

BRIEF REPORT

An electrophysiological assessment of distractor suppression in visual search tasks

VERONICA MAZZA,^{a,b} MASSIMO TURATTO,^{a,b} AND ALFONSO CARAMAZZA^{a,c}

^aCenter for Mind/Brain Sciences (CIMEC), University of Trento, Trento, Italy

^bDepartment of Cognitive Sciences and Education, University of Trento, Trento, Italy

^cCognitive Neuropsychology Laboratory, Harvard University, Cambridge, USA

Abstract

We investigated whether the N2pc is unequivocally linked to distractor-suppression mechanisms, as is commonly assumed. According to the distractor-suppression account of the N2pc, no suppression, and thus no N2pc, should occur when homogeneous distractors help in selecting the target, such as when the target feature is unpredictable. Participants performed a simple detection or a finer discrimination on a singleton target, which had either a variable or a constant color. Contrary to the distractor-suppression account, an N2pc was present for both the variable and the constant conditions, and for both tasks. Additionally, target feature consistency correlated with earlier N2pc onsets relative to variable blocks. Both results indicate that the N2pc is not unequivocally linked to distractor-suppression mechanisms, but may index mechanisms involved in identifying and localizing relevant stimuli through enhancement of their features.

Descriptors: Distractor suppression, Attentional orienting, Visual search, N2pc, Feature repetition, Visual working memory, Event-related brain potentials

Many theories propose that attention operates as a spatial filter of the incoming inputs, suppressing the information relative to distractor objects and thus maximizing the processing of the relevant objects (Desimone & Duncan, 1995). In the ERP field, Luck and colleagues proposed the Ambiguity Resolution Theory (ART; Luck et al., 1997), which posits that attention acts by suppressing the inputs from distractor objects. The N2pc component (a more pronounced negativity occurring at 180–300 ms post-stimulus at posterior sites contralateral to the target location relative to ipsilateral sites) has been considered as the ERP counterpart of such suppressive mechanisms (see Luck, 2005). More specifically, the N2pc would occur whenever interfering distractors are presented with the target, and its amplitude would increase with increasing interference and increasing need for suppression.

Crucially, the ART predicts that distractors are not suppressed when they are useful to determine the presence of a target (Luck, 2005). For example, when the target feature is not known in advance, such as when it varies unpredictably from trial to trial, the visual system would not suppress distractors as they would be helpful in selecting the target, and no N2pc should be observed (Luck & Hillyard, 1994a). Not all previous evidence is consistent with this prediction. Whereas Luck and Hillyard

(1994a, Experiment 2) found no N2pc when the target feature varied unpredictably throughout a block of trials, other researchers failed to find such a modulation (e.g., Schubo et al., 2007). In a recent study, Mazza, Turatto, and Caramazza (2009) manipulated whether the target feature (color) was kept constant or varied unpredictably. Contrary to the predictions of the ART, no modulation of the N2pc as a function of target-color variability emerged. However, whereas in Luck and Hillyard's experiment (1994a) participants had to simply detect the target's presence, in our experiment they performed the additional operation of discriminating the target's shape from similarly shaped distractors. This additional discrimination component might require suppression of distractors also in the variable target condition and, therefore, N2pc amplitude modulation (see Leblanc, Prime, & Jolicoeur, 2008).

For this reason, in the present study we compared the variable and constant conditions both in a detection and in a discrimination task. In the detection task, participants reported the presence/absence of a uniquely colored diamond; in the discrimination task, the uniquely colored diamond was presented on each trial, and participants judged its shape. Within each task, the target (when present) could have the same color for an entire block of trials (constant condition) or could vary its color unpredictably (variable condition). According to the ART, we should find a modulation of the N2pc amplitude as a function of target variability, with a clear N2pc for the constant condition, where distractors supposedly represent a real source of interference and should thus be suppressed; in addition, we should not

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Address reprint requests to: Veronica Mazza, Corso Bettini 31, 38068 Rovereto, Italy. E-mail: veronica.mazza@unitn.it

find an N2pc for the variable condition (at least for the detection task) because distractors should help in determining the target's presence and thus should not be suppressed (Luck, 2005).

Methods

Participants

Sixteen volunteers, aged 19–35 years and with normal or corrected vision, participated in the experiment, after providing informed consent. The study was approved by the University of Trento Ethics Committee.

