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## Research report

# Attention selection, distractor suppression and N2pc

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### ARTICLE INFO

#### Article history:

Received 10 April 2008

Reviewed 13 August 2008

Revised 27 October 2008

Accepted 31 October 2008

Action editor Gus Bachtel

Published online 14 November 2008

#### Keywords:

Attentional orienting

N2pc

Distractor suppression

Visual search

Event-related brain potentials

### ABSTRACT

N2pc is generally interpreted as the electrocortical correlate of the distractor-suppression mechanisms through which attention selection takes place in humans. Here, we present data that challenge this common N2pc interpretation. In Experiment 1, multiple distractors induced greater N2pc amplitudes even when they facilitated target identification, despite the suppression account of the N2pc predicted the contrary; in Experiment 2, spatial proximity between target and distractors did not affect the N2pc amplitude, despite resulting in more interference in response times; in Experiment 3, heterogeneous distractors delayed response times but did not elicit a greater N2pc relative to homogeneous distractors again in contrast with what would have predicted the suppression hypothesis. These results do not support the notion that the N2pc unequivocally mirrors distractor-suppression processes. We propose that the N2pc indexes mechanisms involved in identifying and localizing relevant stimuli in the scene through enhancement of their features and not suppression of distractors.

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## 1. Introduction

What is attention and why do we need it? Theories of visual attention postulate that because of the limited computational resources of the human brain, these need to be selectively dedicated to some stimuli at the expense of others (e.g., Desimone and Duncan, 1995). Attention appears to be the way the visual system limits the analysis of unwanted stimuli, but the mechanism(s) underlying this function still remain controversial. For instance, does attention act through enhancement of the relevant stimulus or through suppression mechanisms that filter out irrelevant information? Several behavioral and neuroimaging studies in humans (e.g., Awh et al., 2003; Caputo and Guerra, 1998; Mounts, 2000; Serences

et al., 2004) have been interpreted to support the view that attention solves ambiguities during target analysis by suppressing irrelevant stimuli, and their corresponding features, in order to prevent erroneous coding or binding (Treisman and Schmidt, 1982). Some neurophysiological studies in monkeys provided evidence consistent with the filtering role of attention, showing that in V4 and IT cortex the neuron's preferential response to a given stimulus was physiologically suppressed when the stimulus was not attended (Moran and Desimone, 1985; Chelazzi et al., 1993; Desimone and Duncan, 1995; Reynolds et al., 1999).

In humans, event-related potentials (ERPs) studies of attention have been used to build a bridge between theories of visual selection and single neuron responses in monkeys.

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doi:10.1016/j.cortex.2008.10.009

These studies have revealed the occurrence of a specific brain response, named N2pc, to the presence of a relevant stimulus (target) among distractors (Eimer, 1996; Luck and Hillyard, 1994). In a similar fashion to the neurophysiological findings mentioned above, the N2pc typically arises at post-stimulus latencies of 180–300 msec, and consists of a more pronounced negative activation of the posterior sites contralateral to the visual hemifield where the target is presented, relative to ipsilateral sites (e.g., Eimer, 1996; Eimer and Mazza, 2005; Hickey et al., 2006; Luck et al., 1997; Mazza et al., 2007; Wascher and Wauschkuhn, 1996; Woodman and Luck, 1999; for a review, see Luck, 2005).<sup>1</sup> In the Ambiguity Resolution Theory (ART), Luck and colleagues proposed that the N2pc reflects the process of suppressing interfering distractor stimuli in the context of target identification (Luck, 2005; Luck and Hillyard, 1994; Luck et al., 1997). According to this theory, the primary role of attention, as reflected by the N2pc, is to solve ambiguity in target coding in extrastriate visual areas, such as V4 and IT, through filtering of distractors. The extent to which this filtering mechanism needs to operate, which would be reflected by the N2pc amplitude, depends on the presence of distractors and on their increased proximity to the target location, as this increases the likelihood that target and distractors are coded by the same population of neurons, a condition that generates the maximum level of ambiguity and competition in the visual system.

The suppression hypothesis is consistent with the observation that increasing the number of distractors, which presumably increases interference and attentional demands, delays response times (RTs) for target identification and correlates with a larger N2pc (Luck et al., 1997). It would also be consistent with the finding that no N2pc is observed when no distractors are presented (Luck and Hillyard, 1994), as in this condition there is no source of interference in the visual field. However, not all experimental evidence supports the suppression hypothesis. Recent findings have shown the presence of the N2pc in experimental paradigms in which the existence of suppression mechanisms may be less plausible, such as when a salient distractor is presented together with the target (see Hickey et al., 2006) or when masked stimuli are used (see Woodman and Luck, 2003). For instance, Hickey et al. (2006) found that an irrelevant salient distractor presented in the opposite hemifield to the target elicited an N2pc relative to its position, prior to a second N2pc associated with the target position. It is not clear what kind of suppression would take place in this condition. Moreover, in some studies a clear N2pc is found even when only one distractor is present in the hemifield opposite to the target's one, a situation that should strongly reduce the need for suppression, and thus no N2pc should be observed (Dell'Acqua et al., 2006; Eimer, 1996; Jolicoeur et al., 2006).

The results of an experiment showing that the N2pc amplitude did not vary between conditions with one and three distractors, led Eimer (1996) to propose that the N2pc may

reflect target enhancement rather than distractor suppression. According to this proposal, the N2pc may reflect the selection of a relevant stimulus mainly on the basis of its similarity to the target template, independently of the number of irrelevant items presented in the scene and of their spatial proximity to the target location. In Section 4, we interpret the N2pc data of the present study as showing that the N2pc may reflect the allocation of extra computational resources to one hemifield in order to analyze the target in detail by enhancing its features. However, differently from Eimer's (1996) interpretation of target enhancement, our data show that distractor numerosity has an important role in the generation of the N2pc, at least when comparison between few and many items is considered.

Overall, the suppression hypothesis predicts that multiple distractors elicit more pronounced N2pcs as they represent a strong source of interference during target coding. Interference, and thus N2pc amplitudes, would be enhanced by their spatial proximity to the target location (Luck et al., 1997; Luck, 2005). Interestingly, a different pattern of results is expected when the target feature is not known in advance, such as when it changes unpredictably from trial to trial. In this situation, the target can be selected only by comparison with the other "distractor" elements and, thus, they would not represent a real source of interference. Consequently, the suppression hypothesis predicts that distractor suppression should not take place and no N2pc should be observed (Luck, 2005; Luck and Hillyard, 1994).

