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N2pc and attentional capture by colour and orientation-singletons in pure and mixed visual search tasks

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Abstract

The capture of attention by singleton stimuli in visual search is a matter of contention. Some authors propose that singletons capture attention in a bottom-up fashion if they are salient. Others propose that capture is contingent upon whether or not the stimuli share task-relevant attributes with the target. This study assessed N2pc elicited by colour and orientation singletons in a mixed task (the singleton defined as target changed block-to-block), and a pure task (the target was the same across the whole task). Both singletons elicited N2pc when acting as targets; when acting as non-targets, orientation singletons elicited N2pc only in the mixed task. The results suggest that the singletons were not salient enough to engage attention in a purely bottom-up fashion. Elicitation of N2pc by non-targets in the mixed task should be attributed to top-down processes associated with the current task. Stimuli that act as targets in part of the blocks become not completely irrelevant when non-targets.

Keywords: ERP; N2pc; Visual search; Singletons; Attentional capture; Pure task; Mixed task

1. Introduction

It is widely known that adaptive behaviour in normal life requires selection of the relevant information from the available external stimuli, while ignoring other surrounding information. As regards the visual modality, visual search tasks are employed to evaluate how attention is focused in these situations. In the standard visual search task, the subject looks for a target item among a number of distractors, and has to indicate whether the target is present or absent in each stimulus array. It has been established that access to the strength of attention is driven both by the properties of the stimuli, especially salience (bottom-up or stimulus-driven processes), and by the interests, memories or internal motivation of the subject (top-down or goal-driven processes) (Theeuwes et al., 2000).

Certain features, such as colour or shape, appear to stand out against the background and capture subjects' attention. This attentional capture can accelerate performance if the singleton feature is part of the target, or can slow the performance down if it is a part of the distractor, and thus interferes with target processing even though the feature is irrelevant to the task (Pashler, 1988). Some studies have reported that only abrupt-onset visual stimuli can capture attention (e.g., Yantis, 1993; Theeuwes et al., 1999), but others conclude that features such as colour, shape, motion and luminance are able to capture attention (e.g., Johnson et al., 2001; Turatto and Galfano, 2000). Some authors propose that bottom-up attentional capture is automatic by default but can be suppressed or enhanced by top-down endogenous attentional processes. However, there is a certain degree of controversy about this issue because of the opposing ideas proposed by Theeuwes (e.g., Theeuwes et al., 2000) and by Folk (e.g., Folk and Remington, 2006). Theeuwes and colleagues suggest that attentional capture is driven solely by bottom-up saliency factors at early stages of processing (less than 200 ms) that can be overridden by top-down attentional control at later stages. Folk and colleagues propose that preattentive processing can produce attentional capture, but such capture is contingent on whether the eliciting stimulus carries a feature property consistent with the current attentional set.

Event-related potentials (ERP) research on this matter focuses on negative components in the N2 latency range to study attentional capture and selection in visual search. Negativity in this time range over frontocentral regions (anterior N2) has been related to cognitive control (response inhibition, response conflict and error monitoring) and perceptual novelty (see Folstein and Van Petten, 2008, for a review). N2 components with a posterior scalp distribution (posterior N2, or N2p) have been linked to target processing in different visual attention paradigms. Studies using discrimination tasks reported that the posterior N2 is sensitive to different task-relevant visual features, including orientation, colour, size and spatial frequency (Aine and Harter, 1986; Harter and Guido, 1980; O'Donnell et al., 1997). N2p has been associated with target detection effects (Potts and Tucker, 2001) and the difficulty of visual discrimination processes (Senkowski and Herrmann, 2002). Enhanced N2p

components have been also found in visual search paradigms related with target stimulus classification (N2pb, Luck and Hillyard, 1994a), and in oddball visual tasks (Potts et al., 1996).

However, the ERP component most closely related to attentional engagement by singleton stimuli in visual search tasks is N2pc (N2 posterior contralateral). It was first described by Hillyard, Luck and colleagues (Luck et al., 1990; Heinze et al., 1990), and it was named to denote its N2 latency range (between 175 and 300 ms post-stimulus), its posterior scalp distribution, and its contralateral topography relative to the location of the target (Luck and Hillyard, 1994a,b). N2pc has been recorded for target stimuli and also for non-target stimuli that require careful scrutiny to be distinguished from the targets, but it has been reported to be absent for non-target stimuli that can be rejected on the basis of preattentive feature information, and when distractors are absent (Luck and Hillyard, 1994b).

The characteristics of N2pc indicate that it reflects the selection of the target item and/or the suppression of irrelevant and competing distractor items (Eimer, 1996; Luck and Hillyard, 1994b; Woodman and Luck, 2003). Moreover, the N2pc component has been related to attentional modulations of single-unit neuron activity observed in monkeys performing visual search tasks (Desimone, 1998; Luck et al., 1997). Magnetoencephalographic studies indicate that N2pc reflects neural activity in the parietal and occipito-temporal visual areas (Hopf et al., 2000, 2002). Recently, it has been suggested that the parietal component is associated with spatially specific processing of stimulus features at task-relevant locations and that the occipito-temporal component is related to the target selection process (Kiss et al., 2008a).

The issue about the ability of salient singletons to capture attention in a purely bottom-up fashion when they are irrelevant to the task is still not resolved and it is studied using N2pc as an index of the allocation of attention. In a seminal study in this field, Luck and Hillyard (1994a) presented four types of arrays: 50% were homogeneous arrays, composed of eight vertical blue small bars; on the remaining trials, one of the bars was horizontal ($p = 0.17$), green ($p = 0.17$) or large ($p = 0.17$), and clearly popped out from the array; one of the three pop-out arrays was designated as target at the beginning of each trial block. The authors reported that pop-out stimuli captured attention, as reflected by the presence of N2pc, even when they were not relevant to the task. However, they found that capture did not occur in another task in which pop-out detection was not required (subjects had to respond to the colour of the array, whereas pop-out stimuli were defined by orientation). Girelli and Luck (1997) found that motion singletons captured attention whether they were targets or non-targets, whereas colour and orientation singletons only captured attention when they were targets. More recently, Hickey et al. (2006) proposed that exogenous attentional capture could be evoked by salient stimuli, defined by colour, which were irrelevant to the task. However, Schubö et al. (2007) failed to find capture by irrelevant colour and orientation singletons. Several recent studies have shown that only singletons that share attributes with targets elicit N2pc, leading some authors to propose, in

agreement with Folk et al. (1992), that attentional capture is determined by task set (Eimer and Kiss, 2008; Kiss et al., 2008b).

