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Neurobiology of Aging 29 (2008) 1101–1110

NEUROBIOLOGY OF AGING

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Feature processing during visual search in normal aging: Electrophysiological evidence

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Received 20 September 2006; received in revised form 22 January 2007; accepted 5 February 2007
Available online 7 March 2007

Abstract

Event-related potentials (ERPs) were recorded from healthy young and older subjects during the execution of a visual search task in which they were required to detect the presence of a target stimulus that differed from distractors in a salient feature (orientation). Apart from the orientation target, a task-irrelevant singleton defined by a different feature (color) was also presented without instruction. The effects of normal aging on the N2pc component, an electrophysiological correlate of the allocation of visuospatial attention, were evaluated for the first time. Behavioral results showed an increase in the mean reaction time (RT) and a reduction in the hit rates with age. Electrophysiological results showed a consistent N2pc for orientation target pop-outs but not for irrelevant color pop-outs in both age groups, suggesting that the irrelevant color singleton did not induce attentional capture. Furthermore, the N2pc component observed for orientation targets was significantly delayed and attenuated in older subjects compared to young subjects, suggesting a specific impairment of the allocation of visuospatial attention with advancing age.

Keywords: Event-related potentials (ERPs); N2pc; Visual search; Pop-out; Attentional capture

1. Introduction

The visual search paradigm has been extensively used in laboratory studies to examine the basic properties of the human visual selective attention (Luck and Ford, 1998; Luck and Hillyard, 1995). In this paradigm, subjects search for a predefined target stimulus in arrays containing a variable number of distractor stimuli, and they are required to indicate whether the target is present or absent in each array of stimuli.

Several previous behavioral and neuroimaging studies of age-related cognitive changes have reported a decline in visual selective attention with age (Kok, 2000; Madden et al., 2005; Raz, 2000), suggesting that older subjects are less able to selectively focus on relevant stimuli in their environment than young subjects. In particular, there is considerable evidence in the literature that older subjects are behaviorally slower and less accurate than young subjects in tasks involving visual search, especially in difficult or complex search conditions (Hommel et al., 2004; Madden and Whiting, 2004; McDowd and Shaw, 2000). Because this age-related deficit in visual search is exacerbated as the number of distractor stimuli in the search array increases, it has been interpreted in terms of an age-related decline in the ability to ignore or inhibit the irrelevant information (Colcombe et al., 2003; Madden and Whiting, 2004). However, it is not clear whether these age differences represent a specific slowing in the allocation of attention itself, or a generalized age-related slowing of information processing (Salthouse, 1996). In order to shed new light on this unsolved issue, we focused on a specific component of the visual ERPs, the N2pc, which has been well validated as an electrophysiological correlate of the allocation of visuospatial attention to lateralized positions in the search array (Luck and Hillyard, 1994a,b; Woodman and Luck, 1999, 2003). In

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doi:10.1016/j.neurobiolaging.2007.02.007

this regard, previous electrophysiological studies of visual search in humans have revealed a posterior negative-going ERP component that appears contralateral to the visual hemifield in which the target is located, 200–300 ms after the onset of a bilateral stimulus array (Eimer, 1996; Luck and Hillyard, 1994a,b; Woodman and Luck, 1999). This component was first described as the N2pc (N2-posterior-contralateral) to indicate its polarity, latency range, and scalp distribution (Luck and Hillyard, 1994a), and it has been observed for different visual attributes (color, form, motion, words) in the search array (Eimer, 1996; Girelli and Luck, 1997; Hirai and Hiraki, 2006; Luck and Hillyard, 1994a,b). The question of what specific attentional process is reflected by the N2pc component has been a point of debate in the literature. Since N2pc was absent when the target was presented without distractors, it was initially conceived as a correlate of an attentional selection process suppressing interference from such distractors (Girelli and Luck, 1997; Luck et al., 1997; Luck and Hillyard, 1994a,b). More recently, N2pc has been interpreted as an electrophysiological index of visuospatial shifts of attention to the location of the potential target (Eimer, 1996; Luck et al., 1997; Woodman and Luck, 1999, 2003).

Research has shown that searching for a stimulus in a visual array modulates neural activity in the extrastriate visual cortex. Specifically, several early ERP studies employing current source density analyses have shown that the search-related N2pc component has a posterior scalp distribution, focused over the lateral occipito-temporal cortex (Girelli and Luck, 1997; Luck and Hillyard, 1994a,b). Recent magnetoencephalographic (MEG) studies have provided evidence that the magnetic counterpart of the N2pc, known as the mN2pc, consists of early neural activity (180–200 ms) arising from posterior parietal cortex related to the initiation of an attentional shift, and slightly later activity (220–240 ms) localized in lateral occipito-temporal cortex related to the implementation of visual attentional selection (Hopf et al., 2000, 2002, 2004).

To our knowledge, no studies have been published which explore the effects of normal aging on the amplitude and time course of the N2pc component. In previous research, the latency of this component has proved to be a precise measure of rapid shifts of attention to possible targets during visual search tasks (Luck et al., 2000; Woodman and Luck, 1999, 2003). In this regard, measuring this parameter makes it possible to explore the effects of aging on the speed with which visuospatial attention can be shifted to a target stimulus. Thus, if normal aging involves a slowing in the allocation of attention itself, then the N2pc latency should be delayed in older relative to young subjects. Furthermore, the N2pc amplitude has been considered as a measure of attentional focusing during visual search, reflecting the amount of attention allocated to a stimulus (Luck et al., 1997). Thus, if normal aging implies a deficit in focusing attention, then a decrease in the N2pc amplitude should be observed in the older subjects.

