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Faster target selection in preview visual search depends on luminance onsets: behavioral and electrophysiological evidence

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Abstract To investigate how target detection in visual search is modulated when a subset of distractors is presented in advance (preview search), we measured search performance and the N2pc component as an electrophysiological marker of attentional target selection. Targets defined by a color/shape conjunction were detected faster and the N2pc emerged earlier in preview search relative to a condition in which all items were presented simultaneously. Behavioral and electrophysiological preview benefits disappeared when stimuli were equiluminant with their background, in spite of the fact that targets were feature singletons among the new items in preview search. The results demonstrate that previewing distractors expedites the spatial selection of targets at early sensory-perceptual stages, and that these preview benefits depend on rapid attentional capture by luminance onsets.

Keywords Visual search · Visual marking · Luminance onset · ERPs · N2pc

In visual search, the processing of new objects can be prioritized over processing of objects that have been visible for some time. When a subset of distractors is presented in advance and the remaining items are then added to the search display, search performance is more efficient than when all items are presented simultaneously. According to Watson and Humphreys (1997), this preview benefit reflects the active inhibition of distractor locations during the preview interval ("visual marking"). In line with this hypothesis, such benefits only emerge when the preview interval is sufficiently long (400 ms or longer); they are reduced by a secondary task during the preview interval; and they are associated with impaired probe detection performance at previewed distractor locations (Watson & Humphreys, 2000) and at empty locations between previewed distractors (Osugi, Kumada, & Kawahara, 2009).

The hypothesis that preview benefits in visual search are due to location-based inhibition has not gone unchallenged (see Donk, 2006, for a review). It has been suggested that feature-based inhibition can also play a role (Olivers & Humphreys, 2002; but see Theeuwes, Kramer, & Atchley, 1998). Others have argued that the prioritization of new objects in visual search does not involve top-down inhibition at all. According to Jiang, Chun, and Marks (2002), temporal asynchrony between old and new items is critical, and preview benefits emerge when attention can be selectively allocated to a temporally segregated perceptual group that contains the target. Donk and Theeuwes (2001) claimed that new objects are prioritized when their appearance is associated with an abrupt luminance change, which will trigger automatic attentional capture. In support of their claim, they demonstrated that search performance is not affected by the number of old items when new stimuli are accompanied by a luminance onset, but is determined by the numbers of both new and old items when new stimuli are equiluminant with the background.

In previous behavioral studies, preview-induced improvements of search efficiency have been inferred from search slope differences between preview and standard visual search (Watson & Humphreys, 1997) or from a reduced impact of the number of old items on search

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performance (Donk & Theeuwes, 2001). While these observations suggest that previewing distractors facilitates target processing, it is difficult to gain precise insights into the locus and time course of preview effects on attentional selectivity from behavioral measures alone. In the present study, event-related brain potential (ERP) markers of selective attentional processing were measured to find out how previewing distractors affects the onset of spatially specific target selection in extrastriate visual areas and whether such preview benefits depend on luminance changes. In contrast to a previous ERP study of visual marking (Jacobsen, Humphreys, Schröger, & Roeber, 2002) that focused on ERP components that followed preview displays, we measured the N2pc component to target arrays. The N2pc is an enhanced negativity at posterior scalp sites contralateral to the location of a target with an onset latency of about 200 ms; this negativity is triggered during the spatial selection of targets among distractors (Eimer, 1996; Luck & Hillyard, 1994) and has recently been used to study the time course of attentional capture in visual search (e.g., Eimer & Kiss, 2008; Hickey, McDonald, & Theeuwes, 2006). If previewing distractors expedites the onset of spatially selective target processing, the N2pc should emerge earlier on preview trials than on trials in which all stimuli in a search array are presented simultaneously. If such preview benefits occur only for luminance-onset stimuli (Donk & Theeuwes, 2001), preview-induced modulations of N2pc onset should disappear for equiluminant stimuli.