However, besides the shared attributes between distractor and target, there are other factors related to the demands of the task that could partly explain why some studies but not others demonstrate attentional capture by distractors that do not share physical attributes with the target. The present study focuses on the influence of experimental designs in which the role of a singleton as target or distractor is changed among conditions across the same task, such as in the classical studies of Luck and colleagues.

It is known that switching between tasks that overlap in perceptual and response characteristics has “switch costs” and “mixing costs” even when there is sufficient time to prepare for a new task (Meiran et al., 2000; Reynolds et al., 2006). These costs have been reported to be reflected by N2pc characteristics, thus indicating that the selection of targets among distractors is affected: Ruge et al. (2006), using a paradigm in which each trial contained a target and a distractor, reported that the latency of the N2pc elicited by target stimuli was elongated when the item designated as target varied from trial to trial (mixed block condition), compared with the pure block condition, where the targets were the same across the block. The increased demands on working memory exerted by the mixed blocks compared with pure blocks have been suggested to explain switch and mixing costs. Another explanation, the “intraselection” account, suggests that set mixing directly affects target selection because currently irrelevant stimuli have served as targets in preceding trials, making them more difficult to ignore than in pure blocks, and targets have served as distractors in preceding trials, making them less salient than in pure blocks (Ruge et al., 2006).

Thus, it is possible that the discrepancies among studies assessing the ability of certain features to elicit attentional capture when irrelevant may be related to the experimental design. Some singleton distractors could be rejected, as Luck and Hillyard (1994b) proposed, on the basis of preattentive feature information when they are completely irrelevant, but could capture attention in task contexts that confer them some significance.

The present study aimed to ascertain the task conditions in which singleton stimuli defined by colour and orientation features automatically capture attention. With this aim, N2pc was assessed during feature visual search under different conditions. The task was based on those described by Luck and Hillyard (1994a). The stimuli consisted of arrays of eight bars defined by colour and orientation. Each block contained three types of array randomly presented (homogeneous, orientation singleton and colour singleton).

Two experiments were conducted to vary the general conditions in which the singleton stimuli appear. In Experiment 1, a mixed task condition was used. One of the two types of singleton was designated as the target at the beginning of each block, with each type of singleton serving as a target in part of the blocks and as non-target in the others. It would be expected that singleton targets, both defined by colour and orientation, might elicit N2pc. With regard to singleton non-targets, they would elicit N2pc if, despite irrelevant, they engage attention.

However, the presence of N2pc to singleton non-targets at this experiment would not allow us to conclude that they capture attention because of their salience, in a pure bottom-up fashion. As it was said above, this capture could be related to the attentional set or the working memory demands derived from the change of the role of the singletons from target to non-target across the task.

To test this hypothesis, Experiment 2 was designed as a pure task condition, where only one type of singleton (colour or orientation) was defined as target for each group of participants, and the other type of singleton was completely irrelevant across the whole task. If N2pc is elicited by non-target singletons in the two Experiments, it might be concluded that they capture attention in a bottom-up fashion. Conversely, if this ERP component is present to non-targets in Experiment 1 but absent in Experiment 2, it might be concluded that their access to the strength of attention is associated to top-down processes determined by the task context.

In sum, this study must enable evaluation of whether or not the N2pc component is elicited (1) by colour and orientation features, (2) by targets and non-targets, and (3) in a pure and in a mixed task. It would be expected that singleton targets, both defined by colour and orientation, might elicit N2pc in the pure and mixed tasks. With regard to singleton non-targets, if the capture by distractor singletons is determined by the task context, it would be expected that N2pc might be present in the mixed task, but absent in the pure task.

2. Methods

2.1. Subjects

There were initially 24 participants in Experiment 1. However, four of them were rejected because they were unable to keep their gaze fixed on the central point, and another one because of excessive artefacts in the electroencephalographic (EEG) record. Thus, a total of 19 subjects (12 females), aged 18–29 years (mean 21 years), ultimately participated in the experiment.

Of an initial—24 participants in Experiment 2, two were rejected because of artefacts in the EEG. Thus 22 subjects (11 females), aged 18–28 years (mean 20 years), finally participated in the experiment.

All participants were right-handed, with reported normal or corrected-to-normal vision and normal colour vision, and had no history of neurological or psychiatric disorders. All were volunteers; they were paid for their participation and gave written informed consent.

2.2. Stimuli and procedure

Participants had to perform a visual search task. They had to fix their gaze on a white cross at the centre of a CRT monitor with a black background, placed 100 cm in front of their eyes. The trial arrays contained eight bars ($0.3 \times 0.9^\circ$ visual angle) placed at random locations within an imaginary rectangle ($9.2 \times 6.9^\circ$), with the only restriction being that the same number of items was displayed on the left and right visual hemifields. Trials had a duration of 750 ms, with an intertrial interval (offset-onset) of 600–900 ms. The orientation of the bars (horizontal or vertical) and their colour (green or blue) depended on the condition. The stimuli were presented in blocks, each containing 200 trials.

There were three types of trials (Fig. 1) randomly intermixed in each block with a different probability of appearing: homogeneous trials ($p = 0.6$), consisting of eight vertical bars of the same colour (green for half of the subjects, blue for the other half); colour-singleton trials ($p = 0.2$), consisting of seven vertical bars of the standard colour, and one vertical bar of a different colour (blue for half of the subjects, green for the other), and orientation-singleton trials ($p = 0.2$), comprising one horizontal and seven vertical bars, of the same colour as the homogeneous arrays. The blue and green stimuli were isoluminant, and the singleton bars appeared with equal probability in the right and left visual hemifields.