We were also interested in determining whether salient but task-irrelevant color singletons capture attention in the absence of a previously developed intention to attend to this singleton. To this end, we employed an 'additional singleton paradigm' in which an irrelevant color singleton was presented in separate trials without prior announcement, while the subjects searched for a target defined by its orientation. In this context, the appearance of the N2pc component was considered as a mean to determine whether attention is captured by this irrelevant color singleton. If attention is attracted towards the location of this color singleton in the search array, then a negative-going ERP component should be elicited over the contralateral visual cortex (the N2pc) and the performance in the orientation search should be slowed in arrays containing a color singleton. In this regard, several studies have shown that the presence of an irrelevant stimulus that pops-out from their surroundings can automatically attract attention to its spatial location (Bacon and Egeth, 1994; Theeuwes, 1991, 1992, 1994). This attentional capture can speed performance if the pop-out stimulus is the target or slow performance if it is a distractor (for a recent review, see Ruz and Lupiáñez, 2002).

Because some previous studies have pointed out the possibility that attentional capture rapidly habituates to the repeated presentation of an irrelevant nontarget pop-out (Gibson and Jiang, 1998; Warner et al., 1990), we also explored this question. In this regard, it is possible that an attentional capture (e.g., reflected by the presence of the N2pc component) occurs only at the onset of the experimental session (Horstmann, 2002), with the repeated stimulus presentation along the trial blocks resulting in a reduction or disappearance of the N2pc. Thus, if a consistent N2pc is observed only during the initial trial blocks, then it can be concluded that color irrelevant nontargets become less able to attract attention to its location with practice.

We also examined the question of whether healthy older subjects would be more susceptible than young subjects to the possible attentional capture by these irrelevant color nontargets. In this regard, the literature provides evidence in support of the notion of greater susceptibility of older subjects to distraction by irrelevant singletons, which has been interpreted as an age-related decline in the ability to maintain an inhibitory set (Colcombe et al., 2003; Greenwood and Parasuraman, 2004; Kramer et al., 2000).

2. Methods

2.1. Participants

Seventeen young (10 females, 19.6 ± 1.9 years, range 18–24) and 22 older subjects (11 females, age 68.5 ± 6 years, range 60–84) were tested. All were healthy well-functioning subjects without a history of neurological or psychiatric disorder, had normal or corrected-to-normal visual acuity, and reported normal color vision. None of the older subjects had

received a diagnosis of glaucoma or cataracts, and they performed the Mini-Mental State Exam (MMSE) (Folstein et al., 1975) showing normal scores (>28). Informed consent was obtained from all subjects and they were paid for their participation in the experiment.

2.2. Stimuli and experimental procedure

Recordings were made in an electrically shielded and sound attenuated room. Subjects sat in a comfortable armchair at 100 cm viewing distance from a computer screen with a black background and a continuously visible fixation white cross. Subjects were instructed to maintain central fixation on this cross while they performed a visual search task consisting in detecting a singleton target stimulus presented among an array of distractors (experimental task based on Luck and Hillyard, 1994a). On each trial, a multi-element search array was presented composed of eight bars subtending a visual angle of $0.3^\circ \times 0.9^\circ$, which were located at random positions within an imaginary rectangle of $9.2^\circ \times 6.9^\circ$ of visual angle around fixation cross. There were always four bars in each hemifield. Three types of search arrays were randomly presented: homogeneous arrays, arrays containing a singleton pop-out target defined by orientation, and arrays containing a singleton pop-out nontarget (i.e., an irrelevant distractor singleton that was deviant from the target in a different feature dimension as color). Homogeneous arrays ($p = 0.6$) consisted of eight blue-horizontal (RGB 0,0,255) identical bars. Target arrays ($p = 0.2$) consisted of seven blue-horizontal bars and one blue-vertical bar. Nontarget arrays ($p = 0.2$) consisted of seven blue-horizontal bars and one red-horizontal (RGB 255,0,0) bar. The pop-out stimuli (both target and nontarget) were equally likely to appear in the right or left visual hemifield and their location was unpredictable. Each search array was presented for 750 ms, followed by a variable intertrial interval of 900–1100 ms during which only fixation cross was present. The same feature (orientation) defined the target across all trials and the subjects were not informed about the appearance of the irrelevant color singleton. All the stimuli and search arrays were created, presented, and controlled using the Presentation software application (Neurobehavioral Systems, Inc., Version 0.76). The experimental session was divided into six blocks of trials, and several training trials were run before testing to ensure a good level of performance in both age groups. Each block consisted of at least 10 orientation pop-out arrays and at least 10 color pop-out arrays presented to each hemifield, and at least 80 homogeneous arrays, to a maximum of 250 arrays in total. The task of the subjects was to indicate as rapidly and accurately as possible whether the target stimulus (a vertical bar) was present or absent in each search array, pressing a button with one hand for target-present trials and another button with the other hand for target-absent trials. Thus, the nontarget arrays required the same response as the homogeneous arrays. Response buttons were counterbalanced across subjects.