As in Watson and Humphreys (1997), targets were defined by a conjunction of color and shape (e.g., a blue diamond among blue circles and green diamonds). To avoid sensory asymmetries in the visual ERPs, circular search displays were used (Fig. 1). In the *preview* condition, four nontarget-color distractors were presented for 1,000 ms, before four target-color items (including the target, when present) were added to the display. Among the new items, the target was a shape singleton. Preview benefits were assessed relative to a *full-element* baseline condition, in which all eight items were presented simultaneously. In the *half-element* baseline condition, only the four target-color items were presented, so that targets were always shape singletons. These three search conditions were delivered in separate blocks. Participants had to report the presence or absence of a target, and a target was present in two thirds of all trials. In one half of the experiment, stimuli were presented against a black background. In the other half, they were equiluminant with a gray background. Preview benefits on RT and N2pc onset measures were quantified by comparing the preview and the full-element baseline conditions. To determine whether previewed distractors can be completely ignored,

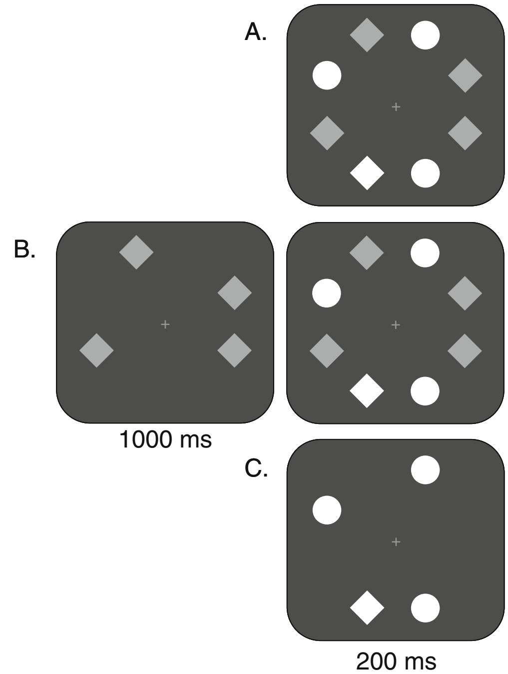

Fig. 1 Examples of search displays in full-element (A), preview (B), and half-element (C) blocks in which the target was a blue diamond. Green items are depicted as gray and blue items as white

the preview condition was contrasted with the half-element baseline condition.

Method

Participants

A group of 31 paid volunteers participated in this experiment. Four were excluded because of excessive alpha activity, and 3 others because of poor eye movement control, resulting in the rejection of more than 50% of all trials. All of the remaining 24 participants (11 male, 13 female; mean age 25.9 years) had normal or corrected-to-normal vision.

Stimuli and procedure

Stimuli were presented on a CRT monitor (refresh rate: 100 Hz) at a viewing distance of 80 cm. On each trial, a circular search array was displayed at a radial angular distance of 3.9º from a central fixation cross. There were three blocked search conditions (Fig. 1). In the full-element condition, targets were defined by a color/shape conjunction and were presented simultaneously with seven distractors that shared either the target color (blue or green) or its shape (diamond or circle). Target color and target shape were counterbalanced independently across participants.

Each search array consisted of eight shapes, half of which were green (CIE x/y chromaticity coordinates: .296/.567), and the other half blue (CIE x/y: .185/.188). In the preview condition, four identical nontarget-color distractors were presented for 1,000 ms, before four additional target-colored items were added to the display. Among these new items, the target, when present, was a shape singleton. In the half-element condition, the displays contained the same four stimuli that had appeared as new items in the preview condition, but were not preceded by a preview display. In all displays, equal numbers of items in a given color (green or blue) were presented in the left and right visual fields. The blue and green search items were equiluminant (10.1 cd/m^2), and their angular size was 0.72° × 0.72°.

Search arrays were presented for 200 ms in the full-element and half-element conditions. In the preview condition, the display containing both old and new items was presented for 200 ms. The intertrial interval was 1,800 ms. A target was present on two thirds of all trials and appeared randomly and equiprobably at one of the eight locations in the left or the right hemifield. Participants were instructed to report the presence or absence of a target as quickly and accurately as possible, by pressing one of two vertically arranged keys with their left or right index finger. Mappings of response categories to keys, and of keys to response hands, were counterbalanced within participants.