Stimuli and Procedure

Stimuli consisted of equiluminant red and green diamonds (17 cd/m^2) presented on a black background (1 cd/m^2). Each diamond ($0.6^\circ \times 0.8^\circ$) had a 0.4° corner trimmed on the left or right side (see Figure 1a). On each trial, the display contained 20 diamonds, equally distributed to the left and right side of fixation. The diamonds were located within a 10 (columns, 11.4°) \times 8 (rows, 8.6°) matrix. On half of the trials of the detection task (target-present trials), one of the diamonds (the target) had a unique color (either red or green) and appeared with equal probability and in random order to the left or right of fixation, with the restriction that it always occurred either in the third or fourth column of the matrix relative to fixation. On the other half of the trials (target-absent trials), 20 homogeneously colored di-

amonds (either red or green) were presented. In the discrimination task, the target was presented on each trial. In both tasks, there were variable and constant blocks. In the variable blocks, the target varied unpredictably in color, sometimes red and sometimes green. In the constant blocks, it always had the same color, either red or green (counterbalanced across participants). Each visual display was presented for 150 ms.

In the detection task, participants reported whether the target was present or absent by pressing one of two keys on a computer keyboard with their left or right hand. In the discrimination task, they indicated the side of the cut (left/right) of the target by pressing one of the two keys used in the detection task. In both tasks, speed and accuracy were emphasized equally. Maximum time for responding was 1,500 ms. The inter-trial interval was 1,500 ms. In the detection task, participants performed ten blocks (five variable and five constant) of 112 trials per block; in the discrimination task, ten blocks (five variable and five constant) with 56 trials per block were delivered. The detection task was always performed first, to ensure that an N2pc for this task is not simply a carryover effect from the discrimination task where we expect to find an N2pc (Mazza et al., 2009). The order of the target-color variability (either variable or constant) was counterbalanced across participants. Two training blocks of 20 trials, one for each task, were delivered prior to the start of each part of the experimental session.

EEG Recording and Data Analysis

EEG was recorded from 25 electrodes (including the following posterior sites: P7, PO7, P3, O1, O2, P4, PO8, and P8). These electrodes and the left earlobe electrode were recorded with a right-earlobe reference, and then re-referenced offline to the average of the left and right earlobe sites. Horizontal electro-oculogram (HEOG) was recorded with two electrodes positioned on the outer canthi of both eyes. Impedance was kept below $6 \text{ K}\Omega$ for all electrodes. Amplifier bandpass was 0.01–40 Hz, and digitization rate was 500 Hz. Trials with horizontal eye movements (HEOG exceeding $\pm 30 \mu\text{V}$), eye blinks, and other artifacts (any electrode exceeding $\pm 80 \mu\text{V}$) were excluded. The average of trials retained was 86%.

Averages for correct responses were computed relative to the 100-ms interval preceding the display onset, separately for each task and target-color variability. Statistical analyses were conducted on mean difference amplitudes obtained by subtracting event-related potential (ERP) waveforms at ipsilateral posterior electrodes (PO7, P7, P3, O1 for left target locations and PO8, P8, P4, O2 for right target locations) from those recorded at contralateral sites (i.e., PO8, P8, P4, O2 for left targets and PO7, P7, P3, O1 for right targets) for the following post-stimulus intervals: N2pc (180–300 ms), late sustained contralateral negativity (350–600 ms). The factors considered were electrode (PO7/PO8 versus P7/P8 versus P3/P4 versus O1/O2), task (detection versus discrimination), and target-color variability (variable versus constant). Greenhouse-Geisser corrections for sphericity violations were applied, and corrected *p*-values are reported.