2.3. ERP recordings

The electroencephalogram (EEG) was recorded with a NeuroScan system using scalp electrocaps (ECI, Inc.) with electrodes placed at FP1, FP2, FPz, Fz, Cz, Pz, POz, Oz, F7, F8, F3, F4, C3, C4, T3, T4, PO3, PO4, FCz, CPz, CP3, CP4, T5, T6, P3, P4, FC3, FC4, O1 and O2 (10/20 International System). All the active electrodes were referred to the nosetip and grounded with an electrode placed at nasion. Vertical and horizontal electrooculogram (EOG) activities were recorded bipolarly from above and below the left eye and from the outer canthi of both eyes. Electrode impedance was kept below 10 kΩ. The EEG signals were continuously amplified (10 K) and digitized at a rate of 500 Hz/channel, and filtered on-line with a band pass of 0.05–100 Hz.

2.4. Data analysis

Reaction times (RTs) were on-line recorded for all subjects to the three types of search arrays in all experimental blocks. Only RT values associated with correct responses were considered for data analyses. Hit rates were calculated as the percentage of correct responses with RTs no longer than 1100 ms. Mean correct RTs were then compared across groups using a mixed design analysis of variance (ANOVA) with age (young, older) as the between-subjects factor and search array (homogeneous, target pop-out, nontarget pop-out) as the within-subject factor. Hit rates were also compared across groups using one-way ANOVA with age (young, older) as the between-subjects factor.

All EEG data were analyzed using NeuroScan software (Version 4.1). The EEG was digitally filtered off-line with a 0.1–30 Hz bandpass filter, and was averaged for epochs of 500 ms post-stimulus and 100 ms pre-stimulus. Epochs exceeding ±100 μV and those containing blinks, and horizontal or vertical eye movements were rejected and excluded from averaging, as well as epochs associated with incorrect or no responses. EEG was averaged separately for target and nontarget pop-outs occurring in the right visual field (RVF) and in the left visual field (LVF) and for homogeneous arrays, resulting in five waveforms for each participant. This procedure makes it possible to investigate the ERP modulations depending on the array type. Because the N2pc component is defined as a more negative response for contralateral stimulus than for ipsilateral stimulus, the N2pc was not measured for homogeneous arrays.

Since this study focused on the N2pc component, analyses were confined to posterior electrode locations. Thus, mean amplitude values of N2 posterior component were measured at P3/P4, PO3/PO4, O1/O2 and T5/T6 sites in each subject. The latency window in which the N2 mean amplitude was measured was determined considering the interval where the component appeared in the corresponding grand mean waveforms of both age groups. Since these average waveforms revealed a longer N2 duration in older subjects than in young subjects, individual averages were visually inspected in order

to discard that it was due to longer older individual variability. This inspection showed a similar individual effect for both young and older subjects. Thus, in young subjects, N2 was measured as the mean amplitude from 200 to 275 ms, relative to a 100 ms pre-stimulus baseline, and in older subjects it was measured from 210 to 375 ms. These data were entered into an initial overall mixed model ANOVA in which age (young, older) was entered as the between-subjects factor. The within-subject factors were array type (target, nontarget pop-out), electrode location (parietal, parieto-occipital, occipital, temporal), hemisphere (left or right hemisphere electrode site), and laterality (ipsilateral or contralateral relative to the electrode location). Separate ANOVAs were also performed for each search array, with age as the between-subjects factor, and electrode location, hemisphere, and laterality as the within-subject factors.

To isolate the N2pc from overlapping bilateral ERP components unrelated to shifts of attention, difference waveforms were calculated in both age groups by subtracting the ERPs for arrays containing an ipsilateral target (relative to the electrode location) from those for arrays containing a contralateral target (for detailed justifications of this approach, see Girelli and Luck, 1997; Luck and Hillyard, 1994a). Specifically, for left-hemisphere electrode sites, the waveforms elicited by a target in the LVF were subtracted from those elicited by a target in the RVF, and for right-hemisphere electrode sites, the waveforms elicited by a target in the RVF were subtracted from those elicited by a target in the LVF. In the resulting waveforms, the amplitude of the N2pc component was quantified as the mean voltage, and the N2pc peak latency as the time point of the maximum peak, within the previously mentioned latency windows in each age group. In order to test the effects of age on N2pc amplitude and latency values, these data were entered into mixed model ANOVAs with age (young, older) as the between-subjects factor, and electrode location (parietal, parieto-occipital, occipital, temporal) as the within-subject factor.

To examine the possible changes in the scalp distribution of N2pc amplitude among groups, voltage maps were also computed with EEGLAB program (Delorme and Makeig, 2004) in each group of subjects separately. This program plots topographic maps of EEG fields as a 2D circular view derived from cointerpolation of voltage values between scalp electrodes. The maps were created from the difference waveforms, using the time point of the maximum N2pc peak indicated by the previous ANOVAs.