In the present study, we tested two specific predictions made by the suppression hypothesis. Experiment 1 was conducted in order to test the prediction that no N2pc should arise when multiple "distractors" are necessary for determining the presence of a target, such as when the target is simply defined as the odd element among a set of distractors (Luck and Hillyard, 1994, Experiment 2). In Experiment 2 we tested the prediction that spatial proximity between target and distractors is a crucial factor in determining the level of interference needed for target recognition and, therefore, of the degree of distractor suppression and N2pc modulation. Finally, in Experiment 3 we considered a different context in which ambiguity may arise, namely when variation in distractor color increases. Although no explicit prediction has been formulated by proponents of the suppression hypothesis in this regard, it seems plausible to assume that dissimilarity among distractors should increase ambiguity in target coding, thus presumably requiring more suppression, and consequently larger N2pcs.

In all experiments of the present study participants viewed displays containing a variable number of colored diamond shapes that had a corner cut off on the left or right side. The target was defined as the diamond with a unique color, and participants performed a discrimination task on the singleton's shape.

In Experiment 1 the target was presented together with few or many homogeneously colored distractors. In the variable blocks, the target color changed unpredictably from trial to trial, whereas in the constant condition it remained the same throughout each block of trials. According to the suppression hypothesis, N2pc amplitudes should be modulated as a function of whether target color is constant or variable, because

<sup>1</sup> Since this differential ERP activation is sometimes clearly visible in the N2 range, while it is mostly evident in the P2 range in other conditions, it has also been denoted as Posterior Contralateral Negativity (see Jaśkowski et al., 2002; Van der Lubbe and Verleger, 2002).

different selection processes are involved in the two cases. More specifically, the N2pc should be present in the constant condition, because selection is based on the knowledge of the target features, and thus distractors represent a real source of interference and should be suppressed. In addition, since the suppression hypothesis predicts that multiple distractors interfere more than few distractors, because of the increased proximity to the target location (Luck et al., 1997), the N2pc in the constant condition should be more pronounced in larger than in smaller displays. The suppression hypothesis makes a different prediction for the variable condition, since here distractors are strategically necessary for defining the target (see Luck, 2005). Because of this, distractors should not be suppressed, resulting in little (or no) N2pc modulation. This prediction is particularly clear for the condition with multiple distractors (see Luck and Hillyard, 1994), where the presence of multiple, homogeneous elements should lead to easier target individuation from the uniform background (Duncan and Humphreys, 1989). This prediction is supported by the observation that when target color is variable, larger displays result in better behavioral performance relative to smaller displays (e.g., Bacon and Egeth, 1991; Bravo and Nakayama, 1992; Nothdurft, 2000; Sagi and Julesz, 1987; Turatto et al., 2007), indicating that increasing distractor numerosity facilitates target selection. For instance, Nothdurft (2000) found that the salience of a target, defined either by motion or orientation, varies as a function of array density, being maximal for medium levels of distractor density.

Experiment 2 examined in more detail whether proximity between target and distractors is indeed a key factor for N2pc modulation. According to the ART, when multiple distractors are present in the visual field, ambiguous coding and the resulting attentional suppression occur because of the increased spatial proximity of distractors to the target location, which in turn increases the probability that the two items are processed by the same neural populations (Luck et al., 1997, Experiments 1 and 2). Thus, one should predict that the closer the distractors are to the target the larger the degree of interference, and therefore the N2pc. Luck et al. (1997) have interpreted the increase in N2pc amplitude when more distractors are displayed as evidence that spatial proximity is a crucial factor that increases ambiguity and suppression. However, what they attributed to spatial proximity may in fact have been caused by distractor numerosity. For this reason, in the present experiment we modulated spatial proximity independently of distractor numerosity by using a fixed number of distractors and by varying their distance to the target (for a similar procedure, see Bacon and Egeth, 1991).

Finally, in Experiment 3 we tested a different context in which ambiguity may arise, namely when variation in distractor color increases. According to some models of visual attention, distractor homogeneity greatly affects target search (e.g., Duncan and Humphreys, 1989; Humphreys and Müller, 1993). For instance, in their Attentional Engagement Theory, Duncan and Humphreys (1989, 1992) proposed that besides target-distractor similarity, which has an important role in many theories of attention (e.g., Treisman and Gelade, 1980; Wolfe, 1998), the degree of similarity among distractor elements significantly affects the way target selection is

accomplished. While similar (homogeneous) distractors can be segmented into a single unit, thus rendering target selection relatively easy, dissimilar (heterogeneous) distractors create multiple discontinuities in the visual field, hampering the segmentation process and ultimately target selection. It seems logical to hypothesize that heterogeneous distractors represent a stronger source of interference during target coding than homogeneous distractors. Since the ART predicts that a strong source of interference in target coding should require more suppression and thus lead to more pronounced N2pcs, following a further reading of the suppression hypothesis heterogeneously colored distractors should elicit greater N2pcs than homogeneous distractors. In Experiment 3 we explicitly tested this hypothesis by having the target element surrounded by few or many distractors that could have either one (homogeneous) or two (heterogeneous) colors. Schubo et al. (2007b) investigated this issue in a task in which participants reported the presence versus absence of a singleton presented among several distractors. They found that distractor homogeneity correlated with modulations in the bilateral posterior N2. More specifically, in the target-present condition homogeneous distractors led to a smaller N2 relative to heterogeneous distractors. By contrast, the N2pc showed exactly the opposite trend, with more pronounced amplitudes for homogeneous than heterogeneous distractors. The authors interpreted this effect as evidence of differential difficulties in target template matching. It is not clear why less efficient template matching should lead to less pronounced amplitudes. Nonetheless, this result, if replicated, would undermine the assumption that more interference in target coding, as is the case of heterogeneous distractors, always correlate with larger N2pc.

