical or lateral positions. If the target was shown on one of the vertical positions, it was always accompanied by a distractor on the close or far position. On these trials, the top and bottom target positions as well as the left and right distractor positions were equally likely. For the remaining distractor-present trials, target and distractor positions were random except that the target was never shown on the vertical positions. As a result of these restrictions, the distractor was presented more frequently on the four lateral positions adjacent to the vertical midline (see Table 2). We return to this issue in the Discussion section. Finally, horizontal and vertical target lines were equally likely.

Table 1. Frequency of Target–Distractor (TD) Distances in the Distractor-Present Condition of Experiments 1 and 2

	Target Position	
TD Distance	*Vertical*	*Lateral*
1	8.3%	~7.4%
2	–	~7.4%
3	–	~7.4%
4	8.3%	~7.4%
5	–	~3.7%
Sum	16.7%	33.3%

A distractor was shown on 50% of trials. There were 10 possible positions, which allowed for TD distances between 1 and 5. The target could occur on one of the two positions on the vertical midline or on one of the eight lateral positions. Data for the analysis of distractor-elicited ERPs were provided by trials with vertical targets. On these trials, distractors only occurred on the positions adjacent to the vertical midline. These trials correspond to TD distances of 1 (close) and 4 (far). The ~ symbol indicates that positions were determined randomly so that percentages could vary from participant to participant.

Table 2. Frequency of Distractor and Target Positions in Experiments 1 and 2

Distractor			*Target*		
Left	*Vertical*	*Right*	*Left*	*Vertical*	*Right*
	~3.7%			8.3%	
~7.4%		~7.4%	~10.4%		~10.4%
~3.2%		~3.2%	~10.4%		~10.4%
~3.2%		~3.2%	~10.4%		~10.4%
~7.4%		~7.4%	~10.4%		~10.4%
	~3.7%			8.3%	

A distractor was shown on 50% of trials, and the target was shown on 100% of trials. There were 10 possible positions, and the spatial arrangement of the table maps the horizontal and vertical positions of the search displays (see Figure 1). There were two vertical positions and four lateral positions on each side. The ~ symbol indicates that positions were determined randomly so that percentages could vary randomly from participant to participant.

Electrophysiological Recording and Initial Data Processing

The BrainVision Recorder software was used to record electrophysiological signals converted by an actiCHamp amplifier from active Ag/AgCl electrodes (Brain Products). Cutoffs and notchfilters were deactivated in the filter settings of the BrainVision Recorder software. Signals were continuously sampled at 1000 Hz from 26 scalp electrodes and six additional electrodes placed on the outer canthi of each eye, above and below the right eye, and on each earlobe. Cz served as on-line reference and AFz as ground site. The data were analyzed using ERPLAB (Lopez-Calderon & Luck, 2014), an extension of EEGLAB (Delorme & Makeig, 2004). Before analysis, the EEG was rereferenced to the average earlobes and filtered between 0.1 and 30 Hz with a bandpass second-order Butterworth filter (roll-off 12 db/octave, command *pop_basicfilter* in ERP-lab). The horizontal EOG (HEOG) channel was the difference between left and right eye electrodes, and the vertical EOG (VEOG) was the difference between upper and lower eye electrodes. The EEG was segmented into 500-msec epochs extending from 100 msec before to 400 msec after stimulus onset. The first 100 msec served as baseline.

RESULTS

The data from all experiments are available on the page https://osf.io/8eyjh/ in the Open Science Framework.

