What Top-Down Task Sets Do For Us:
An ERP Study on The Benefits of Advance Preparation in Visual Search

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When target-defining features are specified in advance, attentional target selection in visual search is controlled by preparatory top-down task sets. We used ERP measures to study voluntary target selection in the absence of such feature-specific task sets, and to compare it to selection that is guided by advance knowledge about target features. Visual search arrays contained two different color singleton digits, and participants had to select one of these as target and report its parity. Target color was either known in advance (fixed color task) or had to be selected anew on each trial (free color-choice task). ERP correlates of spatially selective attentional target selection (N2pc) and working memory processing (SPCN) demonstrated rapid target selection and efficient exclusion of color singleton distractors from focal attention and working memory in the fixed color task. In the free color-choice task, spatially selective processing also emerged rapidly, but selection efficiency was reduced, with nontarget singleton digits capturing attention and gaining access to working memory. Results demonstrate the benefits of top-down task sets: Feature-specific advance preparation accelerates target selection, rapidly resolves attentional competition, and prevents irrelevant events from attracting attention and entering working memory.

Keywords: selective attention, top-down control, task set, event-related brain potentials, vision

Everybody knows that attentional selectivity can be guided by intentions. The voluntary nature of attention was already highlighted by William James (1890/1981), who referred to "the anticipatory preparation from within of the ideational centers concerned with the objects to which attention is paid" (p. 411). According to James, voluntary attentional selection is controlled by internal representations of currently relevant objects: ". . . the image in the mind *is* the attention; the preperception . . . is half of the perception of the looked-for thing" (p. 419). In modern parlance, James' 'anticipatory ideational preparation' has reappeared in the form of attentional templates (e.g., Duncan & Humphreys, 1989) or top-down task sets (e.g., Folk, Remington, & Johnston, 1992)—representations of current task-relevant features that are held in working memory, and guide the attentional selection of objects and events that match these features. These top-down attentional templates play a critical role in visual search. In concert with bottom-up information about stimulus salience, they are assumed to guide search toward the location of likely target stimuli (e.g., Wolfe, 1994). Under certain conditions, top-down control can completely override the impact of bottom-up salience, such that visually salient events (feature singletons or abrupt onsets) will capture attention only if they match current task sets (e.g., Folk et al., 1992).

Neurophysiological studies have identified a possible neural basis of attentional templates, and have also measured the impact of such templates on selective visual processing. For example, Chelazzi, Duncan, Miller, and Desimone (1998) observed sustained activations of object-selective cells in inferotemporal (IT) cortex when a monkey had to retain specific target objects in working memory for a subsequent attentional selection task. This sustained delay activity may be a neural implementation of an object-specific attentional template (Desimone & Duncan, 1995; see also Luck, Chelazzi, Hillyard, & Desimone, 1997, and Kastner, Pinsk, DeWeerd, Desimone, & Ungerleider, 1999, for neural correlates of preparatory spatial attention). When displays containing both target and nontarget stimuli were presented after the interval where this delay activity was measured, an initial unselective IT response was rapidly replaced by neural activity that was entirely driven by the target stimulus (Chelazzi et al., 1998). The observed pattern of a sustained delay activity followed by object-selective visual processing supports the biased competition model of selective attention proposed by Desimone and Duncan (1995), which postulates that preparatory top-down attentional templates modulate neural competition between simultaneously presented visual stimuli in favor of those stimuli that match the current attentional task set. Evidence for preparatory attentional bias signals have been found not only in IT, but also in earlier visual areas such as V4 (e.g., Chelazzi, Miller, Duncan, & Desimone, 2001). For example, Bichot, Rossi, and Desimone (2005) observed enhanced firing rates for color-selective V4 neurons when their preferred color matched the color of the current visual search target. This effect was observed well in advance of actual target detection, suggesting it reflects feature-specific attentional templates in V4.