Results

Behavioral Performance

An ANOVA on correct response times (RTs) between 200–1,500 ms for target-present trials with task (detection versus discrimination) and target variability (variable versus constant) as

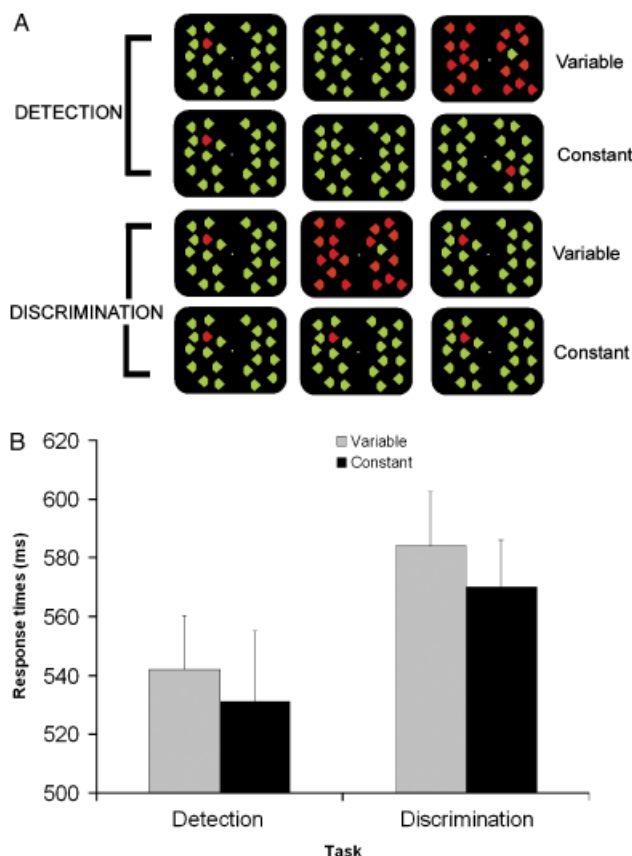


Figure 1. (A) Example of trials in the variable (first and third row) and constant (second and fourth row) conditions, separately for detection and discrimination. (B) Mean RTs (with standard errors) for the variable (gray) and constant conditions (black) in both tasks.