Exclusion of Trials and Data Sets

Trials with behavioral errors and RTs outside the response window of 2 sec were excluded from both behavioral and ERP analysis. Furthermore, individual trials in the ERP analysis were rejected when blinks and vertical eye movements (difference in the VEOG channel exceeding ±50 μV), horizontal eye movements (10 msec-steps in the HEOG channel exceeding ±16 μV), and muscular or other artifacts (any electrode exceeding ±80 μV) occurred between 100 msec before and 400 msec after stimulus onset. Three data sets in Experiment 1 were replaced because more than 30% of the trials were lost because of artifacts (ranging from 36% to 42% lost trials). For the same reason, another eight data sets were replaced in Experiment 2 (ranging from 31% to 62% lost trials). The most frequent cause for trial rejection was that participants did not maintain fixation, which may result from the fact that our participants were not trained on the task and had not participated in electrophysiological experiments before. The 30% criterion applied here is close to the 25% criterion proposed in the literature on the N2pc (Luck, 2014). When more than 25% (or 30%) of the trials have to be removed, the data quality is generally poor and even the remaining "good" trials are likely to be contaminated by artifacts. The 30% criterion guaranteed at least ~67 trials and an average of ~85% in the conditions of interest.

Statistical Corrections and Bayesian Statistics

In multiple-paired *t* tests, we controlled the false discovery rate (Benjamini & Hochberg, 1995), but the uncorrected *p* values are reported for clarity. *t* Tests remained significant after correction unless otherwise noted. In addition to frequentist statistics, we reported Bayesian statistics. For ANOVAs on RTs, we report how much more probable the best model was compared with the remaining models. In our analyses, the best model always included the significant effects from the frequentist analysis. For *t* tests, we reported the Bayes factor H_{10}, which indicates how much more probable the alternative hypothesis H_1 is compared with the null hypothesis H_0. The evidence for H_1 is strong with Bayes factors larger than 10, moderate with values between 3 and 10, and anecdotal with values between 1 and 3. Bayes factors smaller than 1 favor the null hypothesis H_0 with values between 0.33 and 1 providing anecdotal evidence, values between 0.1 and 0.33 providing moderate evidence, and values between 0.03 and 0.1 providing strong evidence for the null hypothesis H_0. Bayesian statistics were calculated using Jasp (JASP Team, 2021).

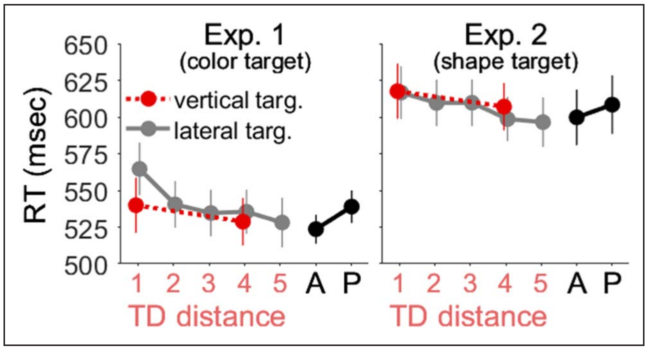

Figure 2. RTs in Experiments 1 and 2. In the left part of each graph, RTs on distractor-present trials are shown as a function of the distance between target and distractor (TD distance). Only trials with targets on vertical positions (red lines) were analyzed in the text, because these trials provided data for the main analysis of ERPs. On these trials, TD distance could be either 1 (close) or 4 (far). In the right part of each graph, RTs collapsed across all spatial positions are shown for distractor-absent (A) and distractor-present (P) trials. Error bars show the standard error of the mean (between-participants).

Behavior

For each experiment, 18 data sets were analyzed. Trials with RTs slower than 2 sec were excluded (0.01%). Subsequently, data were trimmed for each participant and condition by removing trials with RTs that were more than 2.5 *SD*s above the respective condition mean. This resulted in the exclusion of additional 2%–3% of the trials for the behavioral analysis. Mean RTs are shown in Figure 2.

We evaluated differences between close and far distractor positions. We only analyzed RTs from trials with vertical targets because these trials were entered into the analysis of ERPs. We subjected individual mean RTs to a 2 (Target–Distractor Distance: close, far) × 2 (Target Type: color = Exp. 1, shape = Exp. 2) mixed factors ANOVA. As expected, RTs were 11 msec longer with close than with far distractors (579 vs. 568 msec), $F(1, 34) = 12.04$, $p < .001$, $\eta_p^2 = .262$. In addition, RTs were shorter with a color than with a shape target (534 vs. 612 msec), $F(1, 34) = 10.01$, $p = .003$, $\eta_p^2 = .227$. The interaction was not significant, $p = .92$. Conducting a Bayesian ANOVA with the same factors confirmed that a model including the two significant main effects was at least 3.9 times more likely than all other models (i.e., models including only one main effect or a model including two main effects plus the interaction). Conducting the same ANOVA on the percentage of choice errors yielded no significant effects, $ps > .513$. The mean percentage of choice errors was 4.9%.