The experiment included 36 blocks with 36 trials per block. In 18 successively presented blocks, stimuli were presented against a black background, so that the appearance of new items was accompanied by a luminance change (*onset* condition). In the other 18 blocks, a light gray background (CIE x/y: .286/.312) matched the luminance of the foreground stimuli, so that their presentation was not accompanied by a luminance change (*equiluminance* condition). A subgroup of 12 participants completed the onset condition before starting the equiluminance condition, and this order was reversed for the other 12 participants. The three search conditions were always presented in six successive blocks, with order of the search conditions counterbalanced across participants.

EEG data recording and analysis

The Electroencephalogram (EEG) activity was recorded using a BrainAmp amplifier (Brain Products GmbH) from 23 scalp electrodes mounted in an elastic cap at standard positions of the extended International 10/20 system. Data were sampled at 500 Hz with a bandpass filter of 0–40 Hz. The horizontal electrooculogram (HEOG) was recorded from two electrodes positioned at the outer canthi of the eyes. All electrodes were referenced online against the left earlobe, and re-referenced offline to the averaged earlobes. The EEG was segmented from 100 ms before search array onset to 400 ms poststimulus. Trials with saccades (HEOG exceeding ±25 μV), blinks (FPz exceeding ±60 μV), or muscle artifacts (all other electrodes exceeding ±80 μV) were eliminated from analyses. Trials with RTs faster than 200 ms or slower than 1,500 ms were also excluded from all analyses (less than 0.1% of all trials). Average waveforms were computed for target-present trials, separately for each of the six possible combinations of search and luminance condition, and for targets in the left and right hemifields.

The N2pc component was measured at lateral posterior electrode sites PO7/PO8 contralateral and ipsilateral to the target location. N2pc onset latencies were determined with a jackknife-based procedure from difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. This procedure estimates onset latencies from grand averages computed for subsamples of participants obtained by successively excluding 1 participant from the original sample (Miller, Patterson, & Ulrich, 1998). N2pc onset was defined as the time point when the voltage on the ascending flank of the N2pc difference wave exceeded 40% of the peak amplitude. Repeated measures ANOVAs were conducted on N2pc onset latencies for the factors Luminance (onset, equiluminance) and Search Condition (full-element, preview, half-element), followed by comparisons between paired search conditions. F and t values were corrected (denoted with F_c and t_c), as described by Miller et al. (1998) and Ulrich and Miller (2001).

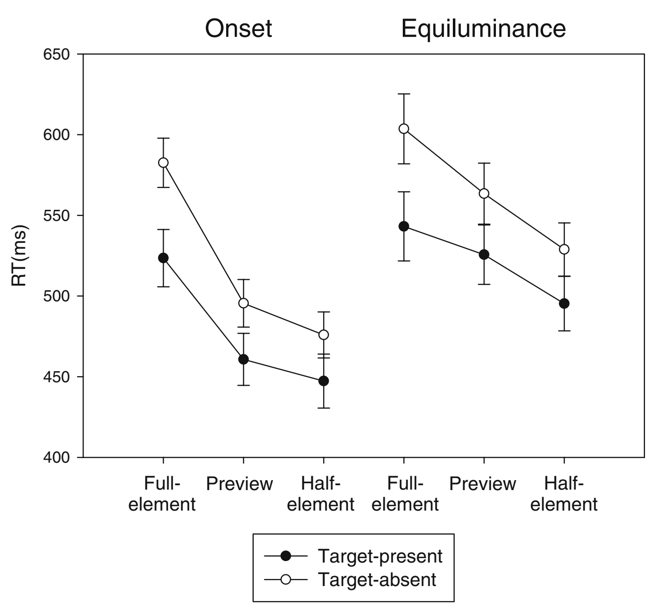

Fig. 2 Response times (RTs) for target-present and target-absent trials in the onset and equiluminance conditions, shown separately for the full-element, preview, and half-element conditions. Error bars represent standard errors of the means