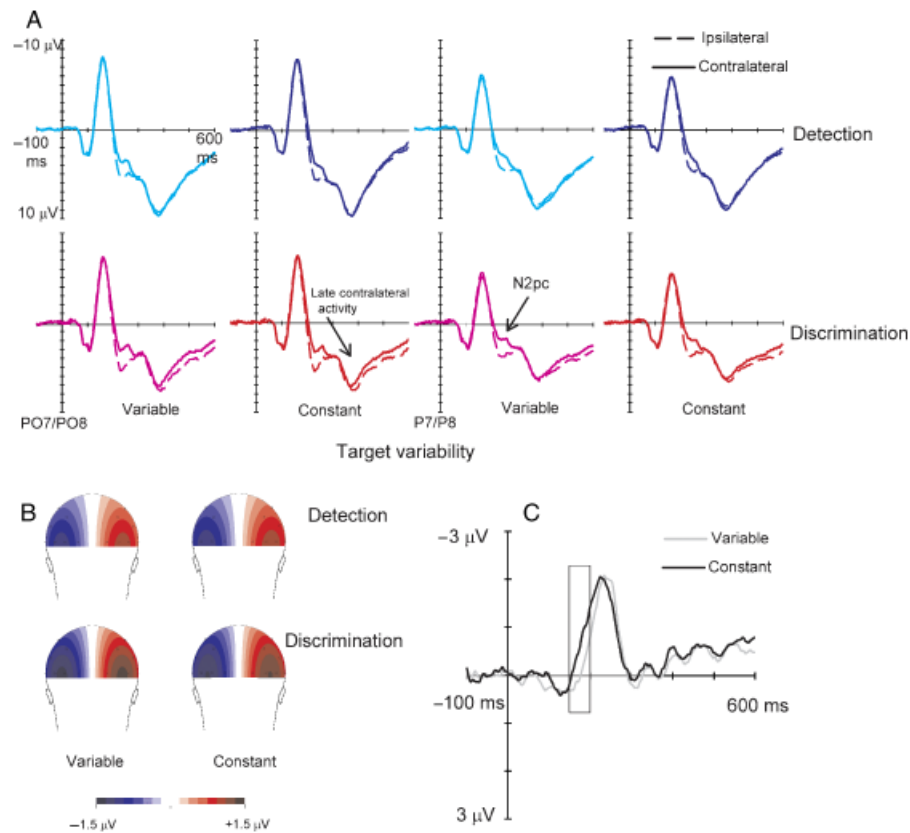


Figure 2. (A) Grand-average ERP waveforms obtained in the 600 ms post-stimulus interval at two representative posterior electrodes (left: PO7/PO8; right: P7/P8) contralateral (solid lines) and ipsilateral (dashed lines) to the target location, as a function of target-color variability and task. (B) Topographical ERP scalp distribution maps of the N2pc (200–300 ms post-stimulus) in the four experimental conditions, obtained by computing the contralateral minus ipsilateral difference activity for each electrode pair, and mirrored across the midline. (C) The grand-average difference waveforms (obtained by subtracting ipsilateral activations from contralateral activations recorded at posterior sites PO7 and PO8, collapsed across tasks) show the earlier N2pc onset in the constant relative to the variable condition (as indicated by the rectangle).

factors revealed a significant main effect of task, $F(1,15) = 10.49$, $p = .006$: participants were faster in the detection ($M = 536$ ms, $SD = 82.7$ ms) than in the discrimination condition ($M = 577$ ms, $SD = 68$ ms; see Figure 1b). In both tasks, RTs were also faster on constant ($M = 550$ ms, $SD = 75.1$ ms) than on variable trials ($M = 563$ ms, $SD = 69.7$ ms), $F(1,15) = 5.67$, $p = .03$. The interaction was not significant, $F < 1$.

Participants were overall highly accurate in both tasks (96% of correct responses). The ANOVA on percentage of correct responses showed a marginally significant effect of target variability, $F(1,15) = 4$, $p = .06$: participants were slightly more accurate on constant ($M = 96\%$) than on variable trials ($M = 95\%$). No other effect approached significance, all $ps > .65$.

ERP Results

As can be seen from Figure 2A, the N2pc amplitude was affected by the task, being larger for discrimination than for detection; no difference, however, emerged between the variable and constant conditions (also see Figure 2B). A subsequent sustained contralateral negativity (350–600 ms) was observable for the discrimination task only.

Confirming these observations, the ANOVA in the N2pc time window (180–300 ms) showed a significant effect of task, $F(1,15) = 8.2$, $p = .01$, with a more pronounced N2pc for discrimination than detection. Post-hoc comparisons (t -tests) against the null mean confirmed the presence of the N2pc for both detection and discrimination, both $ps < .001$. The effect of electrode was significant, $F(3,45) = 6.3$, $p = .009$, with an overall more pronounced N2pc at the most lateral electrode sites (PO7/PO8 and P7/P8) than at the most medial sites (P3/P4 and O1/O2; see Figure 2B). No other effects reached significance, all $ps > .13$.

To assess for differential effects of target-color variability on the N2pc onset, mean difference values at posterior electrodes (collapsed across sites) were tested (via t -test) against the null mean for each successive 5-ms time window in the 170–210 ms time range. The α level for the number of comparisons was adjusted following the False Discovery Rate procedure (Benjamini & Hochberg, 1995), which controls for the ratio between the number of null hypotheses erroneously rejected and the overall rejected hypotheses. Whereas for the constant condition an N2pc was present from 175 ms onwards (i.e., mean difference values significantly differed from zero for all time windows after that point, all $ps < .013$), no reliable N2pc was found for the variable

condition until 195 ms (all $ps > .06$ for the 170–190 ms range; see Figure 2C).¹

In the subsequent sustained contralaterality (350–600 ms), the effect of task was still significant, $F(1,15) = 71.3, p < .001$, with a more pronounced activity for the discrimination task. However, comparisons against the null mean revealed that the contralateral activation was present for the discrimination task only, all $t(15) > 3.9$, all $ps < .001$ (detection task: all $ts < 1.6$, all $ps > .14$).

Discussion

There are several new findings in this study. First, the results challenge one of the assumptions of the ART, according to which the N2pc amplitude should be modulated as a function of target variability, with an N2pc for the constant but not for the variable condition (Luck, 2005). Our data clearly show the presence of an N2pc for both the constant and variable conditions, regardless of whether distractors are strategically useful for target selection.² Schubo et al. (2007) also found a clear N2pc in a detection task with color or orientation singleton targets, which changed their features unpredictably. A potential explanation for the discrepancy between the present results and those by Luck & Hillyard (1994a) is suggested by Schubo et al.'s (2007) results, who found that orientation singletons elicited much smaller N2pc amplitudes than color singletons. In our experiment, the defining dimension of the target was color, whereas it was orientation in Luck and Hillyard's (1994a) experiment. It is possible, therefore, that the absence of an N2pc in Luck and Hillyard's study could be due to an overall lack of power in the N2pc amplitude, perhaps due to the smaller sample of participants relative to the Schubo et al. study.