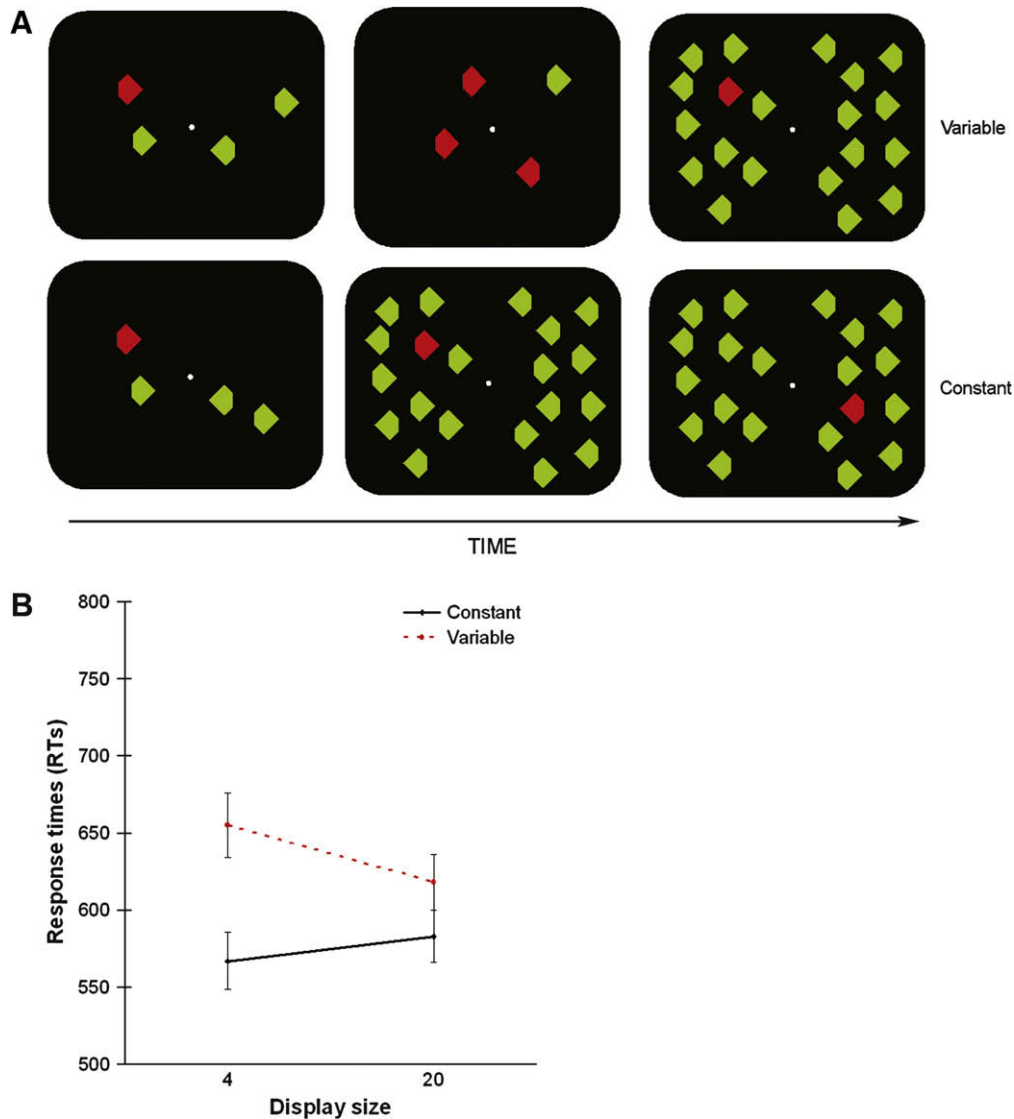
## 2. General methods

### 2.1. Participants

A total of thirty-seven volunteers (Experiment 1: twelve, aged 20–35 years; Experiment 2: ten, aged: 22–32; Experiment 3: fifteen, aged: 19–23) participated in the experiments. Participants reported normal or corrected-to-normal vision and normal color vision, and provided written informed consent. All the experiments were conducted following the guidelines laid down in the Helsinki declaration and were approved by the local ethics committee.

### 2.2. Stimuli

Stimuli consisted of equiluminant red, green and blue diamonds ( $17 \text{ cd/m}^2$ ) presented on a black background ( $1 \text{ cd/m}^2$ ). Each diamond ( $.6^\circ \times .8^\circ$ ) had a  $.4^\circ$  corner trimmed on the left or right side (see Fig. 1A). On each trial, the display randomly contained a variable number of diamonds (Experiment 1: 4 vs 20; Experiment 2: always 20; Experiment 3: 5 vs 21), equally distributed to the left and right side of fixation. The diamonds were located within an  $8 \times 8$  matrix ( $8.6^\circ \times 8.6^\circ$ ) in Experiment 1, and within a  $10$  (columns,  $11.4^\circ$ )  $\times$   $8$  (rows,  $8.6^\circ$ ) matrix in Experiments 2 and 3. One diamond (the target) had a unique color (Experiments 1 and 2: either red or green; Experiment 3:



**Fig. 1 – A.** Example of six trials with few or many distractors in the variable (top) and constant (bottom) conditions of Experiment 1. **B.** Mean RTs (with standard errors) for displays with 4 and 20 elements in the variable (dotted line) and constant condition (solid line) of Experiment 1.

red, green or blue) 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 columns of the matrix relative to fixation. Below are reported the differences between experiments.

*Experiment 1.* Variable condition: the target color varied unpredictably, being on some trials red whilst on others green. Constant condition: the target color was blocked, being either red or green (counterbalanced across participants; see Fig. 1A). Distractors number could be 3 or 19.

*Experiment 2.* On half of the trials, two of the 19 distractors were presented in two of the four positions of the matrix adjacent to the target location along the vertical and horizontal axes. On the remaining trials no distractor was presented in any of the positions immediately close to the target location (see Fig. 3A). The target color varied randomly from trial to trial.

*Experiment 3.* The target varied randomly from trial to trial. On half of the trials the distractors (either 4 or 20)<sup>2</sup> had a homogeneous color (as in the variable condition of Experiment 1), whereas in the remainder of the trials half of the distractors had one color (e.g., red) and the other half were colored differently (e.g., blue, the target being green; see Fig. 4A).

<sup>2</sup> The number of distractors in Experiment 3 was changed in order to have the two colors used for the distractors equally distributed in the two hemifields. This was done in order to avoid a potential confound in the condition with few distractors. If we had used three distractors (as in Experiment 1) we would have had two singletons in the visual display (e.g., the red target, one green distractor and two blue distractors). This situation would have made this experiment not easily comparable with the other experiments of the present study, where only one singleton (the target) was presented on each trial.

### 2.3. Procedure

Stimuli were presented for 150 msec to render eye movements ineffective. Participants' task was to indicate the side of the cut (left/right) for the color singleton by pressing the keys 'B' and 'N' on a computer keyboard with the index or middle fingers of their right hand. In the variable condition of Experiment 1, participants were informed that the target was the uniquely colored item, and that its color varied unpredictably throughout a block of trials. They were also informed that in the constant blocks, the target would always have the same color (either red or green, depending on balancing constraints). Instructions in Experiments 2 and 3 were the same as for the variable condition in Experiment 1. In all experiments, speed and accuracy were emphasized equally. Maximum time for responding was 1500 msec. The inter-trial interval was 1500 msec. In Experiment 1, participants performed six experimental blocks of 80 trials each in the variable condition, alternated with other six blocks for the constant condition. The order of the first block (either variable or constant) was counterbalanced across participants. In Experiment 2, ten blocks of 80 trials each were delivered to participants, whereas twelve blocks of 96 trials each were delivered in Experiment 3.