In behavioral and neuroscientific investigations into the mechanisms of top-down attentional selectivity in visual search, a

specific attentional task set is introduced (usually via experimental instructions that specify target-defining features), and the impact of this task set on the selective processing of target and distractor stimuli is measured. In many studies, preparatory top-down task sets are held constant, and the features of target or nontarget stimuli or the properties of visual search displays are varied to study the efficiency of target detection in different situational contexts (e.g., Chelazzi et al., 1998; Duncan & Humphreys, 1989). Other studies have kept search display properties constant, and changed the content of top-down task sets between experimental blocks to demonstrate task-set contingent attentional capture (e.g., Folk et al., 1992; Eimer & Kiss, 2008). In all of these studies, target detection was guided by preparatory attentional templates because target properties were known in advance. There is, however, another question about the functional role of preparatory task sets that cannot be studied by this traditional approach: How does attentional selection between candidate target events that is guided by advance knowledge about target-defining features differ from intentional target selection processes that do not have the benefit of a preparatory top-down task set? In many real-life situations, several relevant events are simultaneously present in a scene, or appear unexpectedly, and observers have to select one among several potentially relevant stimuli without guidance from search templates that specify precise target stimulus features in advance. In the absence of a preparatory top-down task set, attentional selectivity may be determined primarily by bottom-up salience differences (e.g., Wolfe, Butcher, Lee, & Hyle, 2003), but it can also be based on voluntary top-down control mechanisms that operate in an online fashion upon the arrival of potentially relevant sensory information. The latter situation represents the interesting but rarely studied case where attentional target selection is still intentional, but is not controlled by James' 'anticipatory ideational preparation' for known target features. One aim of the present study was to investigate this type of voluntary attentional selectivity in the absence of a feature-specific preparatory task set. Another aim was to identify the benefits of anticipatory preparation by directly contrasting attentional target selection that takes place either with or without the aid of advance information about target-defining features.

We measured behavioral and electrophysiological correlates of voluntary target selection in response to physically identical search displays in two selection tasks that differed with respect to the presence versus absence of advance information about the target-defining color. Visual search arrays containing eight different digits (digits 2 to 9) were presented. Two of these digits appeared in two different colors (red and blue, red and green, or blue and green), and were presented among gray distractor digits (see Figure 1). Participants had to select one of the two color singleton digits, and respond according to its parity (odd or even). In the *fixed color task*, target color was specified via experimental instructions and remained constant throughout. Because participants knew in advance that they had to select one specific color, and to ignore the other two colors, attentional target selection could be guided by a color-specific anticipatory task set. On the one third of all trials where digits in the two nontarget colors were presented, no response was required. In the *free color-choice task*, search displays were identical, but task instructions were different. Participants now had to select one of the two color singleton digits on every trial, and to report the parity of this target item. Because the
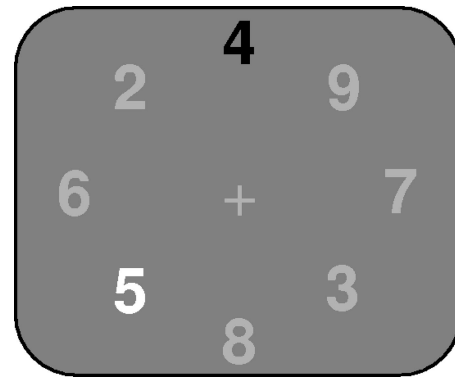

Figure 1. Example of a search array that was used in both tasks. Each array included two digits in different colors (randomly red and green, red and blue, or green and blue, here shown in black and white) among six gray distractor digits. Participants had to report the parity of one target digit. In the fixed color task, target color was specified in advance and remained constant across blocks. In the free color-choice task, there was no fixed target color, and participants had to select one of the two colored digits on each trial. The array shown includes a color digit on the vertical meridian and one in the left visual hemifield.

two digit colors were determined randomly on each trial and were thus unpredictable, participants could not prepare in advance for one specific target color, but instead had to select one of the two colored digits as target in an online fashion, after the search display had been presented. On two thirds of trials, the two colored digits differed in parity, and participants' response was used to determine which of these two items they had selected. Responses on the remaining one third of trials where singleton digits had the same parity were used to assess response selection accuracy in this free color-choice task.