Figure 1

There were two main target conditions: In the “Colour target condition” the trials with a colour-singleton bar were designated as targets, and required a specific response, and those with an orientation-singleton bar acted as distractors; the opposite occurred in the “Orientation target condition”. Subjects had to press one of two buttons with one hand in response to the target, and the other button with the other hand when the target was absent; the hand of response was balanced across subjects. Both speed and accuracy were demanded.

Experiment 1 included a third condition (“Conjunction target condition”), in independent blocks, composed of homogeneous trials ($p = 0.8$) and conjunction singleton trials ($p = 0.2$), consisting of seven vertical bars of the standard colour, and one horizontal bar of a different colour (blue for half of the subjects, green for the other); the conjunction singleton trials were defined as targets, and required a specific response. Note that this condition only included homogeneous and singleton target trials, without presence of singleton distractor trials. This condition was not included in the main analysis and discussion because it is out of the focus of the present study; however, the results will be briefly described.

In Experiment 1 (mixed task), each subject undertook nine blocks of trials, randomly intermixed, per condition. At the beginning of each block, subjects received instructions indicating which feature was the target. In Experiment 2 (pure task), half of the subjects undertook the “Colour target condition” (nine blocks) and the other half executed the “Orientation target condition” (nine blocks).

2.3. ERP recording and data analysis

EEG (analog bandpass filter 0.05–100 Hz, digitalization rate 500 Hz) was recorded at 30 active electrodes (Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FC3, FCz, FC4, T3, C3, Cz, C4, T4, CP3, CPz, CP4, T5, P3, Pz, P4, T6, PO3, PO4, POZ, O1, Oz, O2), referenced to a nasal electrode and grounded with an electrode at the nasion. Vertical and horizontal eye movements were recorded bipolarly from above and below the left eye and from the outer canthi of both eyes. Impedances were kept below 10 k Ω . The EEG and EOG were filtered digitally off-line with a 0.1–30 Hz bandpass filter and epoched from 100 ms pre-stimulus to 900 ms post-stimulus. Eyeblink artefacts were corrected (Semlitsch et al., 1986), and epochs with ocular movements, muscular artefacts and response errors were rejected. The epochs were averaged separately for each type of trial and, in the case of singleton trials, according to the visual hemifield of appearance (homogeneous, right colour singleton, left colour singleton, right orientation singleton and left orientation singleton). The amplitude of the ERP recordings in a 200–275 ms post-stimulus time window was quantified as the mean voltage at this window relative to the mean voltage of the baseline period (100-msec pre-stimulus interval). Only ERPs to singleton-present trials were analysed.

Repeated-measures and mixed-model analyses of variance (ANOVA) were used for the statistical tests. Significance levels were determined with the required number of degrees of freedom, after applying the Greenhouse–Geisser correction when appropriate. Post-hoc comparisons were performed by use of the Bonferroni adjustment for multiple comparisons.

Preliminary statistical analyses were performed to verify the findings from the visual inspection of the recordings, and showed that: (1) the mean amplitude at the selected interval was larger at posterior than anterior scalp regions, and (2) there were no significant differences between hemispheres or laterality by hemisphere interactions. Therefore, only the posterior lateral electrodes (T5, T6, P3, P4, PO3, PO4, O1, O2) were analysed, and the right and left hemispheres were collapsed to study the laterality effects. The data were analysed using a repeated-measures ANOVA in a $2 \times 2 \times 2 \times 4$ design with the factors Target Condition (colour target, orientation target), Trial Type (target singleton, non-target singleton), Laterality (singleton ipsilateral and contralateral to the hemisphere of recording), and Region (temporal, parietal, parietooccipital, occipital). All of these factors were within-subject factors except Target Condition in Experiment 2, which was a between-subjects factor.

Behavioural performance was analysed using the percentage of correct responses and the reaction time (RT) to the correct responses as dependent variables. After preliminary t-tests verifying that there were no differences in RT or accuracy as a function of the hemifield of appearance of the singleton, a repeated-measures ANOVA was used on the data from Experiment 1, with the within-subject factors Target Condition (colour target, orientation target) and Trial type (target singleton, non-target singleton, homogeneous). In Experiment 2, a similar analysis was used, but with Target Condition as a between-subjects factor.

3. Results

3.1. Behavioural performance

3.1.1. Experiment 1

The Target Condition factor was significant, showing that RT were shorter [$F(1,18) = 104.341, p < 0.0005$] in the colour target condition (398.8 ms) than in the orientation target condition (439.05 ms). There were also significant differences in the RT among the three types of trials [$F(2,36) = 199.948, p < 0.0005$], with faster responses to the homogeneous trials (385.5 ms), intermediate responses to the non-target singletons (398.19 ms) and slower responses to the target singletons (473.16 ms) ($p < 0.05$ for all the post-hoc pair comparisons). The finding that RTs to targets were delayed relative to non-targets is not surprising, as “target-present” responses were only required in 20% of all trials. Finally, there was a significant Target Condition by Trial Type interaction in the RT [$F(2,36) = 23.457, p < 0.0005$]. To further explore this interaction, separate analyses of each of the conditions were conducted. These showed that the differences in the RT among the three types of stimulus (shorter to the homogeneous, intermediate to the non-target singletons and slower to the target singletons) were

significant in the two Target Conditions (with $p < 0.05$ for all the post-hoc pair comparisons between type of trials).

There were no significant differences in the Accuracy between the colour target and the orientation target conditions. A significant effect of Trial Type [$F(2,36) = 45.959$, $p < 0.0005$] revealed that the accuracy was lower for targets (85.3%), intermediate for non-target singletons (98.1%) and higher for homogeneous trials (98.6%) ($p < 0.05$ for all the post-hoc pair comparisons).