### 2.4. EEG recording and data analysis

In all experiments of the present study, EEG was recorded with Ag–AgCl electrodes from FPz, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, PO7, P3, O1, Pz, P4, PO8, P8, O2 and Oz. These electrodes and the left earlobe electrode were recorded with a right-earlobe reference (bandpass filter: .01–40 Hz, A/D rate: 1000 Hz in Experiment 1; 500 Hz in Experiments 2 and 3), and then re-referenced offline to the average of the left and right-earlobe sites. Horizontal EOG (HEOG) was recorded by means of two electrodes positioned on the outer canthii of both eyes. Impedance was kept below 6 K $\Omega$  for all electrodes. Trials with horizontal eye movements (HEOG exceeding  $\pm 30 \mu\text{V}$ ), eye blinks, head movements, and other artifacts (any electrode exceeding  $\pm 80 \mu\text{V}$ ) were excluded. The average of retained trials was 78% (Experiment 1), 76% (Experiment 2) and 82% (Experiment 3).

Averages for correct responses were computed relative to the 100 msec interval preceding the display onset, separately for each condition and target side. In all the experiments in this study, statistical analyses were carried out on difference waveforms obtained by subtracting ERP waveforms at posterior electrodes ipsilateral to the target side (i.e., PO7 for left targets, PO8 for right targets) from those recorded at electrodes contralateral to the target side (i.e., PO8 for left targets, PO7 for right targets), collapsed across target side. The first set of analyses was carried out on mean difference amplitude values in the 180–300 msec post-stimulus interval (where the N2pc is maximal for this type of experiments; see Mazza et al., 2007; Mazza et al., in press). In a second set of analyses, N2pc peak amplitudes and latencies were computed for each condition considering a larger time window (150–300 msec post-stimulus interval). An estimation of the effect size (partial eta square) is reported. Post-hoc comparisons were conducted by means of t-tests.

## 3. Results

### 3.1. Experiment 1

For each measure considered (RTs, correct responses, ERP difference amplitudes, N2pc peak amplitudes and latencies), an ANOVA with target color (variable vs constant) and display size (4 vs 20) as factors was conducted.

#### 3.1.1. Behavioral performance

Fig. 1b shows the results on RTs for Experiment 1.

Both the main effects of target color and of display size were significant,  $F(1,11) = 176.3$ ,  $p < .001$ , partial  $\eta^2 = .94$  and  $F(1,11) = 9.4$ ,  $p = .01$ , partial  $\eta^2 = .46$  respectively. In line with Bravo and Nakayama (1992) we found that in the variable condition, participants were faster on trials with larger display sizes than on trials with small display sizes, as substantiated by the statistically significant target color  $\times$  display size interaction,  $F(1,11) = 62.6$ ,  $p < .001$ , partial  $\eta^2 = .85$ , and by a significant subsequent pairwise comparison between large and small display sizes,  $t(11) = 6.2$ ,  $p < .001$ . In contrast, in the constant condition distractor numerosity slightly slowed participants' performance ( $M = 583$  msec) relative to the condition with few distractors ( $M = 567$  msec),  $t(11) = 5.6$ ,  $p < .001$ .

Besides being faster, in the variable condition participants were also slightly more accurate for the larger display size ( $M = 95\%$ ) than for the smallest display size ( $M = 94\%$ ), as confirmed by the significance of both the interaction,  $F(1,11) = 5.77$ ,  $p < .035$ , partial  $\eta^2 = .34$  and the follow-up t-test,  $t(11) = 2.3$ ,  $p < .05$ . No other effect was significant, all  $p > .14$ .