The present finding has important consequences for the interpretation of the N2pc. One possibility, consistent with the distractor-suppression account of the N2pc, would be to assume that distractors are always suppressed, independently of whether or not they benefit target selection. Alternatively, we propose that the N2pc reflects the allocation of extra computational resources to one hemifield in order to analyze the target features in detail (see also Eimer, 1996; Mazza et al., 2009). Some theories of visual attention (e.g., Duncan & Humphreys, 1989) assume that when multiple elements are presented their representations are activated in parallel. The displays used in our experiment contained multiple similar distractors, resulting in high levels of activation of distractors relative to the singleton target. Hence, in

¹We additionally performed an analysis based on jackknifing by Miller, Patterson, and Ulrich (1998) to determine the difference between the constant and variable conditions in the N2pc onset latency. We found that, based on 50% of the peak amplitude values, the overall N2pc onset latency was shifted for both the variable and constant conditions, relative to the analysis reported in the main text. Nonetheless, the onset of the N2pc was significantly earlier for the constant (191 ms) relative to the variable condition (206 ms; overall difference: 15 ms, $t(15) = 2.3, p < .05$), consistent with the analysis in the text.

²Is the effect found in the variable condition for the detection task truly an N2pc, or does it reflect a modulation of a bilateral N2 between target-present and target-absent trials (see Luck & Hillyard, 1994b, Experiment 1)? In a separate analysis (not reported here), we observed that target-absent trials elicited a more pronounced posterior N2 in both ipsilateral and contralateral sites, but, importantly, this was true for both the variable and the constant conditions. In other words, while it is possible that the N2pc interacts with the bilateral N2, it does so equally in both conditions; hence, there is no reason to suppose that the N2pc in the variable condition of the present experiment is not a genuine one.

order to process the target appropriately, the visual system would have needed to direct more attentional resources to the target stimulus. This may be especially true for the discrimination task, and consistent with this idea, we found greater N2pcs for the discrimination than for the detection task.

Second, our results showed for the first time that target consistency affected the latency of the N2pc, with earlier N2pc onsets for the constant relative to the variable blocks. This finding is not predicted by the suppression account of the N2pc, according to which no suppression and thus no N2pc should be observed in the variable condition. However, it is in line with our interpretation of the N2pc, which would reflect the ability of the visual system to use target consistency to more efficiently isolate the location where the relevant item is presented. Future work will have to determine whether the N2pc is mainly driven by feature-based or location-based properties of the visual display; namely, whether it reflects the allocation of attention to a specific location or to an object that contains a critical target feature.

A third interesting finding is that the N2pc was not abolished when participants had to simply detect the presence of a unique feature (i.e., in the detection task). It has been suggested that this type of feature searches may be accomplished either pre-attentively (e.g., Treisman & Gelade, 1980) or with distributed attentional resources (e.g., Bravo & Nakayama, 1992). However, if one assumes that the N2pc is related to focused attention, then the present results challenge the idea of a net separation between pre-attentive (or distributed) and focalized attentional processes.

Finally, a second contralateral posterior negativity was observed in the 350–600 ms interval for the discrimination task only. This sustained activation has been reported in experiments investigating working memory for lateralized stimuli (e.g., McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004). Recently, we observed this contralateral negativity in a visual search task with no explicit memory requirements (Mazza et al., 2007), and proposed that it reflects the active maintenance of briefly displayed visual information when deeper analyses are required. Consistent with this view, the sustained negativity was present for finer judgments of the target (i.e., in the discrimination task), but not when no further processing other than detection of a singleton feature was required. This dissociation suggests that the two ERP activations may reflect at least partially independent processing stages, one (the N2pc) related to the allocation of attentional resources to the relevant element presented at a specific location in the visual field, while the late sustained activity would reflect either the maintenance of information in working memory until a finer analysis is performed, or the in-depth process itself (also see Drew & Vogel, 2008; McCollough et al., 2007).

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