3.1.2. Experiment 2

In this experiment, where each subject only had to detect one type of target throughout the whole session, there were no differences in RT or Accuracy between the two Target Conditions (or groups): colour target condition and orientation target condition. There were also no significant Target Condition by Trial Type interactions. Trial Type was the only factor that was significant, for both RT [$F(2,40) = 169.688$, $p < 0.0005$] and Accuracy [$F(2,40) = 28.629$, $p < 0.0005$]. RT was slower for the target trials (468.4 ms) than for the non-target (396.5 ms) and homogeneous (390.7 ms) trials (post-hoc pair comparisons $p < 0.05$). Accuracy was lower for the target (91.3%) than for the non-target singleton (98.5%) and the homogeneous (98.5%) trials (post-hoc pair comparisons $p < 0.05$).

Descriptive measures of the behavioural performance in the two experiments, are summarized in Table 1.

Table 1

3.2. ERP responses

3.2.1. Experiment 1

Fig. 2 shows the ERPs elicited by the ipsilateral and contralateral target and distractor stimuli at the parietooccipital electrodes in Experiment 1. The mean amplitude values of the ERPs in the 200–275 ms latency window are shown in Table 2.

Figure 2

Table 1

There were significant Target Condition effects [$F(1,18) = 31.959, p < 0.0005$], indicating that the amplitude of the posterior N2 (N2p) was larger for the orientation target condition than for the colour target condition. There were also significant effects of Trial Type [$F(1,18) = 52.783, p < 0.0005$], with larger N2p for target than for non-target singletons. A significant Target Condition by Trial Type interaction was also found [$F(1,18) = 13.293, p < 0.002$], thus additional analyses were conducted in order to explore this interaction.

Separate analyses for each Target Condition (Trial Type \times Laterality \times Region) indicated that N2p was larger for target than for non-target singletons in the two Target Conditions [colour target condition: $F(1,18) = 47.865, p < 0.0005$; orientation target condition: $F(1,18) = 48.115, p < 0.0005$]. Separate analyses for each Trial Type (Target Condition \times Laterality \times Region) indicated that the N2p elicited by the orientation target singleton was larger than that elicited by the colour target singleton [$F(1,18) = 5.912, p = 0.026$]. The Target Condition by Region interaction [$F(3,54) = 10.131, p < 0.0005, \epsilon = 0.715$] indicated that this difference was significant ($p < 0.005$) at parietooccipital and occipital sites, but not at temporal and parietal sites. When acting as a non-target, the N2p was larger for the colour non-target singleton than for the orientation non-target singleton [$F(1,18) = 56.096, p < 0.0005$]. Although the Target Condition by Region interaction was significant [$F(3,54) = 58.150, p < 0.0005, \epsilon = 0.761$], this difference was significant ($p < 0.005$) at the four electrode sites.

The presence of N2pc, the lateralised ERP component most closely related with engagement of attention, is indexed by the statistical effects involving the Laterality factor. This factor was significant [$F(1,18) = 22.850, p < 0.0005$], indicating that, as was expected, there was a larger negativity at the electrode sites contralateral to the hemifield of appearance of the singleton, thus indicating the presence of N2pc. This N2pc was similar for the two Target conditions, as indicated by the lack of a significant Target Condition by Laterality interaction.

More interestingly, the Trial Type by Laterality interaction was significant [$F(1,18) = 44.957, p < 0.0005$]. In order to further explore this interaction, separate analyses were conducted for each Trial Type (target and non-target singleton), with Target Condition, Laterality and Region as within-subject factors.

These analyses revealed that both features (colour and orientation), when targets, elicited N2pc: The Laterality factor was significant [$F(1,18) = 32.054, p < 0.0005$] with larger amplitudes at contralateral than at ipsilateral electrodes. There was no significant Target Condition by Laterality interaction, indicating that the N2pc was similar for the two types of targets. Although there was a significant Laterality by Region interaction [$F(3,54) = 9.025, p < 0.0005$], the post-hoc analyses confirmed that N2pc was significant ($p < 0.0005$) at the four scalp regions studied.

When acting as non-targets, N2pc was observed in the joint analysis of colour and orientation non-target singletons, as revealed by the Laterality main effect [$F(1,18) = 7.830$, $p = 0.012$]. However, the Target Condition by Laterality interaction, [$F(1,18) = 15.035$, $p = 0.001$] and the Laterality by Region interaction [$F(3,54) = 7.805$, $p < 0.0005$], indicated that the N2pc was larger for the orientation non-target singletons than for the colour non-target singletons. The post-hoc analyses showed that for the colour singletons acting as non-target the N2pc was only marginally present at parietooccipital ($p = 0.049$) and occipital ($p = 0.050$) regions. For the orientation non-target singletons, however, the N2pc was robust, as Laterality was significant at the four analysed regions (T5/T6: $p = 0.009$; P3/P4: $p = 0.007$; PO3/PO4: $p < 0.0005$; O1/ O2: $p = 0.001$).

Additional analyses were conducted to go further into the characterization of the N2pc elicited by non-target singletons at this experiment. The presence of this ERP component can be due to the access of the non-target singletons to the strength of attention throughout the whole task, or it can be due to their attentional processing only at the beginning of a new block, during the time needed to reset the attentional control settings towards the new target.

To test these two possibilities, the EEG epochs time-locked to the non-target singletons in the first and the second halves of each block of trials were separately averaged and then statistically compared using a repeated-measures ANOVA with the factors Block Half (first, second), Target Condition (colour target, orientation target), Laterality (ipsilateral, contralateral) and Region (temporal, parietal, parietooccipital, occipital).

The Block Half factor was not significant, and there were no first, second or third order interactions involving this factor, thus indicating that the ERP activity at this time interval was stable across the whole task.

Although there were no Block Half by Target Condition interactions, since the consistency of N2pc was different for the colour and the orientation non-target singletons, separate analyses were conducted for each Target Condition, including Block Half, Laterality and Region as factors.

For the orientation non-target singleton, Block Half was not significant; however, a significant Block Half by Laterality interaction emerged [$F(1,18) = 5.189$, $p = 0.035$], indicating that Laterality effect was larger in the first half of the blocks. However, post-hoc analyses showed that this factor was significant both in the first [$F(1,18) = 10.697$, $p < 0.0005$] and in the second [$F(1,18) = 6.701$, $p = 0.001$] halves, i.e., N2pc was elicited by orientation non-target singletons in the two halves of the task blocks.