To explore the possible effects of practice on attentional capture by the irrelevant color singleton, the six experimental blocks were grouped in three consecutive blocks: an initial block (A) composed by blocks 1 and 2, an intermediate block (B) composed by blocks 3 and 4, and a final block (C) composed by blocks 5 and 6. Then, separate ERP averages were computed for color nontarget pop-outs occurring in each consecutive block. Mean amplitude values of N2 posterior component were then measured and entered into a mixed model ANOVA in which age (young, older) was entered as the between-subjects factor. The within-subject factors were electrode location (parietal, parieto-occipital, occipital, temporal), hemisphere (left or right hemisphere electrode site), laterality (ipsilateral or contralateral relative to the electrode location), and block (block A, block B, block C). An alpha level of 0.05 was used for all statistical tests. Whenever appropriate, degrees of freedom were corrected by the conservative Greenhouse–Geisser estimate. When necessary, post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons.

3. Results

3.1. Behavioral results

Mean RTs are summarized in Table 1. There was a significant main effect of age on mean RTs ($F(1,37) = 26.70$, $p < 0.0001$), with slower RTs in the older group (young: 473 ± 53 ms; older: 600.5 ± 99 ms). The effect of the array type on mean RTs was also significant ($F(2,74) = 46.81$, $p < 0.0001$, $\varepsilon = 0.551$), showing that RTs were slowest for the orientation targets, intermediate for the color nontargets, and fastest for the homogeneous arrays (see Table 1). Pairwise comparisons (Bonferroni) revealed that the mean RT for orientation targets, color nontargets, and homogeneous arrays were all significantly different from each other ($p < 0.0001$).

A significant main effect of age was also observed on hit rates ($F(1,37) = 4.92$, $p < 0.033$; young: $98 \pm 2\%$; older: $91.2 \pm 12.5\%$), revealing a lower performance level for the older subjects in the search task.

3.2. Electrophysiological results

In the initial overall ANOVA where both array types (orientation target, color nontarget) were included, a significant interaction between electrode location and array type ($F(3,111) = 10.55$, $p < 0.0001$) revealed that the distribution of voltage over the scalp was significantly different for target and nontarget arrays, suggesting different attentional mechanisms. In addition, a significant main effect of laterality ($F(1,37) = 85.72$, $p < 0.0001$) was accompanied by a significant interaction between laterality and array type ($F(1,37) = 98.21$, $p < 0.0001$). Thus, to further explore these significant interactions, separate ANOVAs were conducted for each array type.

Grand average ERP waveforms obtained for arrays containing an orientation target are shown in Fig. 1 for the parietal, parieto-occipital, occipital and posterior temporal

Table 1
Mean RTs (mean ± S.D.) as a function of array type in young and older subjects

	Homogeneous	Orientation targets	Color nontargets
Young	448.2 ± 56	507.6 ± 51.4	463.1 ± 57.7
Older	581.7 ± 96	628.9 ± 88.4	590.8 ± 95.8

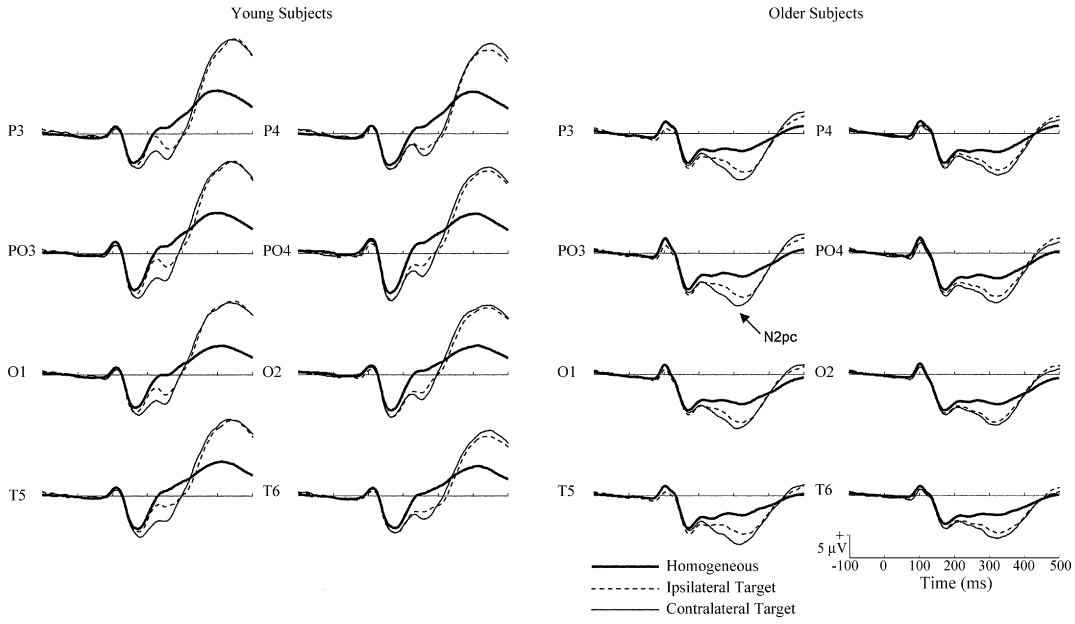

Fig. 1. Grand average ERPs elicited in response to arrays containing an orientation target in the contralateral (solid lines) or ipsilateral (dashed lines) visual field to electrode locations. Also included are ERPs elicited in response to homogeneous arrays (thick solid lines). The ERPs obtained from left and right posterior electrodes are displayed separately. The N2pc component (indicated by an arrow) is visible as a more negative response for the contralateral waveform relative to the ipsilateral waveform in the N2 latency range.

electrode sites. Separate waveforms are depicted for contralateral and ipsilateral targets relative to the hemisphere of the recording electrode. Also included are waveforms for homogeneous arrays. As shown in the figure, for both the young and older subjects, the N2pc component was visible as an enhanced negativity in the N2 time range contralateral to the location of the orientation target (i.e., contralateral to the attended visual hemifield). Consistent with the waveforms, ANOVA conducted for target arrays reflected the presence of this N2pc component by significant main effects of laterality ($F(1,37) = 108.64$, $p < 0.0001$) and electrode location ($F(3,111) = 8.72$, $p < 0.0001$, $\varepsilon = 0.712$).