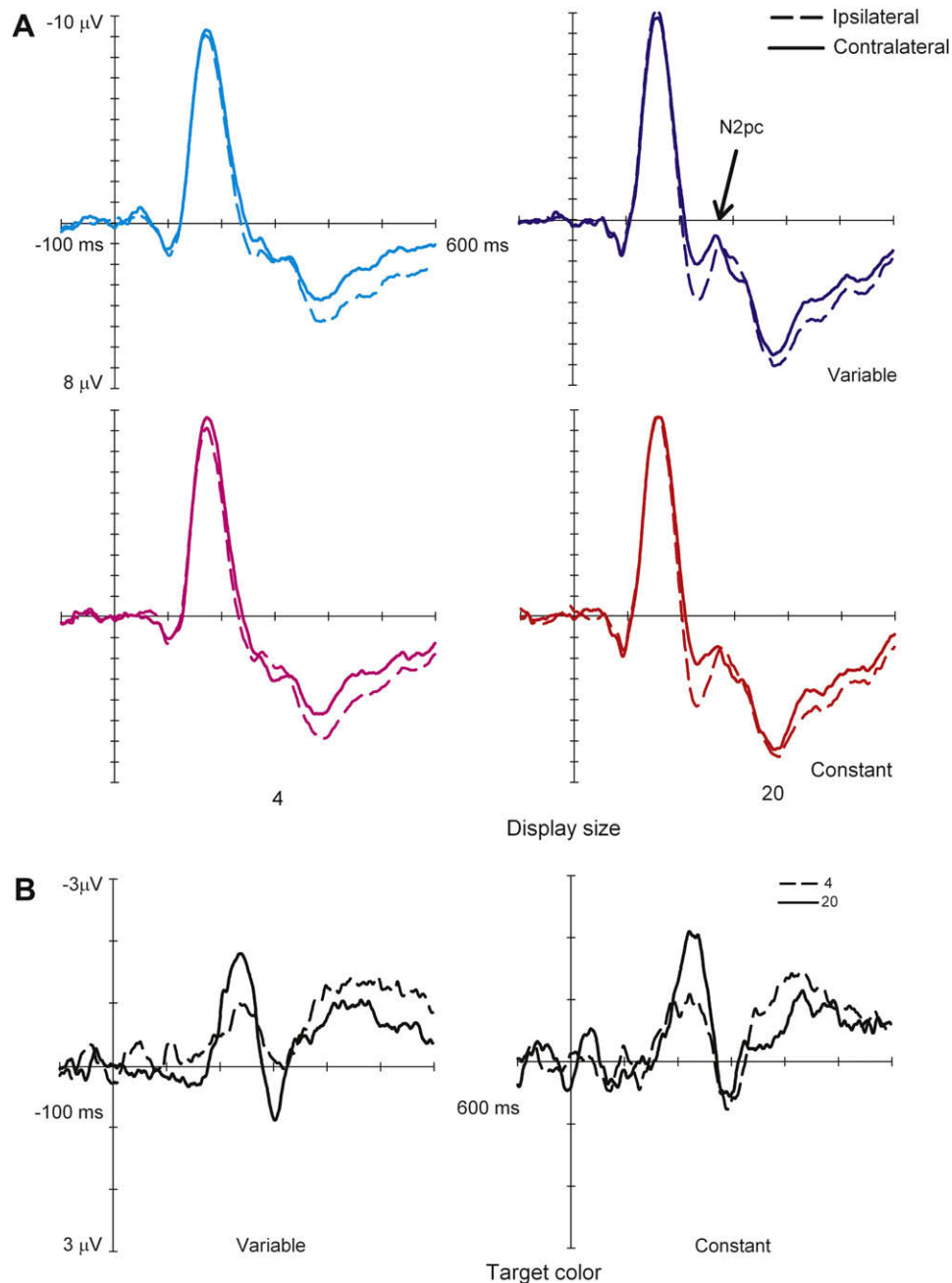
#### 3.1.2. ERP results

As can be seen from Fig. 2a and b, the N2pc amplitude was strongly affected by the numerosity of the distractors presented in the scene, with larger amplitudes for the large display size. However, no difference emerged between the variable and constant conditions. Thus, the present data do not support the prediction of the suppression hypothesis, according to which little (or no N2pc) should be found in the variable condition with multiple distractors when these are useful for selecting the target.

These observations were confirmed by the ANOVAs on mean difference amplitude values in the N2pc time window (180–300 msec) and on N2pc peak amplitude values. The first ANOVA showed a significant main effect of display size,  $F(1,11) = 9.43$ ,  $p < .011$ , partial  $\eta^2 = .46$ , indicating that the N2pc was larger for the large display size than for the small one. Neither the main effect of target color nor the interaction was significant, both  $F < 3.2$ , both  $p > .1$ .

In line with these results, the ANOVA on N2pc peak amplitude values showed a significant main effect of display size,  $F(1,11) = 8.2$ ,  $p < .015$ , partial  $\eta^2 = .43$ , indicating that the N2pc peak was larger for the large than for the small display size; no other effect was significant, both  $F_s < 1$ .

In contrast with the analyses on amplitudes, no significant effect emerged from the ANOVA on peak latencies, all  $F < 1.3$ , all  $p > .27$ .



**Fig. 2 – A.** Grand-average ERP waveforms obtained in Experiment 1 in the 600 msec post-stimulus interval at posterior electrode PO7/PO8 contralateral (solid lines) and ipsilateral (dashed lines) to the target location, as a function of display size (from left to right) and target color (from top to bottom). **B.** Differential waveforms point to the enlarged N2pc for large displays (solid lines) relative to small displays (dashed lines).

### 3.2. Experiment 2

Distractor distance (near vs far, relative to the target location) is the factor considered in the ANOVAs carried out for each measure (RTs, correct responses, ERP difference amplitudes, N2pc peak amplitudes and latencies) recorded in Experiment 2.

#### 3.2.1. Behavioral performance

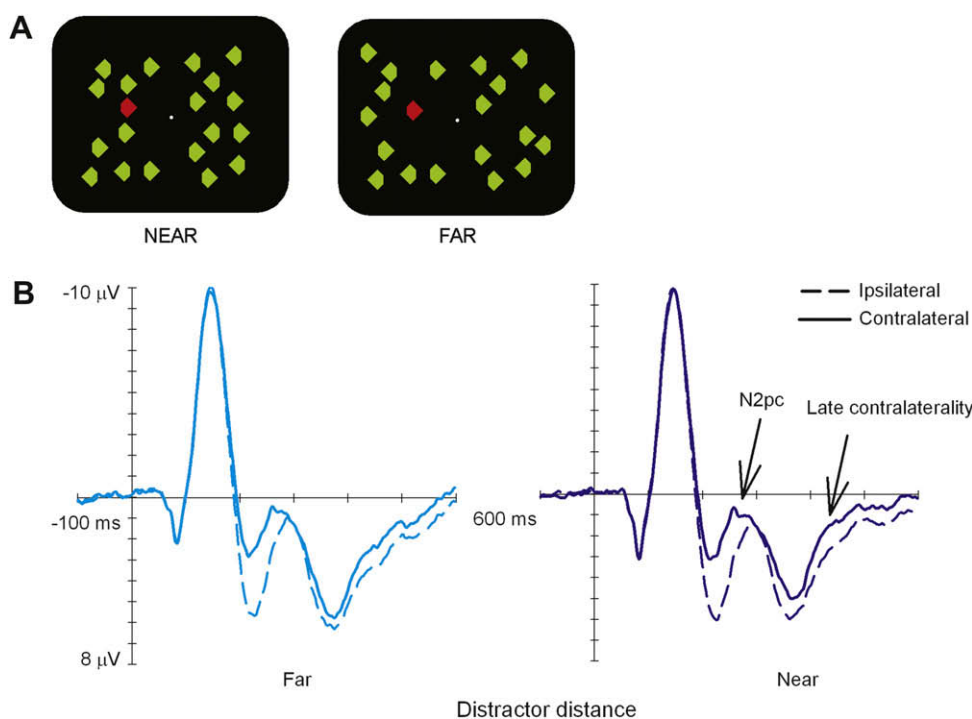
Consistent with the idea that close distractors interfere with target coding more than far distractors (e.g., Caputo and Guerra, 1998; Mounts, 2000), participants were significantly

slower when two distractors were close to the target ( $M = 609$  msec) relative to when they were far from the target ( $M = 576$  msec),  $F(1,9) = 225.08$ ,  $p < .001$ , partial  $\eta^2 = .96$ .

Participants were also slightly more accurate on trials with far distractors ( $M = 98\%$ ) than on trials with near distractors ( $M = 97\%$ ),  $F(1,9) = 10.19$ ,  $p < .011$ , partial  $\eta^2 = .53$ .

#### 3.2.2. ERP results

The suppression hypothesis predicts a larger N2pc for close than far distractors. Fig. 3B shows the presence of a clear N2pc component in both conditions. However, visual inspection



**Fig. 3 – A. Example of trials with far (left) and near (right) distractors, relative to the target location (Experiment 2). B. Grand-average ERP waveforms obtained in Experiment 3 in the 600 msec post-stimulus interval at posterior electrode PO7/PO8 contralateral (solid lines) and ipsilateral (dashed lines) to the target location, as a function of distractor distance.**

suggests no difference in the N2pc between the two conditions. This impression was confirmed by the absence of significant effects from the ANOVAs on mean amplitudes, peak amplitudes and latencies, all  $F_s < 1$ .

### 3.3. Experiment 3

The factors included in the ANOVA for each measure considered (RTs, correct responses, ERP difference amplitudes, N2pc peak amplitudes and latencies) were distractor color (homogeneous vs heterogeneous) and display size (5 vs 21).