For the colour non-target singleton, that elicited a weaker N2pc, this component was only present at the parietooccipital [$F(1,18) = 5.236, p = 0.034$] and occipital [$F(1,18) = 7.065, p = 0.016$] regions in the first half of the blocks, and it was absent in the second half.

Finally, as was said in the Methods section, Experiment 1 included a third condition (“Conjunction target condition”) composed of homogeneous and target trials (without singleton distractors), that was not in the focus of the present study. However, the results are briefly reported here. When compared with the colour target and the orientation target conditions, results indicated that the N2p amplitude was different between target conditions [$F(2,36) = 6.999, p = 0.003$], with larger amplitude in the conjunction target condition than in the colour target condition ($p = 0.023$). There were no differences between the conjunction and the orientation target conditions. The Target Condition by Laterality interaction [$F(2,36) = 18.259, p < 0.0005, \epsilon = 0.727$] indicated that contralaterality was smaller in the conjunction target condition than in the colour target condition [$F(1,18) = 16.489, p = 0.001$] and in the orientation target condition [$F(1,18) = 38.724, p < 0.0005$]. Nonetheless, the N2pc was present in the conjunction target condition [Laterality: $F(1,18) = 27.099, p < 0.005$].

3.2.2. Experiment 2

The ERPs recorded in this experiment are shown in Fig. 3. The mean amplitude values at the 200–275 ms latency window are summarised in Table 3.

Figure 3

Table 3

The general analysis showed that there were no significant differences between the two Target Conditions, which in this experiment were executed by different groups of subjects: The N2p component had similar amplitude in the colour target and the orientation target conditions. There were significant Trial Type effects [$F(1,20) = 38.638, p < 0.0005$], with larger N2p elicited by targets than by non-target singletons. There was no significant Target Condition by Trial Type interaction.

The Laterality factor was significant, indicating the presence of N2pc [$F(1,20) = 40.850, p < 0.0005$]. There was no significant Target Condition by Laterality interaction. However, there was a significant Trial Type by Laterality interaction [$F(1,20) = 56.550, p < 0.0005$]. Separate analyses for the two trial types were conducted in order to explore this interaction, revealing that the N2pc was only elicited by target singletons [Laterality: $F(1,20) = 53.693, p < 0.0005$], and it was absent for non-target singletons, where the Laterality factor was not significant.

3.2.3. Experiment 1 and Experiment 2. Non-target singleton Trial Type

The results of these two experiments indicated that target singletons elicited a robust N2pc. This component was absent to non-target singletons in the pure task (Experiment 2), but it was present in the mixed task (Experiment 1), specially for orientation non-target singletons. In order to provide more direct statistical evidence of the differences between the two experiments, complementary further analyses, comparing the non-target singletons in the both experiments were conducted.

Both colour and orientation non-target singletons were submitted to a mixed-model $2 \times 2 \times 4$ ANOVA, with Experiment as a between-subjects factor and Laterality and Region as within-subject factors. For the orientation non-target singletons there were Laterality effects [$F(1,28) = 7.356$, $p = 0.011$] and also Experiment by Laterality interactions [$F(1,28) = 7.616$, $p = 0.010$], indicating significant differences in the presence/absence of N2pc between the two experiments. As it was said above, the orientation non-target singletons elicited N2pc in the mixed task (Experiment 1) but not in the pure task (Experiment 2). This analysis confirmed that the difference between the two experiments was statistically significant. For the colour non-target singleton, there were differences between the two experiments [$F(1,28) = 9.262$, $p = 0.005$], with larger N2p in Experiment 1. There were not, however, significant Laterality effects, and there was only a trend towards an Experiment by Laterality interaction [$F(1,28) = 2.009$, $p = 0.167$], in accordance with the weak presence of N2pc in Experiment 1, and its absence in Experiment 2.

4. Discussion

In this study, two experiments were carried out with the aim of assessing the effect of the task context in which visual search is executed over the ability of relevant and irrelevant feature singletons to capture attention.

In Experiment 1, the amplitude of the negative ERPs recorded in the 200–275 ms time window at the posterior regions (N2p) was larger for the Orientation target condition than for the Colour target condition. In Experiment 2, conversely, the amplitude of the negativity was equal for both target conditions. This was true for both the target and the non-target singleton trials. The N2-like components of the ERPs are generally associated with selection and categorisation of the stimuli and it is well-known that their amplitude is directly related to the effort required to process the stimuli.

The differences between the results of the two experiments were consistent with the behavioural results, which showed that the RT was longer in the Orientation target condition than in the Colour target condition in Experiment 1, but there were no significant differences between conditions in Experiment 2.

Thus, together the N2p amplitude and RT results indicate that in Experiment 1, when the target conditions were mixed (the singleton defined as target—colour, orientation, and colour plus orientation conjunction—changed block-to-block), the selection and classification of orientation-singleton targets required more attentional processing than the identification of the colour-singleton targets. In Experiment 2, alternatively, where the subjects had to execute the same target condition across the whole task, there was a greater degree of automatisisation, allowing the identification of the orientation target singletons with less attentional resources. This leads us to conclude that in Experiment 1 the non-target singletons were not completely irrelevant, probably due to the conjunction of their salience and their changing value across the whole task (they were target in other blocks).

The ERP component that has been most closely related to the attentional selection of singleton stimuli in visual search tasks is the N2pc. This is a posterior negativity in the N2 latency range, contralateral to the location of the singleton stimuli (Luck and Hillyard, 1994a,b; Eimer, 1996; Woodman and Luck, 2003). In the two experiments reported here, the target trials, both defined by a colour singleton and by an orientation singleton, elicited this N2pc component. There were no differences in the magnitude of this component between the two singleton features.¹ However, when these singletons were not relevant to the task (they did not require a different response from that in homogeneous trials) the presence of N2pc depended on the type of feature and the context of the task. In Experiment 1, where the target conditions were mixed, the non-target orientation singletons elicited a robust N2pc, but this component was weak for the colour singletons (only significant at parietooccipital sites). In Experiment 2, where the subjects were only submitted to one of the target conditions, the contralateralisation was absent for the two types of distractor singletons.