As stated in Section 2, to isolate the N2pc from other overlapping components, difference waveforms were calculated by subtracting the ERPs for arrays containing an ipsilateral target from those for arrays containing a contralateral target (see Fig. 2). The figure illustrates the magnitude and time course of the N2pc component as a function of age. ANOVA tests conducted on these difference waveforms revealed that the N2pc peak latency was significantly delayed in older subjects compared to young subjects ($F(1,37) = 91.63$, $p < 0.0001$; young: 240.9 ± 18.3 ms; older: 308.3 ± 24.1 ms), suggesting that older subjects shifted visuospatial attention to the targets more slowly than young subjects. Analyses also showed that mean N2pc amplitude was significantly reduced in older subjects compared to young subjects ($F(1,37) = 8.30$, $p < 0.007$; young $-1.56 \pm 0.9\,\mu V$; older $-0.87 \pm 0.6\,\mu V$), suggesting that the older subjects allocated less resources in focusing attention to targets. A significant main effect of electrode location was also observed on N2pc mean amplitude ($F(3,111) = 15.08$, $p < 0.0001$, $\varepsilon = 0.743$) irrespective of age. Pairwise comparisons revealed that the N2pc amplitude was significantly higher at parieto-occipital electrode sites than at parietal ($p < 0.0001$) and occipital ($p < 0.0001$) sites, with no significant differences between the N2pc amplitude at parieto-occipital and temporal sites ($p = 0.115$) (see Fig. 2).

Inspection of topographic voltage maps depicted in Fig. 3 showed a largely posterior scalp distribution of N2pc component, maximal over occipital cortex irrespective of age. Note that, as in previous studies and due to the subtraction procedure, the N2pc component appears as a positive voltage over

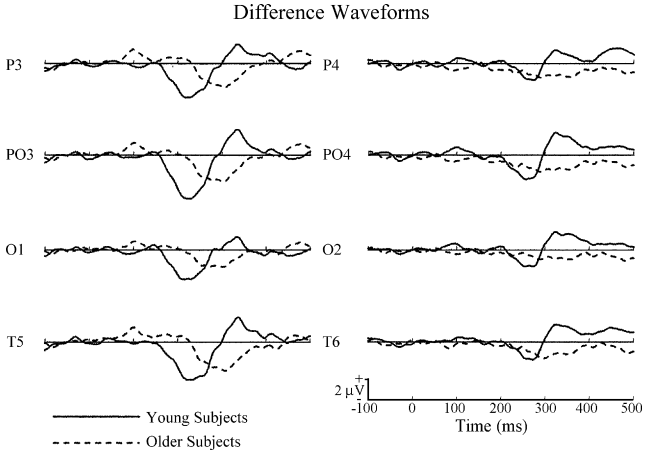

Fig. 2. Grand average ERP difference waveforms formed by subtracting the ERPs for arrays with an ipsilateral orientation target from those for arrays with a contralateral target. Superimposed are waveforms for young (solid lines) and older subjects (dashed lines). The figure shows a prominent N2pc component in young subjects that is delayed and attenuated in older subjects.

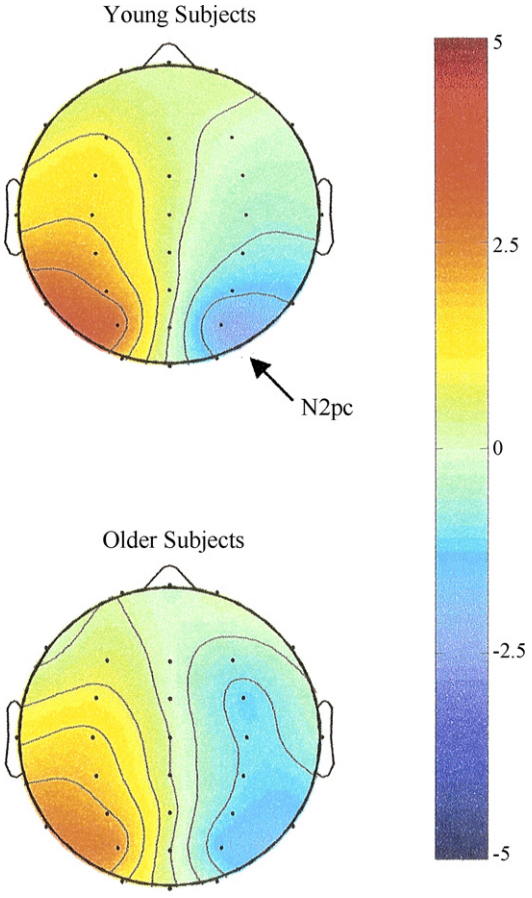

Fig. 3. Voltage topographic maps showing the amplitude distribution of N2pc in young and older subjects. The color scales depict N2pc amplitudes in μV. Note the reduction of N2pc amplitude with age.

the left hemisphere and as a negative voltage over the right hemisphere (Girelli and Luck, 1997; Hopf et al., 2000; Luck and Hillyard, 1994a). Moreover, consistent with the ANOVA results, it can be observed a marked reduction of the N2pc amplitude in older subjects.