Results

Behavioral performance

Figure 2 shows mean correct RTs for target-present trials (black circles) and target-absent trials (open circles) with luminance-onset and equiluminant stimuli, for the full-element, preview, and half-element conditions. Target-present RTs were faster in the preview than in the full-element condition, $F(1, 23) = 24.58$, $p < .001$. Critically, this preview benefit was strongly reduced when search items were equiluminant with their background, as reflected by a Search Condition x Luminance interaction, $F(1, 23) = 16.91$, $p < .001$. Follow-up analyses revealed the presence of a reliable preview benefit in the onset condition, with faster RTs to targets in preview trials relative to the full-element baseline (461 vs. 524 ms), $t(23) = 8.44$, $p < .001$. No reliable preview benefit was found in the equiluminance condition (526 vs. 543 ms), $t(23) = 1.50$, $p = .146$. Similarly, a main effect of search condition, $F(1, 23) = 39.18$, $p < .001$, and a Search Condition × Luminance interaction, $F(1, 23) = 7.47$, $p < .05$, were observed for target-absent responses. The preview benefits observed for luminance-onset stimuli, $t(23) = 10.15$, $p < .001$, were reduced in size, albeit still reliable, for equiluminant stimuli, $t(23) = 2.39$, $p < .05$.

Target-present RTs were faster in the half-element condition than in the preview condition, $F(1, 23) = 7.97$, $p < .05$, but there was no Search Condition x Luminance interaction, $F(1, 23) = 1.86$, $p = .186$. Similarly, faster target-absent responses were found for the half-element relative to the preview condition, $F(1, 23) = 7.6$, $p < .05$, without any Search Condition x Luminance interaction, $F(1, 23) = 1.09$, $p = .307$.[1]

Errors (missed targets and false alarms on target-absent trials) were rare (1.88% and 2.13%, respectively, for onset and equiluminant stimuli). Errors tended to be more frequent in the full-element condition (2.57%) than in the preview (1.68%) and half-element (1.77%) conditions.

N2pc component

Figure 3 shows grand-average ERPs for target-present trials at lateral posterior electrodes PO7/PO8 contralateral and ipsilateral to the target location, separately for luminance-onset and equiluminant stimuli, and for all three search conditions. N2pc components were triggered between 200 and 350 ms after search array onset in all conditions. N2pc differences between search conditions

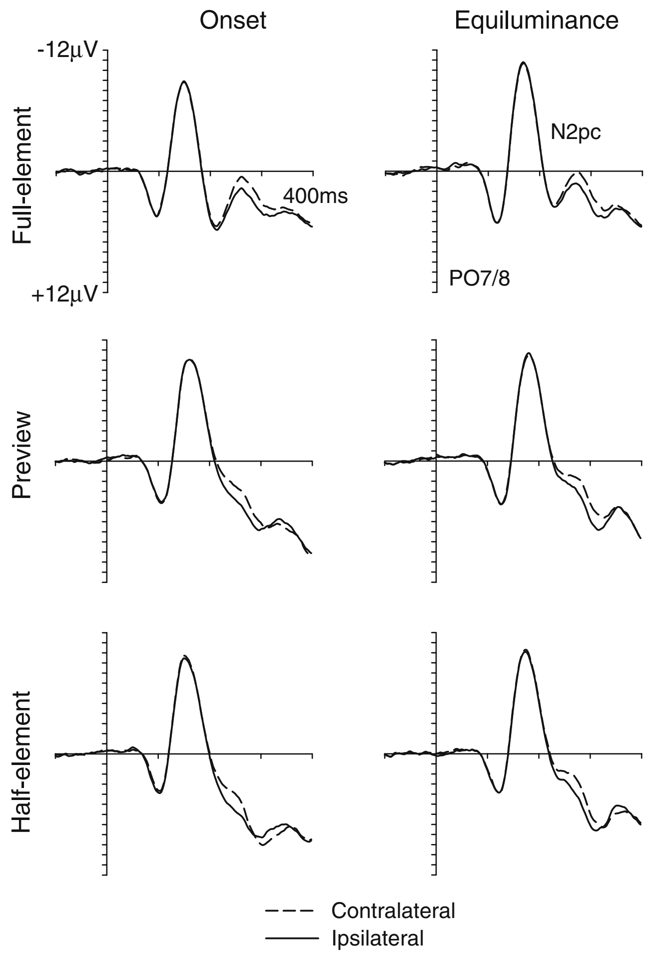

Fig. 3 Grand-average ERPs obtained on target-present trials at lateral posterior electrodes PO7/PO8 contralateral (dashed lines) and ipsilateral (solid lines) to the target location in the onset (left panels) and equiluminance (right panels) conditions. ERPs are shown separately for the full-element (top panels), preview (middle panels), and half-element (bottom panels) conditions

can be seen more easily in the difference waveforms shown in Fig. 4, which were obtained by subtracting ERP activity at PO7/PO8 ipsilateral to the target location from contralateral activity.