The results of Experiment 2 indicate that none of the singleton stimuli was salient enough to engage the attentional process indicated by N2pc in a pure bottom-up manner when they were task-irrelevant. However, according to the results of Experiment 1, when the status of the stimuli as target or non-target changes across the task, the stimuli captured attention and required active processing to be

¹ In the Conjunction target condition included in Experiment 1, the “colour plus orientation” targets also elicited N2pc, which was smaller than the N2pc elicited by the colour and the orientation singleton targets. It must be taken into account that the Conjunction target condition differs to the others in that there were not trials with non-target singleton. The absence of these trials could explain the smaller N2pc found in this Conjunction target condition.

rejected as non-targets. This result suggests that the mixed task does not guarantee that the distractors were completely irrelevant.

In this mixed situation, the conditions in which a distractor singleton stimulus requires focusing of attention before being rejected appear to vary according to the defining feature. When a colour singleton was used as target, the orientation singleton acting as distractor elicited N2pc, indicating that it received further processing. However, this electrophysiological index of attentional engagement was weaker for the colour-singleton distractors among orientation-singleton targets.

These ERP results, suggestive of attentional capture by distractor singletons in mixed tasks, are supported by the behavioural results. These also indicated that singleton distractors engaged attention in the mixed task but not in the pure task. The RT to the trials with distractors (both colour and orientation singletons) in Experiment 1 was significantly slower than the RT to the homogeneous trials, whereas there were no RT differences between these two types of trials in Experiment 2. This cost to the performance of singleton distractors in Experiment 1 is also indicated by the accuracy results in the Orientation target condition, where the accuracy was lower for the distractor-present trials than for the homogeneous trials.

Previous studies have reported discrepancies in results with regard to the ability of colour-singleton distractors to elicit N2pc. Luck and Hillyard (1994a) found N2pc to colour distractors in a mixed task, but Girelli and Luck (1997) failed to find it. Using pure tasks, Hickey et al. (2006) recorded N2pc at parietooccipital sites (PO7/PO8) to colour-singleton distractors in a task requiring a shape decision. It must be noted that in our study, the contralaterality was also significant only at parietooccipital (PO3/PO4) locations. In another recent study, Schubö et al. (2007) failed to find N2pc to colour and orientation singletons when they were not attended and not task-relevant, but in their experiment the subjects were engaged in an go/no-go task that was independent of any kind of visual search.

The present results are inconsistent with the interpretation that the engagement of attention indicated by N2pc is a result of a pure bottom-up or stimulus-driven process. In this study, the colour singletons were more salient than the orientation singletons, as can be inferred by the fact that they were easier to identify, given the smaller N2p and the faster RT (and also by remarks made by the subjects). Thus, it would be expected that a colour singleton would capture attention (if any) in a bottom-up manner when acting as a distractor. Nonetheless, the N2pc was only present for distractors in the mixed task condition (Experiment 1), and not in the pure task condition. Furthermore, it was most robust for the less salient distractors (orientation singleton).

This engagement of attention should then be attributed to top-down processes associated with the current task set. One possible explanation implies a role of working memory processes. It has been

proposed that object working memory is not required when subjects search for the same target across trials within a session (as in Experiment 2), but it is needed when the target changes on each trial (Woodman and Chun, 2006). The results of the present study would suggest that object working memory can also be active, at least under certain conditions, when the target changes from block-to-block (not trial-to-trial). Perhaps because orientation singletons required more effort than colour singletons to be identified (as indicated by the larger N2p amplitude and the slower RT when the orientation singletons acted as targets in Experiment 1), they caused a more persistent working memory template, which was maintained across the whole task and activated by the irrelevant stimuli matching them, biasing attention toward them and preventing preattentive rejection. Another explanation involves the top-down attentional control settings. The mixed task condition requires changing the attentional control settings whenever the target changed. This cognitive operation would need a time during which the previous task set, in favour of the now non-target singleton, could persist in the form of attentional capture by this non-target. The statistical analysis separating the first and second halves of each block of trials tried to deal with this explanation. Although there was a significant Block Half by Laterality interaction, the presence of the N2pc to the orientation non-target singleton during the end part of the blocks indicated that the access of these stimuli to attention persisted throughout blocks. This is too much time to the previous attentional set persisted, and leads us to be inclined to the working memory interpretation. It must be noted, nevertheless, that the amplitude of the N2pc was reduced in the second half of the blocks compared to the first one. Perhaps this reduction indicates a weakening of the working memory template along the block. Working memory template is more persistent than attentional set, so it explains better the results of this experiment, but it is also transient and decays with time. This explanation could be tested in future studies by using longer blocks, which would allow to divide them into several subblocks and to analyse in more detail the N2pc modulations throughout each block.

Whether the present results are attributable to working memory or to pure attentional processes, they provide further evidence that attentional capture by singleton features is not a purely bottom-up effect, but is modulated by top-down control. Several recent studies which involve cues or distractor stimuli that may or may not share any physical attributes with the target (Eimer and Kiss, 2008; Leblanc et al., 2008; Lien et al., 2008) have provided strong evidence in support of the contingent involuntary orientation response hypothesis proposed by Folk et al. (1992). These studies mainly used pure tasks (subjects have to detect the same target across the whole task), and only cues or distractors sharing attributes with the target elicited N2pc. The present study provides evidence that singletons that do not share physical attributes with the target, and that are not salient enough to require the allocation of attention indicated by N2pc to be rejected in situations where they are completely irrelevant, can elicit capture (as indicated by the presence of N2pc) in contexts where their role

changes between target and distractor across the task. Thus, the capture is contingent to task demands beyond the shared attributes between targets and non-targets.