Fig. 4 shows the grand average ERP waveforms obtained for arrays containing a color nontarget for the parietal, parieto-occipital, occipital and posterior temporal electrode sites. ANOVA conducted for nontarget arrays revealed that the difference in mean amplitude between the waveforms obtained for arrays with ipsilateral versus contralateral color singleton was not significant in the N2 latency range (laterality: $F(1,37) = 1.51$, $p = 0.227$), thus confirming the observation that irrelevant color nontargets did not evoke an N2pc component. This result suggests that the irrelevant color singleton did not produce an automatic orienting of attention to their location.

In order to further explore this issue, we compared the ERP waveforms obtained for homogeneous arrays with those obtained for target and nontarget arrays. To this end, we performed a new ANOVA in which the three array types were included. Trials with left and right visual field pop-outs were collapsed in this analysis to permit the comparison with homogeneous arrays. Grand average ERPs elicited by the three search array types are displayed in Fig. 5. The major difference between arrays was observed in the N2 latency range, during which the voltage was significantly more negative for orientation target arrays than for homogeneous and nontarget arrays. An enlarged N2 posterior amplitude for targets compared to nontargets and homogeneous arrays has been previously observed in visual search experiments (Luck and Hillyard, 1994a,b), which was termed N2b (bilateral) to contrast it from the N2pc component. It is important to note that previous components did not appear differentially affected by the array type. In addition, no attention-related components appear to be elicited by homogeneous arrays. Similarly, the waveforms showed no evidence of attentional processing of color irrelevant stimulus. In this regard, ANOVA showed a significant effect of array type on N2 amplitude ($F(2,74) = 159.53$, $p = 0.0001$, $\varepsilon = 0.516$). Pairwise comparisons confirmed that the mean amplitude of the N2 component was significantly higher for arrays containing a target pop-out than for the other two array types (nontarget: $p < 0.0001$;

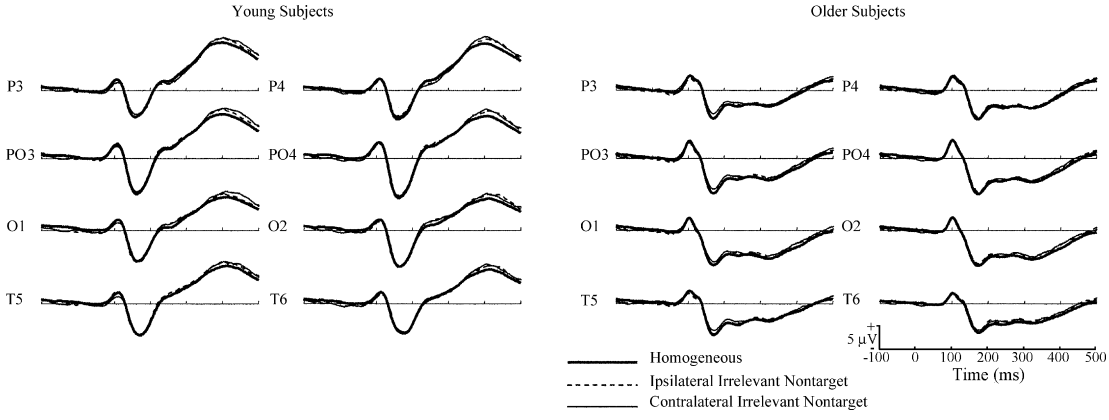

Fig. 4. Grand average ERPs elicited in response to arrays containing an irrelevant nontarget contralateral (solid lines) or ipsilateral (dashed lines) to electrode locations. Also included are ERPs elicited in response to homogeneous arrays (thick solid lines). The ERPs obtained from left and right electrodes are displayed separately. The N2pc component is absent in both age groups.