N2pc preview benefits were quantified by comparing N2pc onset latencies (defined by the 40% peak amplitude criterion) in the preview and full-element baseline conditions. No overall significant N2pc onset difference was found between these two search conditions, $F_c(1, 23) = 3.11$, $p = .09$. Critically, there was a Search Condition x Luminance interaction, $F_c(1, 23) = 4.81$, $p < .05$, demonstrating that preview benefits on N2pc latency were modulated by the difference between luminance-onset and equiluminant stimuli (see Fig. 4). For luminance-onset stimuli, a reliable preview benefit on N2pc onset latencies was observed (216 vs. 235 ms, respectively, for the preview vs. full-element baseline conditions), $t_c(23) = 2.49$, $p < .05$. No such effect was present for equiluminant stimuli (255 vs. 256 ms), $t_c < 1$.

[1] As expected, target-present responses were faster than target-absent responses, and RTs to luminance-onset stimuli were faster than RTs to equiluminant stimuli (see Fig. 2). Additional analyses confirmed that these differences were significant, both $Fs(1, 23) > 16.8$, both $ps < .001$.

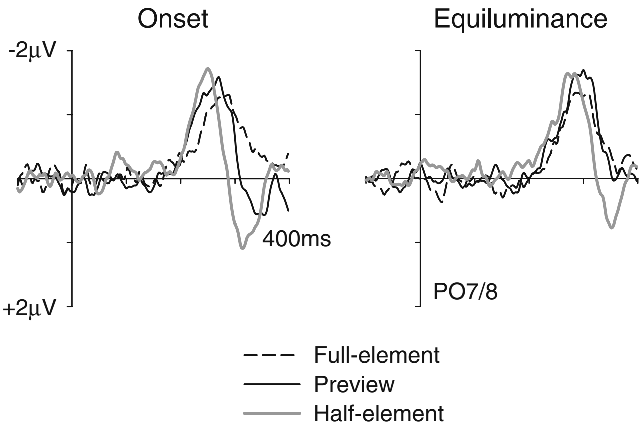

Fig. 4 Grand-average difference waveforms obtained by subtracting ERPs ipsilateral to the target location from contralateral ERPs in the onset and equiluminance conditions, shown separately for the full-element (dashed black lines), preview (solid black lines), and half-element (gray lines) conditions

Essentially the same pattern of preview benefits was obtained when the N2pc onset latency was defined on the basis of an *absolute* amplitude criterion (−0.7 μV).

A comparison of N2pc onset latencies between the preview and half-element conditions revealed no reliable difference with luminance-onset stimuli (214 vs. 216 ms), $t_c < 1$. For equiluminant stimuli, the N2pc in the half-element condition started earlier relative to the preview condition (238 vs. 256 ms), $t_c(23) = 2.22$, $p < .05$. In spite of this difference, the overall Luminance × Search Condition interaction was not significant, $F_c(1, 23) = 2.90$, $p = .102$.[2] Figure 4 shows that the N2pc was more sharply tuned, and therefore returned to baseline faster, in the half-element condition than in the preview search condition, for both luminance onsets and equiluminant stimuli. This was confirmed by N2pc offset latency analyses (with offset defined as the time point when the voltage on the descending flank of the N2pc fell below 40% of peak amplitude). N2pc offset was earlier in the half-element condition relative to the preview condition for onset stimuli (274 vs. 300 ms), $t_c(23) = 7.37$, $p < .001$, and for equiluminant stimuli (314 vs. 329 ms), $t_c(23) = 2.63$, $p < .05$.