Electrophysiology

There were 96 trials for the close and far distractor conditions, respectively, and 576 trials for the distractor-absent condition. After rejecting trials with electrophysiological artifacts, behavioral errors, or RTs longer than 2 secs, 87% of the trials of interest remained for analysis in Experiment 1 and 84% in Experiment 2. In Experiment 1, we retained an average of 85 trials (range: 74–95) with a close distractor and 86 trials (range: 78–95) with a far distractor. An average of 496 trials (range: 434–551) was retained for lateral targets without distractor. In Experiment 2, we retained an average of 82 trials (range: 68–92) with a close distractor and 83 trials (range: 65–96) with a far distractor. An average of 480 trials (range: 408–540) was retained for lateral targets without distractor. The ipsi- and contralateral potentials at electrodes PO7/8 are shown in the three upper rows of Figure 3, and the respective difference waves (obtained by subtracting ipsilateral from contralateral activity) are shown in the bottom row.

Analysis intervals for the Ppc and $\mathrm{P_D}$ were selected according to previous studies and adjusted to fit our data set. To select the analysis intervals, we only considered the far distractor condition where we were sure to observe attentional suppression. Consistent with a Ppc, Schönhammer et al. (2020) found significant positive deflections between 110 and 140 msec after stimulus onset. Similarly, Jannati et al. (2013) found a positive deflection between 100 and 160 msec. Consistent with a $\mathrm{P_D}$, Gaspar and McDonald (2014) found significant positive deflections between 220 and 260 msec or between 250 and 290 msec after searching for maximal deflections. To adjust the analysis interval to our data set, we first calculated the 30-msec sliding average on the difference between contra- and ipsilateral activity. Then, we determined the 30-msec window with the maximum deflection in the search interval from 100 to 160 msec for the Ppc and in the search interval from 220 to 290 msec for the $\mathrm{P_D}$. The resulting analysis windows for the Ppc were highly consistent between the two experiments: 128–158 msec with a color target and 117–147 msec with a shape target. Because of the high consistency, the Ppc components from Experiments 1 and 2 were analyzed together. For the $\mathrm{P_D}$, the situation was not as clear. With a color target, we found the maximal deflection to occur between 249 and 279 msec, which is consistent with Gaspar and McDonald (2014). With a shape target, there was no clear maximum in the search window from 220 to 290 msec, but inspection of Figure 3 suggests that it occurred later. We therefore extended the search window to 350 msec, which resembles the time intervals in studies where a positivity was thought to follow the initial shift of attention (e.g., Sawaki, Geng, & Luck, 2012; Hilimire et al., 2010), and found a positive maximum from 297 to 327 msec. However, the $\mathrm{P_D}$ with shape targets was small, and because the time interval varied considerably between Experiments 1 and 2, the $\mathrm{P_D}$ was analyzed separately.