#### 3.3.1. Behavioral performance

The RT pattern replicated the results of the variable condition of Experiment 1, with faster RTs for the large than small display size, as confirmed by the significant main effect of display size,  $F(1,14) = 105.97$ ,  $p < .001$ , partial  $\eta^2 = .88$  (see Fig. 4B). In line with previous research (Duncan and Humphreys, 1989), RTs were slower for heterogeneous distractors, as confirmed by a significant main effect of distractor color,  $F(1,14) = 321.21$ ,  $p < .001$ , partial  $\eta^2 = .96$ . The distractor color  $\times$  display size interaction was also significant,  $F(1,14) = 48.22$ ,  $p < .001$ , partial  $\eta^2 = .77$ , although follow-up comparisons revealed that RTs for the large display size were faster than RTs for the small display size in both conditions, both  $t > 2.2$ , both  $p < .045$ .

Participants' accuracy was overall quite high (>93%) and greater for the large than for the small display sizes in the heterogeneous condition, as revealed by a significant interaction between distractor homogeneity and display size,

$F(1,14) = 38.32$ ,  $p < .001$ ,  $\eta^2 = .73$ , and confirmed by successive comparisons,  $t(14) = 6.32$ ,  $p < .001$ .

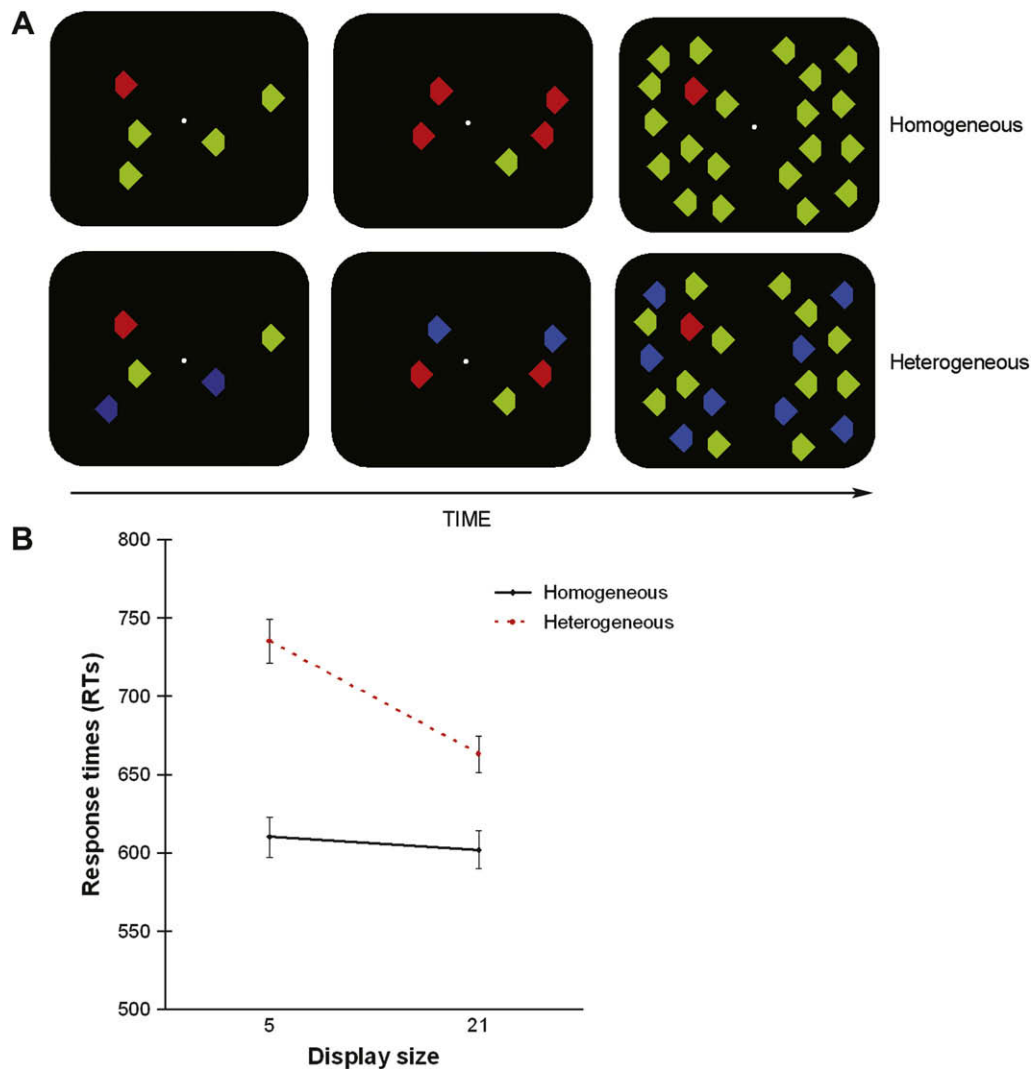
#### 3.3.2. ERP results

As in Experiment 1, the N2pc was clearly larger for the large display size (Fig. 5A). However, contrary to the suppression hypothesis, the heterogeneous condition did not elicit greater N2pc relative to the homogeneous condition. More specifically, the homogeneous condition seemed to elicit larger N2pcs relative to the heterogeneous condition; in addition, for the large display size the N2pc peak appeared shorter in latency in the homogeneous condition than in the heterogeneous condition (see Fig. 5B). Due to an apparent smearing of the N2pc for the heterogeneous condition, the N2pc was also longer lasting in this condition.

These observations, based on visual inspection, were confirmed by the results of the ANOVAs. The ANOVA on mean amplitudes showed significant main effects of display size,  $F(1,14) = 22.65$ ,  $p < .001$ , partial  $\eta^2 = .62$ , with larger N2pcs for the large display size, and of distractor color,  $F(1,14) = 26.34$ ,  $p < .001$ , partial  $\eta^2 = .65$ , with larger N2pcs for the homogeneous condition. The interaction was not significant,  $F < 1$ .

Consistent with these results, the ANOVA on the N2pc peak amplitudes showed a significant main effect of display size,  $F(1,14) = 23.96$ ,  $p < .001$ , partial  $\eta^2 = .63$  and of distractor color,  $F(1,14) = 24.93$ ,  $p < .001$ , partial  $\eta^2 = .64$ , but no significant interaction was observed,  $F(1,14) = 2$ ,  $p = .17$ .