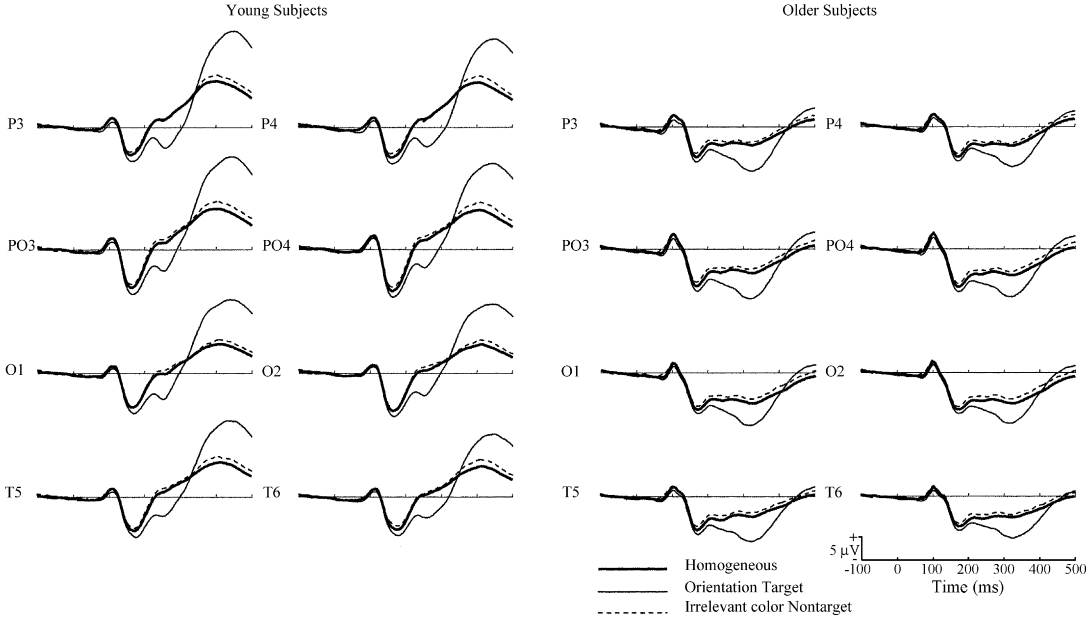

Fig. 5. Grand average ERPs for homogeneous arrays, target pop-outs and nontarget pop-outs recorded at posterior sites. ERPs from left and right visual field stimulus were collapsed.

homogeneous: $p < 0.0001$), with no significant differences in N2 amplitude between nontarget and homogeneous arrays ($p = 0.256$). These results indicated that target arrays received additional processing compared to the other two array types, and that color nontarget pop-outs and homogeneous arrays were not differentially processed in both age groups, confirming that irrelevant color singleton did not produce an attentional capture.

As described above, in order to determine the possibility that N2pc is observed only during the initial trial blocks, separate ERP averages were computed for color nontarget pop-outs occurring in three consecutive blocks. In the ANOVA test where these three blocks (block A, block B, block C) were included, the main effect of block did not reach statistical significance ($F(2,74) = 0.77$, $p = 0.463$). Similarly, the interaction between laterality and block was not significant ($F(2,74) = 0.39$, $p = 0.675$), revealing that the difference in mean amplitude between the ipsilateral and contralateral waveforms was not significant in the N2 latency range in either block. Thus, no N2pc was observed across the experimental session to nontarget pop-outs.

4. Discussion

In the present study, ERPs were recorded while young and older subjects searched for a singleton feature target defined by an orientation difference to the distractors (target pop-out). In order to evaluate the effects of normal aging on the possible deployment of attention to pop-out distractor locations, a task-irrelevant singleton stimulus defined by a different unique feature was also presented (color nontarget pop-out) without knowledge of the subjects while they performed the search task. To detect the possible attentional capture by these irrelevant color singletons, we focused on the N2pc component of visual ERP that appears to reflect brain activity specifically related to the allocation of visuospatial attention in visual search.

Mean RTs were delayed and hit rates were significantly reduced in the older group. These results are consistent with previous behavioral studies showing that older subjects are slower and less accurate than young subjects in visual search tasks (Hommel et al., 2004; Madden and Whiting, 2004; McDowd and Shaw, 2000).

Previous studies have reported that some distractor pop-out stimuli can capture attention slowing the target processing (Bacon and Egeth, 1994; Theeuwes, 1991, 1992, 1994). However, in the present experiment, the presence of an irrelevant color singleton did not increase the search times. Thus, we failed to find interference effects from a task-irrelevant color singleton on search for an orientation target. Moreover, young and older subjects were similar in their ability to ignore these irrelevant stimuli, suggesting an age-related preservation of top–down inhibition of nontarget stimuli.

A consistent N2pc component was observed in both age groups when the subjects were presented with orientation targets. As in previous studies, this effect consisted in an enhanced negativity at posterior electrode sites contralateral to the attended visual hemifield in the typical N2 time range, with a maximum located over the occipital lobe (Luck et al., 1997; Luck and Hillyard, 1994a; Woodman and Luck, 2003). However, the N2pc peak latency was delayed by approximately 68 ms in older subjects compared to young subjects. Because the N2pc latency has proved to be a precise measure of the time needed to shift attention to possible targets (Luck et al., 2000; Woodman and Luck, 1999, 2003), this result

suggests that older subjects localized the target stimulus in the search array more slowly than young subjects. Thus, the differential time course of the N2pc effect observed in young and older subjects appears to indicate that normal aging involves a significant slowing of the allocation of visuospatial attention to orientation targets. This finding confirms previous behavioral results that revealed an age-related slowing in search speed (Hommel et al., 2004; Madden and Whiting, 2004; McDowd and Shaw, 2000). In addition, a significant reduction in N2pc mean amplitude was also observed in older subjects compared to young subjects. Since the N2pc amplitude has been considered as a measure of attentional focusing, reflecting the amount of attention allocated to a stimulus (Luck et al., 1997), this result might indicate a reduction in the proportion of attentional processing resources dedicated by healthy older subjects to orientation target stimuli. Thus, the present results provide the first evidence that normal aging delays and attenuates the magnitude of the attention-related N2pc component in a feature detection task. A similar pattern of age-related changes has been previously observed affecting other attention-related negativities elicited during nonspatial feature selection tasks. Specifically, a prominent negative component termed the 'selection negativity' (SN), which occurs over the N2 latency range at posterior sites, has been also shown to be sensitive to normal aging. In this regard, previous studies have shown an age-related amplitude decrease and a latency delay of this component (Czigler, 1996; Kenemans et al., 1995). These findings suggest that normal aging affects the target selection process and have been interpreted as evidence of an age-related reduction on the capacity to keep attention focused on nonspatial stimulus features. In our opinion, the pattern of electrophysiological results found in our study contribute to specify which processes are affected in the significant slowing of RTs frequently observed in older subjects, providing evidence that is consistent with the proposal that age-related deficits in visual search might be partially explained by a specific slowing in the allocation of attention itself, rather than by an age-related generalized slowing of information processing.