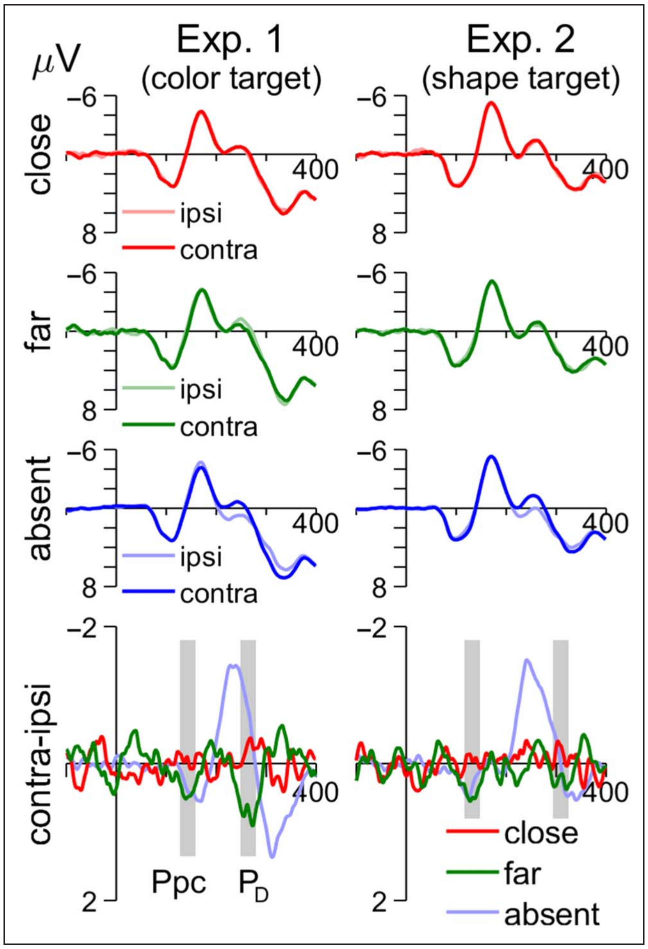

Figure 3. Electrophysiological results from electrodes PO7/8 in Experiments 1 and 2. Distractor-elicited responses (distractor lateral, target vertical) are shown for close and far distractors in the first and second rows. Target-elicited responses (target lateral, distractor absent) are shown in the third row. The upper rows show voltages at electrodes ipsi- and contralateral to the distractor/target, whereas the bottom row shows the difference waves (contra-ipsilateral). The shaded areas indicate the averaging intervals corresponding to the Ppc and $\mathrm{P_D}$.

Ppc

We subjected the distractor-elicited voltage differences to a 2 (Target–Distractor Distance: close, far) × 2 (Target Type: color = Exp. 1, shape = Exp. 2) mixed factors ANOVA. The analysis interval was 128–158 msec with color targets and 117–147 msec with shape targets. The Ppc was larger to far than close distractors (0.45 vs. −0.04 μV), $F(1, 34) = 11.98$, $p = .001$, $\eta_p^2 = .261$. The effect of Target–Distractor Distance was not qualified by Target Type, $p = .828$. Conducting a Bayesian ANOVA confirmed that a model with a single factor (Target–Distractor Distance) was at least 3.3 times more likely than all remaining models. One-sample t test against zero showed that the Ppc to far distractors was significantly different from zero, $t(35) = 4.57$, $p < .001$, Cohen's $d_z = 0.76$, $\mathrm{BF}_{10} = 401.15$, whereas the Ppc to close distractors was not, $t(35) = 0.37$, $p = .715$, Cohen's $d_z = 0.06$, $\mathrm{BF}_{10} = 0.19$. These results were confirmed by separate t tests for each experiment. In both experiments, the Ppc was larger to far than close distractors, $ts(17) > 2.4$, $ps < .028$, Cohen's $d_z > 0.56$, $\mathrm{BF}_{10} > 2.31$, and the Ppc to far distractors was significantly different from zero, $ts(17) > 2.86$, $ps < .011$, Cohen's $d_z > 0.68$, $\mathrm{BF}_{10} > 4.98$. In contrast, the Ppc to close distractors was not significantly different from zero, $ts(17) < 0.17$, $ps > .746$, Cohen's $d_z > 0.07$, $BF_{10} < 0.26$.