The ANOVA on peak latencies revealed a significant main effect of distractor color,  $F(1,14) = 4.91$ ,  $p = .04$ , partial  $\eta^2 = .26$  and, more importantly, a significant interaction,  $F(1,14) = 14.77$ ,  $p < .003$ , partial  $\eta^2 = .51$ , indicating, as confirmed by successive



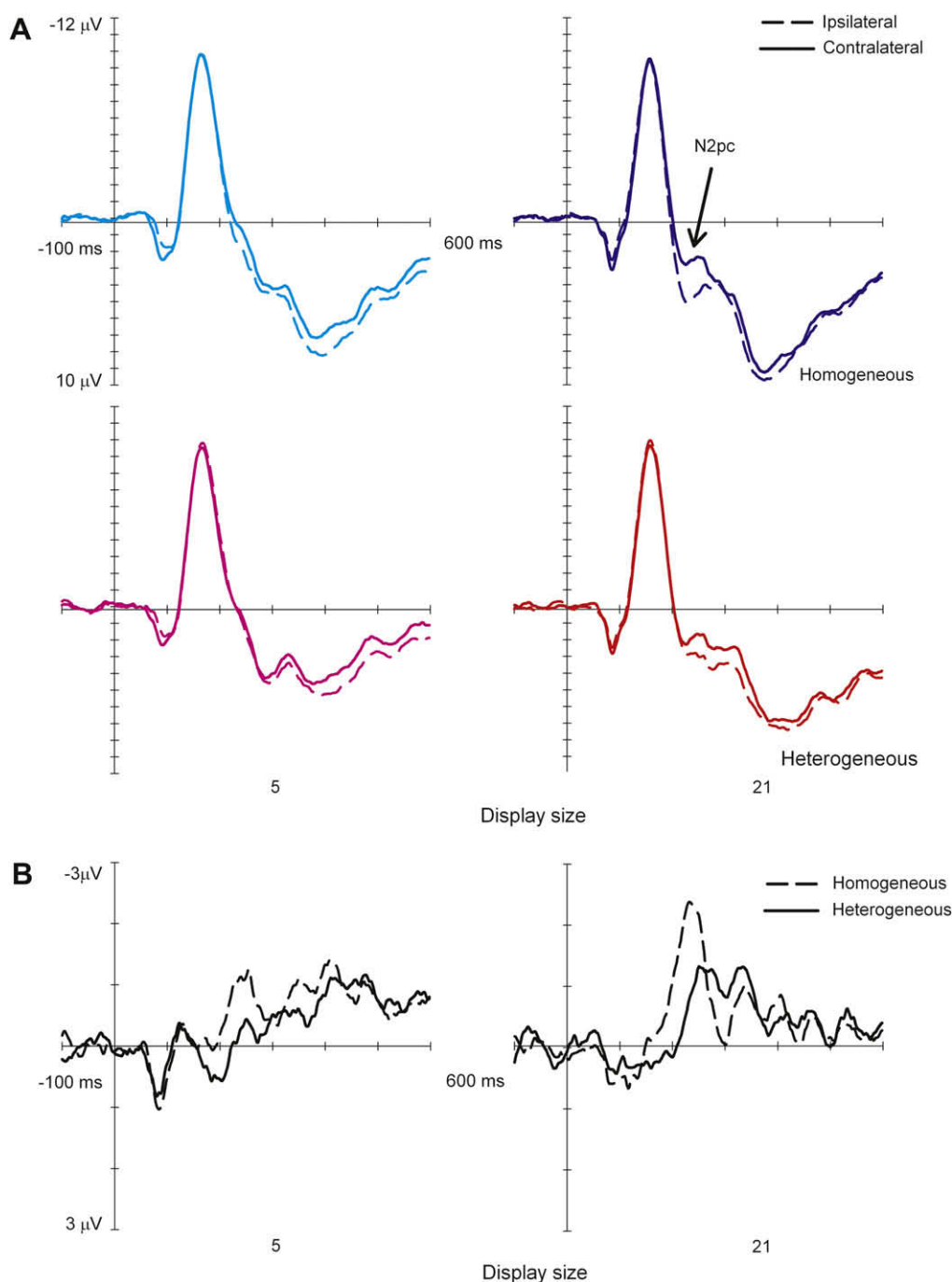
**Fig. 4 – A.** Example of six trials with few or many distractors in the homogeneous (top) and heterogeneous (bottom) conditions of Experiment 2. **B.** Mean RTs (with standard errors) for displays with 5 and 21 elements as a function of distractor color (homogeneous, solid line, vs heterogeneous, dotted line) of Experiment 3.

comparisons, that for the large display size the N2pc peak was delayed in the heterogeneous condition relative to the homogeneous condition,  $t(14) = 5.4$ ,  $p < .001$ , whereas no difference emerged for the small display size,  $p > .8$ .

#### 4. General discussion

According to the ART, the N2pc reflects suppression of distractor analysis in extrastriate areas whenever ambiguity arises in the context of target coding. More precisely, the suppression hypothesis predicts that the N2pc amplitude is modulated by whether distractors are strategically useful to select the target (Luck, 2005; Luck and Hillyard, 1994), and by their spatial proximity to the target location (Luck, 2005; Luck et al., 1997). However, the present data do not support such conclusions. Below we summarize the main findings of our study, and their implications for the concept of distractor suppression.

In Experiment 1, we found no support for the ART, in that multiple distractors always elicited an N2pc, independently of the RT pattern and regardless of whether they might supposedly benefit target selection by not being suppressed (i.e., in the variable condition). The observation of the N2pc component in a situation where distractors seem strategically useful to target selection, and thus according to the ART they should not be suppressed, has also been reported in a recent study by Schubo et al. (2007a), in which participants reported the presence of a singleton item (a bar with a unique orientation or color) that varied from trial to trial. Differently from the original study of Luck and Hillyard (1994, Experiment 2), in all experiments of the present study we used a discrimination task, where participants had to detect the presence of the color singleton in addition to performing a judgment on its shape. Because all distractors had a similar or even identical shape to the target (i.e., they were all diamonds with a left or right cut-off corner), it might be argued that the interference created by distractors was caused by their shape rather than color. On



**Fig. 5 – A.** Grand-average ERP waveforms obtained in Experiment 3 in the 600 msec post-stimulus interval at posterior electrode PO7/PO8 contralateral (solid lines) and ipsilateral (dashed lines) to the target location, as a function of display size (from left to right) and distractor color (from top to bottom). **B.** Difference waveforms show a larger N2pc for homogeneous distractors (dashed lines), and a delayed N2pc peak in the large display condition for the heterogeneous distractors (solid line in the right graph).

this view, the degree of interference and distractor suppression, which in turn determines the magnitude of the N2pc, would be the same in both the variable and constant conditions, and thus not surprisingly the N2pc would not change its amplitude. Results from our recent study (Mazza et al., in press) undermines this interpretation. In that study, we directly compared variable and constant repetitions of the

target color not only in a task identical to the present one, but also in a condition where participants had to simply report on the presence versus absence of the target, defined by its unique color. In this condition, item shapes are clearly irrelevant; nonetheless, in line with the present results, even in this latter condition we failed to find a modulation of the N2pc amplitude for the variable condition relative to the constant one.