As mentioned above, the N2pc component was observed for orientation targets in both age groups. However, this component was not observed when subjects were presented with irrelevant nontarget pop-out distractors. Because N2pc component has been closely associated with the focusing of attention (Eimer, 1996; Luck and Ford, 1998; Luck et al., 1997; Luck and Hillyard, 1994a,b), this finding may suggest that the color feature did not capture the attention of the subjects (i.e., attention was not attracted towards its location) when it was irrelevant for the detection task. In previous visual search studies, the N2pc component has been used as a tool to investigate the ability of irrelevant salient stimuli to capture attention (Eimer and Kiss, 2006; Girelli and Luck, 1997; Hickey et al., 2006). In such studies, the presence of the N2pc to the irrelevant stimulus has been interpreted as an electrophysiological evidence of attentional capture. In our study, if irrelevant color stimulus were able to attract attention to their location, an N2pc component should emerge in response to stimulus arrays containing a color singleton, and this was not the case. Furthermore, since the ERP waveforms obtained for arrays containing an irrelevant color singleton did not significantly differ from those obtained for homogeneous arrays, we can conclude that they did not capture attention to their location in the visual field. Thus, we failed to find evidence that color feature can elicit attentional capture. This result is in line with other ERP visual search studies of healthy young subjects that found little or no N2pc component for color singletons when they were irrelevant nontargets (Girelli and Luck, 1997; Luck and Hillyard, 1994a,b). We now extend this finding documenting a similar result in healthy older subjects.

In previous visual search studies, the N2pc was observed for nontargets that were so similar to the target that an attentional process was required to distinguish between them; however, it was absent for nontargets that were easy to differentiate from the target, which can be rejected on the basis of pre-attentive feature information (Luck, 1995; Luck and Ford, 1998). Since irrelevant nontargets were easily discriminable from targets in our study, it is possible that spatially focused attention was unnecessary for rejecting them. Thus, the lack of attentional shifts to the nontargets locations, reflected by the absence of the N2pc component in both age groups, may indicate that the preliminary stimulus analysis responsible for the pre-attentive rejection of irrelevant color singletons was not affected by normal aging.

It should be noted that the identity of the relevant target and irrelevant nontarget pop-outs remained constant along all the experimental blocks in the present study. Thus, because it has been previously reported that attentional capture might rapidly habituate to the repeated presentation of a task-irrelevant singleton (Gibson and Jiang, 1998; Horstmann, 2002; Warner et al., 1990), one could object that it is possible that an N2pc is only elicited by the irrelevant feature at the onset of the experimental task. Nevertheless, our results have discarded this possibility, showing that the N2pc component was absent in response to arrays containing an irrelevant color nontarget across the task, as the analyses of the three consecutive blocks showed, suggesting that the color feature did not induce attentional capture irrespective of practice in the present experiment.

Due to the fact that in our study the irrelevant color singleton was never the target, it is also likely that subjects efficiently ignored color dimension adopting a specific attentional set to search for relevant dimension (orientation). This point of view is consistent with the proposal that attentional capture by a feature singleton is not purely stimulus-driven and can be modulated or suppressed by the top–down attentional state of the subjects (Bacon and Egeth, 1994; Connor et al., 2004; Folk and Remington, 1998; Peterson and Kramer, 2001; Theeuwes and Burger, 1998). Thus, it is possible that top–down factors enabled both young and older subjects to ignore the distracting effects of the irrelevant singleton in the

present study. In this line, previous behavioral research has demonstrated that both young and older subjects can benefit from top–down attentional guidance to reduce distracting effects (Colcombe et al., 2003; Madden et al., 2004; Whiting et al., 2005). However, our findings are inconsistent with studies showing that the presence of an irrelevant singleton ineluctably captures attention to its location, interfering with search for a target singleton (Hickey et al., 2006; Theeuwes, 1991, 1992, 1994).

In summary, the present results provide the first evidence that normal aging delays and attenuates the magnitude of the attentional mechanism reflected by the N2pc. This finding might be taken as evidence that the brain structures involved in N2pc generation are also affected by advancing age. Moreover, our findings appear to indicate that the mechanism of top–down inhibition of irrelevant nontarget stimuli is preserved for older subjects, at least in a singleton detection task in which the target and the irrelevant nontarget features are easily distinguishable, and remained constant across trials.

Conflicts of interest

There are no actual or potential conflicts of interest that could inappropriately influence this work.

Disclosure statement

Informed consent was obtained from all subjects that participated in the experiment and their rights were protected.

Acknowledgements

This study was supported by grants from the Spanish *MEC* (SEJ2004-01377) and *Xunta de Galicia* (PGIDT-05PXIC21101PN). The authors are grateful to the anonymous reviewers for their valuable comments on an earlier version of the paper.

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