P_D

For color targets in Experiment 1, we compared the distractor-elicited voltage differences in the 30-msec interval from 249 to 279 msec after stimulus onset. The P_D was larger to far than close distractors (0.75 vs. −0.20 μV), $t(17) = 2.95$, $p = .009$, Cohen's $d_z = 0.70$, $BF_{10} = 5.83$. By one-sample t test, the P_D was significantly different from zero with far, $t(17) = 3.90$, $p = .001$, Cohen's $d_z = 0.92$, $BF_{10} = 32.91$, but not with close distractors, $t(17) = 1.07$, $p = .298$, $BF_{10} = 0.4$. For the shape targets in Experiment 2, the distractor-elicited voltage difference in the 30-msec interval from 297 to 327 msec after stimulus onset did not differ significantly between far and close distractors, although the means were in the same direction as with color targets (0.27 vs. −0.14 μV), $t(17) = 1.51$, $p = .15$, Cohen's $d_z = 0.36$, $BF_{10} = 0.64$. One-sample t tests showed that the P_D to far targets approached significance $t(17) = 1.77$, $p = .095$, Cohen's $d_z = 0.42$, $BF_{10} = 0.89$, whereas the P_D to close targets was far from significance, $t(17) = 0.71$, $p = .489$, Cohen's $d_z = 0.17$, $BF_{10} = 0.30$. Overall, we did not find a significant difference between close and far distractors or a significant P_D to far distractor in Experiment 2. However, the evidence in favor of the null hypothesis was only anecdotal as the BF_{10} scores were between 0.33 and 1. Nonetheless, BF_{10} scores smaller than 1 favor the null hypothesis over the alternative hypothesis.

Target-elicited Components

Although the target-elicited components were not the focus of the present investigation, their analysis may shed some light on the mechanisms and time-course of distractor suppression. Inspection of Figure 3 shows that there was a positivity to the lateral target stimulus in the time windows of the Ppc. The positive deflection was significant in the time interval from 128 to 158 msec for color targets in Experiment 1 (0.34 μV), $t(17) = 3.70$, $p < .001$, Cohen's $d_z = 0.87$, $BF_{10} = 22.70$, and also in the time interval from 117 to 147 msec for shape targets in Experiment 2 (0.34 μV), $t(17) = 3.91$, $p = .001$, Cohen's $d_z = 0.92$, $BF_{10} = 33.42$. By independent-samples t test, there was no difference between color and shape targets, $t(34) = 0.16$, $p = .876$, Cohen's $d_s = 0.05$, $BF_{10} = 0.33$. Inspection of Figure 3 further suggests that there was a positivity occurring after the target-elicited N2pc, which may be related to the termination of a shift of attention (Sawaki et al., 2012). Using the same approach as for the P_D, we located the maximal deflection for color targets between 301 and 331 msec and between 319 and 349 msec for shape targets. The positivity was significant for color targets (1.18 μV), $t(17) = 3.03$, $p = .008$, Cohen's $d_z = 0.71$, $BF_{10} = 6.69$, but only approached significance for shape targets (0.48 μV), $t(17) = 1.95$, $p = .068$, Cohen's $d_z = 0.46$, $BF_{10} = 1.14$.

HEOG

We analyzed the voltages at the lateral eye electrodes to rule out potential contamination of EPRs by eye movements. Therefore, the voltage at the eye electrode ipsilateral to the distractor was subtracted from the voltage at the eye electrode contralateral to the distractor. For close and far distractor conditions, we evaluated whether these differences were significantly different from zero by one-sample t test. The only significant difference occurred with close distractors in the interval of the Ppc (−0.25 μV), $t(35) = 2.39$, $p = .023$, Cohen's $d_z = 0.4$, $BF_{10} = 2.13$. However, the corresponding voltage difference at PO7/PO8 was not significant, suggesting that effects at electrodes PO7/8 were not contaminated by eye movements. In addition, the mean voltage differences in the HEOG were too small (ranging from −0.35 to 0.28 μV) to account for results at the posterior electrodes. Lins, Picton, Berg, and Scherg (1993; see their Table 5) showed that only 1% ± 3% of the voltage propagates from ocular to posterior electrodes (in their case, electrodes O1/O2, which are adjacent to electrodes PO7/8).