Discussion

With luminance-onset stimuli, previewing distractors expedited attentional target selection. Target-present RTs were faster in the preview than in the full-element condition, and this behavioral preview benefit was accompanied by a corresponding N2pc onset difference. Because the N2pc component reflects the spatially selective processing of visual search targets in extrastriate visual cortex, preview-induced N2pc onset modulations demonstrate that preview benefits are linked to the speed of attentional target selection at early sensory–perceptual stages. There were only small RT and no N2pc latency differences between the preview and half-element conditions, indicating that previewed distractors were effectively ignored, making preview search comparable to search for a shape singleton (but see below).

Very different results were found for equiluminant stimuli, suggesting that preview effects critically depend on luminance changes. The absence of behavioral preview benefits for equiluminant stimuli confirms previous findings by Donk and Theeuwes (2001). Importantly, the lack of RT preview effects was mirrored by the absence of N2pc onset differences between the preview and full-element conditions, indicating that previewing distractors did not speed up attentional target selection in the absence of luminance changes.[3]

These findings provide no evidence for location-based inhibition (Watson & Humphreys, 1997), which should have been similarly effective for luminance-onset and equiluminant stimuli. However, Braithwaite, Hulleman, Watson, and Humphreys (2006) found preview benefits for equiluminant stimuli with longer preview intervals, suggesting that inhibition may develop more slowly for these stimuli. Because the present 1,000-ms preview interval may have been too brief for preview benefits to emerge with equiluminant stimuli, we ran a behavioral follow-up experiment in which a 3,000-ms preview condition (as in Braithwaite et al., 2006) was compared to a full-element baseline condition for equiluminant stimuli. No reliable RT differences were found between these two conditions for target-present responses (584 vs. 563 ms), $t < 1$, or target-absent responses (615 vs. 630 ms), $t(7) = 1.06$, $p = .326$, demonstrating that at least with the present stimulus design, behavioral preview benefits for equiluminant stimuli remain absent, even with long preview intervals.

The present findings are not in line with a pure feature-based inhibition account (Olivers & Humphreys, 2002): Previewed and new items differed in color in both luminance conditions, but observers could restrict their search to new items only in the onset condition. Because the temporal structures of the preview trials were identical in both luminance conditions, the temporal segregation hypothesis (Jiang et al., 2002) also cannot account for the

[2] The N2pc emerged earlier in response to search arrays that were associated with a luminance onset than for search arrays that were equiluminant with their background. A follow-up analysis using the 40% peak amplitude criterion confirmed that this general luminance-related onset difference was reliable (222 vs. 249 ms), $F_c(1, 23) = 35.62$, $p < .001$.

[3] The absence of preview benefits in the equiluminance condition, which is consistent with previous studies in which stimuli were perceptually equiluminant (e.g., Donk & Theeuwes, 2001), also confirms that the photometrically determined equiluminance was close to perceptual equiluminance.

present findings. They are, however, fully in line with the hypothesis that new items are prioritized in visual search only when they are associated with an abrupt luminance change, and therefore capture attention (Donk & Theeuwes, 2001). Although attentional capture provides a sufficient explanation for the preview benefits observed in this study, mechanisms such as location-based inhibition may still play an important role when the stimulus configuration or task demands of a visual search task are different. For example, preview benefits for equiluminant stimuli might emerge in tasks in which visual search targets are harder to find or in which larger set sizes are used (cf. Braithwaite et al., 2006).

Another notable finding was that relative to the preview condition, the N2pc was more narrowly tuned both for onset and equiluminant stimuli in the half-element condition, in which search arrays contained only four stimuli, resulting in an earlier N2pc offset (Fig. 4). The apparent reduced temporal variability of target selection in this condition could reflect the absence of attentional filtering costs (Kahneman, Treisman, & Burkell, 1983) that are produced when previewed distractors remain present in target search displays. In line with this hypothesis, RTs were indeed faster in the half-element condition than during preview search.

Overall, the present findings demonstrate that previewing distractors results in faster spatially selective target processing in extrastriate visual cortex, but only when target displays are accompanied by luminance onsets. When such luminance onsets are not present, distractor preview has no impact on the speed of target selection, even when the target is a feature singleton among new items. These results underline the critical role of dynamic changes in the visual environment for attentional selectivity.

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