A limitation of the present study must be noted: Experiment 1 included a third condition (Conjunction target) that could have enhanced the status of currently irrelevant non-target singletons as target candidates. For example, if orientation served as the joint target feature together with colour in one block, it would elicit some capture in the next block where colour is the exclusive target feature. Thus, the inclusion of this third condition might be partly responsible for the differences between experiments. However, in our opinion, this does not invalidate the conclusion that the capture is contingent to task demands defined by the whole experimental set.

Another limitation of this study is that target and distractor singletons were not simultaneously present in the same trials. They did not thus compete for attentional resources in the same time period. It would be interesting if future studies could verify whether the N2pc is also absent—or attenuated—to distractor singletons that appear in the same trials as targets in pure tasks.

In summary, attentional capture by singleton stimuli in visual search tasks is a complex process in that the physical properties of the stimuli, the subjects' goals or intentions, and the context in which the search is developed, all interact. The results of the present study suggest that future studies must be cautious in attributing the engagement of attention by distractor stimuli to pure stimulus-driven processes in tasks where several conditions are mixed within blocks. The experimental tasks must be designed carefully to prevent or to assess the different factors that affect attentional capture in visual search tasks.

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Table 1. Behavioural performance in the two experiments. Reaction time (in ms) and percentage of accuracy.

Condition	Trial type	Experiment 1		Experiment 2	
		RT (S.D.)	Accuracy (S.D.)	RT (S.D.)	Accuracy (S.D.)
Colour target	Target singleton	456.2 (33.1)	85.8 (8.8)	455.2 (29.8)	92.9 (3.6)
	Non-target singleton	372.4 (27.6)	98.9 (1.6)	381.9 (36.1)	98.5 (0.9)
	Homogeneous	367.9 (27.9)	98.5 (1.2)	379.2 (37.1)	98.8 (0.4)
Orientation Target	Target singleton	490.1 (32.2)	84.8 (8.9)	481.5 (32.4)	89.6 (8.9)
	Non-target singleton	424.0 (34.0)	98.1 (1.1)	411.2 (43.5)	98.5 (1.7)
	Homogeneous	403.0 (34.2)	98.8 (0.6)	402.1 (41.0)	98.3 (1.4)

Table 2. Experiment 1. Mean amplitudes of ERPs (μV) in the 200–275 ms time window for each type of stimulus in the ipsilateral and contralateral hemispheres to the hemifield where the singleton appears.

		Colour target		Orientation target	
		Target singleton	Non target singleton	Target singleton	Non target singleton
Temporal	Ipsilateral	– 3.0 (4.1)	0.2 (3.3)	– 3.6 (3.6)	– 1.5 (3.2)
	Contralateral	– 5.0 (4.6)	– 0.5 (3.3)	– 5.5 (4.4)	– 1.8 (3.2)
Parietal	Ipsilateral	– 1.9 (4.2)	2.2 (3.1)	– 2.4 (3.2)	– 0.9 (3.0)
	Contralateral	– 3.3 (4.6)	1.7 (3.2)	– 3.8 (3.7)	– 1.2 (3.0)
Parietooccipital	Ipsilateral	– 2.7 (5.0)	0.9 (4.0)	– 3.7 (4.3)	– 1.7 (4.2)
	Contralateral	– 4.8 (5.6)	– 0.1 (4.0)	– 6.0 (4.9)	– 2.2 (4.3)
Occipital	Ipsilateral	– 3.9 (5.1)	– 0.6 (4.1)	– 5.0 (4.5)	– 2.5 (4.5)
	Contralateral	– 5.4 (5.4)	– 1.3 (4.2)	– 6.8 (4.7)	– 2.9 (4.5)

Table 3. Experiment 2. Mean amplitudes of ERPs (μV) in the 200–275 ms time window for each type of stimulus in the ipsilateral and contralateral hemispheres to the hemifield where the singleton appears.

		Colour target		Orientation target	
		Target singleton	Non target singleton	Target singleton	Non target singleton
Temporal	Ipsilateral	– 1.8 (2.8)	0.6 (3.0)	– 1.9 (2.7)	1.0 (1.8)
	Contralateral	– 3.2 (3.0)	0.7 (3.1)	– 3.9 (3.5)	1.2 (1.7)
Parietal	Ipsilateral	– 0.3 (3.3)	3.1 (2.7)	1.1 (3.2)	3.0 (2.3)
	Contralateral	– 1.7 (3.6)	3.1 (2.8)	– 0.9 (3.8)	3.0 (2.3)
Parietooccipital	Ipsilateral	– 0.8 (3.6)	2.1 (3.3)	– 0.5 (3.5)	2.3 (2.6)
	Contralateral	– 2.7 (3.6)	2.0 (3.2)	– 3.2 (4.5)	2.3 (2.6)
Occipital	Ipsilateral	– 1.8 (3.0)	0.9 (2.9)	– 3.0 (3.5)	0.7 (2.1)
	Contralateral	– 2.8 (3.0)	0.9 (2.8)	– 4.3 (3.9)	0.7 (1.9)

Figures

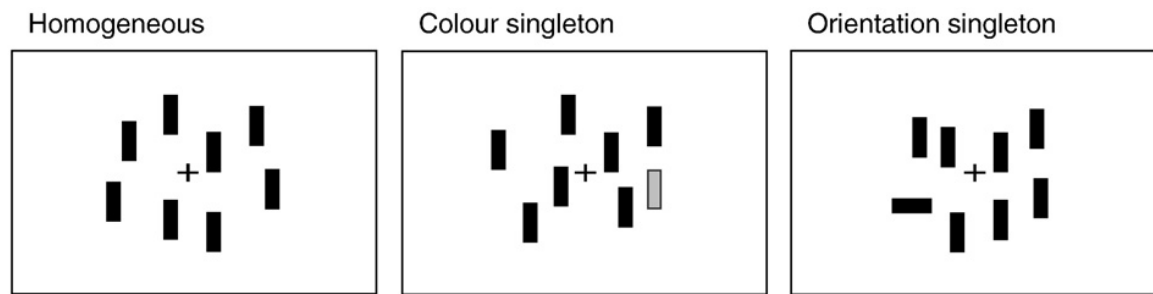


Fig. 1. Illustration of the homogeneous, colour singleton and orientation-singleton trial types. The stimulus bars ($0.3 \times 0.9^\circ$ of visual angle) were placed at random locations within an imaginary $9.2^\circ \times 6.9^\circ$ rectangle.