DISCUSSION

We investigated effects of target–distractor distance on attentional suppression. In the condition of interest, the target was placed on the vertical midline where it had no effect on lateralized components. The distractor was placed on a lateral position either adjacent to the target or four positions away, but both positions had an equal eccentricity with respect to central fixation. We measured two lateralized components related to distractor suppression, the Ppc between 100 and 150 msec and the P_D between 250 and 350 msec. Both indices of distractor suppression were attenuated with close compared with far distractors. This result is consistent with biased competition because spatial proximity between target and distractor increases the likelihood that both are represented in the same receptive field, which increases competition and reduces attentional resources for both target and distractor processing. In contrast, the results are at odds with ambiguity resolution theory, which predicts a greater need for attention with close distractors. That is, more attentional suppression is predicted with close than far distractor, but we found the opposite. Furthermore, there were some differences between color and shape targets. Whereas the effect of distance on the Ppc was reliable with both target types, the effect of distance on the P_D was only reliable with color targets in Experiment 1, but not with shape targets in Experiment 2.

Overall, the results are in line with previous electrophysiological investigations confirming predictions of the biased competition account. Hilimire et al. (2010) found that reducing the distance between two target stimuli reduced an index of target enhancement, the N2pc. Here, we show that reducing the distance between a target and a distractor stimulus attenuated two indices of attentional suppression, the Ppc and P_D components. In contrast, Feldmann-Wustefeld et al. (2021) found that the P_D was larger for close than far distractors, which contradicts the biased competition account. As outlined in the introduction, the distractor in Feldmann-Wustefeld et al. (2021) was not completely irrelevant and there may have been a large sensory imbalance resulting from rendering the distractor as a new object in the display. Another difference is the range of target–distractor distances. In the current study, the far distractor was separated by four positions from the target, but only by two positions in the work of Feldmann-Wustefeld et al. (2021).

Distractor-elicited P_D Component

We found that the distractor-elicited P_D was absent with shape targets in Experiment 2, but present with a color target in Experiment 1. A similar reduction of the P_D with shape compared with color targets was observed in the work of Gaspar and McDonald (2014). It is possible that the difference between the two experiments resulted from dimensional weighting (Liesefeld, Liesefeld, Pollmann, & Müller, 2019; Liesefeld & Müller, 2019; Krummenacher & Müller, 2012). The color target in Experiment 1 was defined along the same dimension as the distractor, whereas the shape target in Experiment 2 was defined along a different dimension. Gaspar and McDonald (2014) suggested that it was possible to increase the weight of the shape dimension relative to the color dimension in Experiment 2, resulting in color-defined distractors to have less impact on visual processing. In contrast, it was not possible to down-weigh the color dimension in Experiment 1 as target and distractor were defined by the same dimension (unless it is assumed that there are independent color subdimensions; see Footnote 3 in the work of Liesefeld & Müller, 2021). Alternatively, it may be that the difficulty of the task affected distractor suppression. Analysis of RTs showed longer RTs in the shape than color task. A previous study observed that distractor suppression, as indexed by the P_D and Ppc, was attenuated in difficult search tasks where the target was less salient (Barras & Kerzel, 2017). However, the previous study found stronger behavioral interference with less efficient search, whereas in the current study, the opposite result was observed. When all trials were considered, interference was weaker in the more difficult shape task than in the color task (9 vs. 15 msec, see Figure 2), $t(34) = 2.11$, $p = .042$, Cohen's $d_s = 0.70$, $BF_{10} = 1.73$. Thus, the reasons for the difference between color and shape targets are not entirely clear. In particular, previous research demonstrated reliable P_D components to color distractors with a fixed shape or orientation target (Liesefeld, Liesefeld, & Müller, 2022; Drisdelle & Eimer, 2021; Kerzel & Burra, 2020; Gaspelin & Luck, 2018; Liesefeld et al., 2017; Barras & Kerzel, 2016; Feldmann-Wüstefeld, Uengoer, & Schubö, 2015; Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2013; Jannati et al., 2013; Kiss, Grubert, Petersen, & Eimer, 2012), which we did not replicate here.