In Experiment 2 results failed to show an effect of target-distractor proximity on the N2pc amplitudes. One might argue that the distance between the two distractors and the target was too small to affect the activity of extrastriate visual areas, which presumably drive the N2pc (see Hopf et al., 2000), since the neurons' receptive field in these areas can encompass several degrees of the visual field. This is not always the case, however, as some experimental evidence in monkeys has shown that neurons in IT can be very selective to small positional changes, with a sensitivity of approximately  $1^\circ$  (e.g., DiCarlo and Maunsell, 2003; for a discussion, see Rousselet et al., 2004). Furthermore, even if we accepted the viewpoint that the neurons in those extrastriate areas where attentional operation is maximal can encompass an area of  $7\text{--}10^\circ$  centered on the target, this would render problematic the interpretation of two crucial experiments supporting the suppression hypothesis (Luck et al., 1997; Experiments 1 and 2), where a subtle spatial manipulation (of approximately  $1^\circ$ , similar to the present one) between target and distractors effectively modulated the N2pc. In the present experiment we modulated spatial proximity independently of distractor numerosity. By contrast, Luck et al. (1997) added more distractors to the visual field, which could erroneously lead one to conclude that spatial proximity (rather than distractor addition) is a crucial factor for distractor suppression to occur and thus for the modulation of the N2pc. We suspect that distractor numerosity, rather than target-distractor proximity *per se*, is responsible for the observed N2pc modulation in Luck et al.'s experiments and, conversely, for the lack of such observation in the present experiment, in which display size was kept constant. As a consequence, one of the main assumptions of the ART, namely that target-distractor proximity should affect the amplitude of the N2pc, seems unwarranted. Finally, it is noteworthy that the distance modulation used in the present study was large enough to create an interference effect in RTs, showing that spatial proximity can effectively increase interference during target coding.

In Experiment 3 distractor heterogeneity did not increase the N2pc, contrary to what one might predict on the basis of the hypothesis that links an increase in ambiguity with enhanced N2pcs. Specifically, the N2pc for the heterogeneous condition with the large display size was clearly delayed and longer lasting relative to the homogeneous condition; in addition, it even appeared lower in amplitude, although this may be the consequence of a higher ERP latency variability. Therefore, our data did not provide clear support to the suppression hypothesis, since this hypothesis is exclusively based on N2pc amplitudes rather than latencies. In addition, these findings converge with the study by Schubo et al. (2007b) on texture segmentation in visual search, which points to a trend similar to our data, with more pronounced N2pc amplitudes for homogeneous relative to heterogeneous distractors.

Overall, the only aspect of the present data that is consistent with predictions derived from the ART is the finding of a distractor numerosity effect on N2pc amplitudes. Hence, at the very least, this theory would have to be modified so as to clarify: 1) why, contrary to expectations derived from this theory, multiple distractors would always be suppressed in visual searches such as the present one and other recent

studies (e.g., Mazza et al., *in press*; Schubo et al., 2007a), independently of whether they are strategically useful for finding the target (cf. Luck, 2005; Luck and Hillyard, 1994, Experiment 2); 2) why target-distractor proximity, when manipulated independently of distractor numerosity, does not consistently affect the magnitude of the N2pc; and 3) why distractor heterogeneity, which causes substantial interference in feature search, does not lead to a clear increase in the N2pc, as shown in our Experiment 3.

Alternatively, we may enlarge the hypothesis space and consider different explanations of the N2pc that do not invoke distractor suppression. For example, the N2pc may reflect the enhancement of the relevant stimulus in the scene (Eimer, 1996). On this view, the N2pc found in the present study would reflect the allocation of more attentional resources to the target stimulus, resulting in an enhanced coding of its features. This does not imply that distractor features do not play any role on the generation of the N2pc. Nonetheless, in what follows, we propose that distractors may have effects on target-related activity (i.e., enhanced coding) rather than undergo suppression.

Let us consider first the effect of distractor numerosity on the N2pc found in Experiments 1 and 3. Several theories have assumed that when multiple elements are presented, there is a parallel activation of their representations, and that the more identical elements are presented together, the more their representations are activated (e.g., Duncan and Humphreys, 1989). In the case of the stimuli used in our experiments, this translates into higher levels of activation of the distractor elements when there are many compared to when there are only a few. This may be true even when the target is a singleton. We may suppose, then, that in order to process the target appropriately, and because of the limited computational resources available at any given time, the visual system needs to enhance the target stimulus more when there are many compared to when there are few elements in the visual field. This may be especially true in our task, where we asked participants not just to detect the presence of the singleton, but to additionally perform a fine discrimination on it. On this view, the N2pc amplitude would reflect the degree of enhancement of the target features, rather than suppression of the non-target features. In addition, according to this account, the N2pc should be present to some extent even when only one distractor is displayed, and this is consistent with the results from previous studies where only two elements (the target and the distractor) were presented (e.g., Eimer, 1996; Jolicoeur et al., 2006).

The two other outcomes of the present study, namely the lack of an effect of proximity on the N2pc (Experiment 2) and the delayed and prolonged N2pc for heterogeneous distractors (Experiment 3) may be explained as follows. The lack of an effect of proximity on the N2pc in Experiment 2 is due to the fact that, because they are homogeneous in color, distractors are grouped together and treated as a single chunk of information, whose weight is modulated by their numerosity rather than their relative proximity to the target. Given that numerosity was fixed in this experiment, no change in the N2pc amplitude would be expected and none emerged. When heterogeneous distractors are added in the display (Experiment 3), there are multiple discontinuities in the visual

field, making it difficult to immediately identify the target location. In the present case, at least two different groups of distractors are segregated, occasionally delaying the enhancing process. This in turn would generate multiple N2pcs, which when averaged out would result in a smearing of the whole component, as found for the heterogeneous condition in Experiment 3.

Finally, it is also conceivable that the N2pc does not reflect the effects of a single mechanism, but rather a summation of distractor-related (positive) and target-related (negative) activities, which may be both present in typical visual search paradigms, such as the one adopted here (see Hickey et al., 2009). Although future work will need to address these hypotheses in greater detail, this study begins to shed some light on the long-lasting debate regarding the enhancement versus suppression interpretation of the N2pc. Specifically, the present findings challenge the suppression view as it stands, favoring an alternative interpretation of the N2pc as reflecting target enhancement. Resolution of this issue would allow the use of the N2pc to directly address the nature of attentional processes.

## Acknowledgements

This research has been supported by a grant from the Fondazione Cassa di Risparmio di Trento e Rovereto (Italy) and from the Ministero dell'Istruzione, dell'Università e della Ricerca (Italy).

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