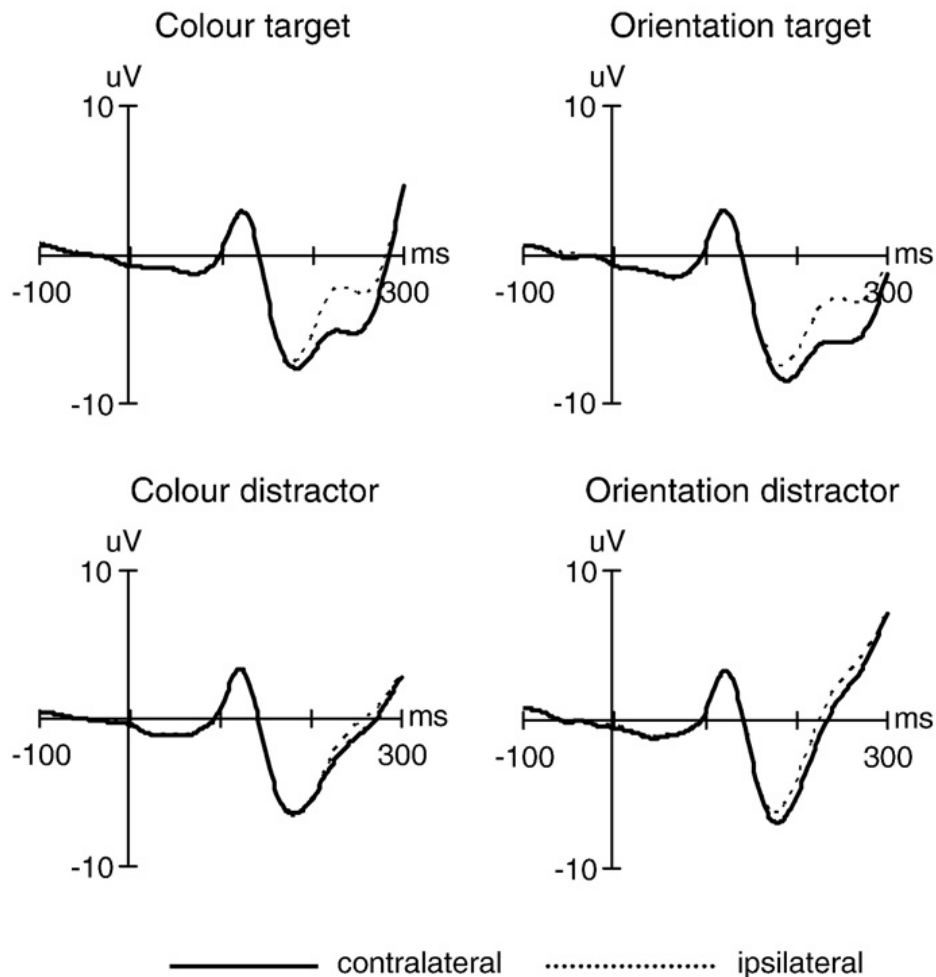


Fig. 2. Experiment 1. Grand mean event-related potentials contralateral (solid line) and ipsilateral (dashed line) to the hemifield of appearance of the singleton, for the parietooccipital (PO3/PO4) region.

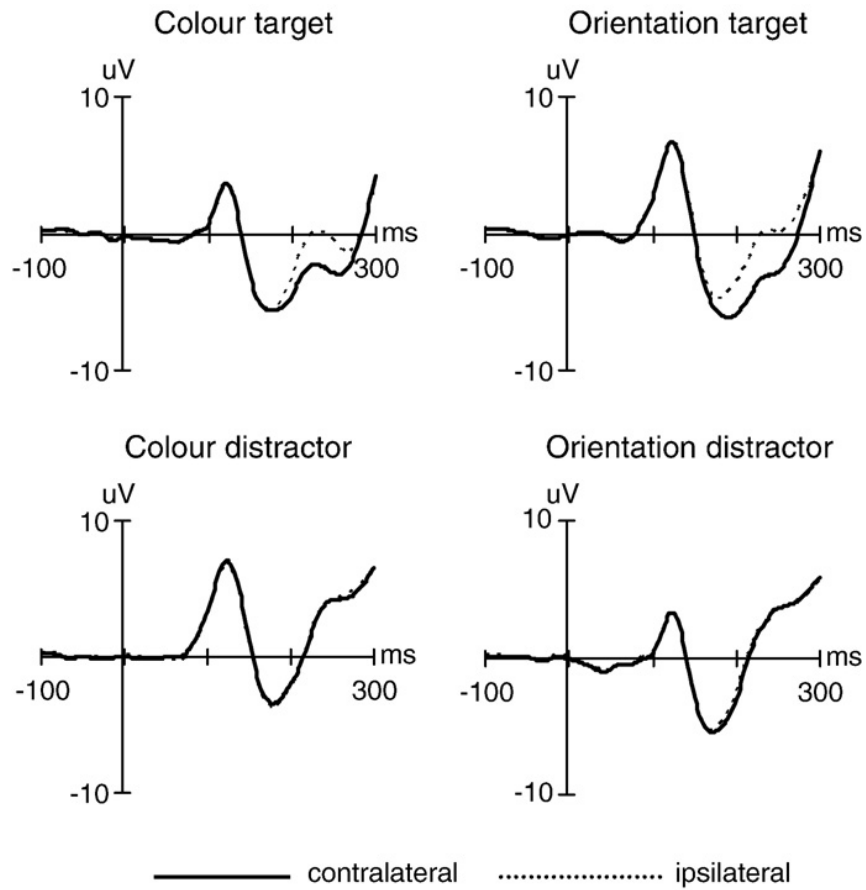


Fig. 3. Experiment 2. Grand mean event-related potentials contralateral (solid line) and ipsilateral (dashed line) to the hemifield of appearance of the singleton, for the parietooccipital (PO3/PO4) region