Furthermore, Figure 3 shows that the distractor-elicited P_D component occurred at about the same time interval as the target-elicited N2pc component, albeit toward its end. A similar time course was observed in other studies using a fixed shape target with a color distractor (e.g., Gaspar & McDonald, 2014; Burra & Kerzel, 2013; Jannati et al., 2013). In the study of Feldmann-Wustefeld et al. (2021), however, the P_D to the distractor was preceded by an N2pc to the distractor. Similar findings have been reported in paradigms with dense (Liesefeld et al., 2017, 2022; Feldmann-Wüstefeld & Schubö, 2013) or sparse (van Moorselaar & Slagter, 2019) search arrays. The early and late occurrence of the P_D have been associated with two different functions. Sawaki et al. (2012) argued that the early P_D in the time interval of the N2pc is associated with preventing attentional capture by the distractor, whereas the late P_D occurring after the N2pc is associated with the termination of the allocation of attention. Thus, the P_D in the current study may show that attentional capture was prevented, whereas the P_D in the work of Feldmann-Wustefeld et al. (2021) may show that attentional capture by the distractor was terminated. However, the same neural mechanism of attentional suppression is thought to underlie both cases (Sawaki et al., 2012). Thus, we would expect the same effects of target–distractor distance regardless of whether the P_D reflects preventing or terminating the allocation of attention.

Distractor-elicited Ppc Component

In addition to the modulation of the P_D by target–distractor distance, we observed a similar modulation of the earlier Ppc component. Previously, the Ppc was sometimes considered to reflect stimulus saliency independently of attentional processing (Schönhammer et al., 2016, 2020; Jannati et al., 2013; Sawaki & Luck, 2010). In other studies, the Ppc was thought to reflect attentional processes (Barras & Kerzel, 2017; Weaver et al., 2017; Fortier-Gauthier et al., 2012). Here, we find that both perspectives may be partially true. On the one hand, the Ppc was elicited by both target and distractor stimuli (see also the work of Jannati et al., 2013), suggesting that the Ppc reflects saliency independently of attentional demands. However, the Ppc was sensitive to competition from nearby targets, suggesting that it does reflect attentional processing to some degree. In a similar vein, Barras and Kerzel (2017) concluded that the Ppc only occurred to distractors that were unlikely to be selected. Applied to the current experiments, only far distractors were unlikely to be selected because close distractors may have ended up in the focus of attention because of their spatial proximity to the target. The current results are also consistent with the idea that the Ppc reflects an attend-to-me signal, which may guide subsequent attentional selection or suppression (Sawaki & Luck, 2010). When the distractor was close to the target, its saliency may have been reduced because the stimuli in the distractor's vicinity were less homogeneous (Itti & Koch, 2001; Duncan & Humphreys, 1989). As a result of the reduced saliency, the attend-to-me signal conveyed by the Ppc was smaller. Thus, it remains difficult to decide whether the Ppc reflects bottom–up or top–down effects. The reason is that task demands and saliency were simultaneously affected by the manipulation of target–distractor distance.

In contrast to the current study, Feldmann-Wustefeld et al. (2021) observed no modulation of the Ppc by target–distractor distance. In their study, the Ppc was very large, with a peak amplitude approaching 2 μV, which may have been caused by the large difference in luminance resulting from the distractor stimulus. In the current study, the peak amplitudes of the Ppc are much closer to the typical Ppc amplitudes observed with isoluminant stimuli in the additional singleton paradigm (less than 1 μV, e.g., Barras & Kerzel, 2017; Weaver et al., 2017; Burra & Kerzel, 2013; Feldmann-Wüstefeld & Schubö, 2013; Jannati et al., 2013). Possibly, the overall larger Ppc in the work of Feldmann-Wustefeld et al. (2021) masked effects of target–distractor distance, but other explanations may apply.

Effects of Target–Distractor Distance on the Target-elicited N2pc

Whereas effects of target–distractor distance on the distractor-elicited components in Feldmann-Wustefeld et al. (2021) are compromised by alternative explanations, effects of target–distractor distance on target-elicited components do not suffer from similar problems. To measure the target-elicited N2pc on distractor-present trials, the target in the work of Feldmann-Wustefeld et al. (2021) was placed on a lateral position whereas the distractor was shown on a vertical position. As a result, the sensory imbalance associated with the distractor had no effect. In addition, the eccentricity of all stimuli with respect to central fixation was the same for close and far targets, which may not have been the case in other studies (Jannati et al., 2013; Mazza et al., 2009). Feldmann-Wustefeld et al. (2021) found the target-elicited N2pc to be smaller when the lateral target was close to the vertical distractor compared with when it was far. We replicated this effect in a supplementary experiment that is reported in the Open Science Framework at https://osf.io/8eyjh/. While these results are consistent with biased competition, it could also be explained by differences in saliency. If the target–distractor distance was short, the visual context around the target was less homogeneous and both stimuli may have popped out less. As a result, both target- and distractor-elicited components decreased. Consistently, previous research demonstrated that target-elicited components were larger when the target was salient (Töllner, Zehetleitner, Gramann, & Müller, 2011). Thus, the question arises whether effects of target–distractor distance are nothing but effects of saliency, which would reflect the importance of saliency in both perception (e.g., Nothdurft, 1993) and memory (e.g., Constant & Liesefeld, 2021). However, saliency and biased competition may be considered complementary, not exclusive concepts. For instance, Itti and Koch (2001) suggested that "neurons in each feature map spatially compete for saliency" (p. 196). Thus, saliency may be considered an outcome of (biased) competition, not an alternative to it.

Effects of Distractor Frequency

The longer RTs with close than far distractors are in line with numerous studies on effects of target–distractor distance on perception (Mounts, 2000; Caputo & Guerra, 1998) and response latencies (Barras & Kerzel, 2016; Gaspar & McDonald, 2014; Jannati et al., 2013; Hickey & Theeuwes, 2011; Mathot, Hickey, & Theeuwes, 2010; Mounts, McCarley, & Terech, 2007; Kwak, Dagenbach, & Egeth, 1991). In addition to target–distractor distance, however, we inadvertently varied the frequency of distractor positions in the search array. In order to have a sufficient number of trials in the conditions of interest, the distractor appeared more frequently on the positions adjacent to the vertical midline (see Table 2). Previous research has demonstrated that presenting the distractor more frequently on one position reduces attentional capture on the high-frequency position compared with the low-frequency positions (Kerzel, Balbiani, Rosa, & Huynh Cong, 2022; Liesefeld & Müller, 2021; Allenmark, Zhang, Liesefeld, Shi, & Müller, 2019; Failing, Feldmann-Wüstefeld, Wang, Olivers, & Theeuwes, 2019; Wang, van Driel, Ort, & Theeuwes, 2019; Wang & Theeuwes, 2018). Lin, Li, Wang, and Theeuwes (2021) manipulated the ratio of high- to low-frequency positions from 2:1 to 8:1 and observed a linear increase of the difference between high- and low-frequency positions. Table 2 shows that the ratio between positions with high and low distractor frequency was 2.2:1 in the present experiments, which is close to the lowest ratio investigated by Lin et al. (2021). Because Lin et al. (2021) did not find any difference between high- and low-frequency positions at this ratio, it is unlikely that effects of distractor frequency had an impact on our results. Furthermore, there were four positions with a higher frequency in the current study, whereas there was only a single high-frequency position in a previous work. Therefore, it appears unlikely that differences in distractor frequency affected the results, but more research is needed to understand the effects of multiple high-frequency distractor positions.

In summary, the current investigation confirmed predictions of the biased competition account. When target and distractor are close together, they may be represented in the same receptive fields, which triggers competition such that the respective neural responses are initially suppressed. Consistently, it was previously demonstrated that the neural signature of target enhancement, the N2pc, was attenuated for close compared with far targets. Here, we show that neural signatures of distractor suppression, the Ppc and P_D components, were attenuated in the proximity of a target. Thus, both target-related enhancement and distractor-related suppression decrease when competition is induced by spatial proximity.

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Data Availability Statement

Neither of the experiments reported in this article was formally preregistered. The data are available at https://osf.io/8eyjh/, and requests for the program code can be sent via e-mail to D. K.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

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