This design made it possible to directly contrast intentional target selection that is guided by anticipatory ideational preparation for a specific target color (fixed color task) and target selection that has to be based on an online choice between two candidate target stimuli (free color-choice task). Because the two color singleton digits were equally salient, this choice could not be determined by bottom-up factors, but instead required a voluntary decision. The critical question was whether and how the voluntary selection of target events benefits from advance knowledge about and anticipatory preparation for a specific target-defining feature. To address this question, behavioral and event-related brain potential (ERP) measures were obtained during task performance. In particular, we focused on two lateralised ERP components at posterior electrodes (N2pc and SPCN) that are known to be associated with attentional selectivity in perception and working memory.

The N2pc component is an enhanced negativity over posterior scalp electrodes that emerges around 200 ms after the onset of a visual search array contralateral to the side of an attended stimulus, and is assumed to reflect the attentional selection of candidate target items among distractors in visual search tasks (Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999; Mazza, Turatto, Umiltà, & Eimer, 2007; Eimer & Kiss, 2008). The sustained posterior contralateral negativity (SPCN), also referred to as contralateral delay activity (CDA), is an ERP component that has

been observed in working memory tasks. It is associated with the spatially selective maintenance of working memory representations (McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004). The SPCN is similar to the N2pc in its scalp distribution, but has a later onset (around 300 ms poststimulus). In experiments that require both the spatial selection of target events and their subsequent maintenance in working memory (e.g., Vogel & Machizawa, 2004; Mazza et al., 2007; Eimer & Kiss, 2010) the N2pc precedes the SPCN, in line with the view that these two components reflect the successive stages of attentional target selection followed by the activation of a target representation in working memory. Importantly, the SPCN can be observed to nonlateralised postcues presented at fixation when these cues signal which side of a memorized search array needs to be accessed (Eimer & Kiss, 2010). This result underlines that the SPCN is not confounded with asymmetric visual responses to lateralised memory-related stimuli, and demonstrates that this component is also associated with spatially selective attentional access to visual representations in working memory.

Due to the lateralised nature of the N2pc and SPCN (i.e., the fact that both are elicited over the hemisphere contralateral to the visual hemifield of attended or remembered stimuli), these components are not present when task-relevant stimuli appear on the vertical midline. In search displays with two salient potential target stimuli, it is therefore possible to isolate the spatially selective processing of one laterally presented item by presenting the other item on the midline. For such displays, N2pc and SPCN components will exclusively reflect attentional and working memory processes that are triggered in response to the candidate target stimulus in the left or right hemifield.

We measured N2pc and SPCN components in response to search arrays that required participants to select one color singleton digit and ignore the other colored digit. This was done separately for the fixed color task where this selection was guided by advance information about the target-defining color, and for the free color-choice task where no such advance information was available. Lateralised posterior ERP components were computed separately for three types of search arrays that differed with respect to the positions of target and distractor color digits—lateral target with distractor on the vertical midline, lateral target with distractor in the opposite hemisphere, and lateral distractor with target on the vertical midline. The central question was whether and how preparatory feature-specific top-down task sets affect the speed and efficiency of attentional target selection. Fast and efficient selection will be reflected by a short-latency N2pc component in response to laterally presented targets and a subsequent SPCN, indicative of the spatially selective processing of selected items in working memory. If attentional selection is efficient, color singleton distractors should not capture attention or gain entry into working memory, and target processing should therefore be minimally affected by the simultaneous presence of such distractors. In this case, no N2pc and SPCN components should be triggered by laterally presented distractors in search arrays where selected targets appear on the midline, and N2pc/SPCN components to lateral targets should not differ between trials where color distractors appear in the opposite hemifield and trials where they are presented on the vertical meridian. If a preparatory top-down task set that specifies target color enables efficient target selection, this is

the pattern of results that should be observed in the fixed color task.

In the free color-choice task, where no color-specific top-down task set was available in advance, the attentional selection of one target color had to proceed concurrently with the visual analysis of the search array. Together with the absence of a color-defined attentional template at search array onset, the presence of this additional task load should have reduced the speed and efficiency of attentional target selection in the free color-choice task relative to the fixed color task. When the efficiency of target selection is impaired, color singleton distractors may be able to attract attention and may even gain access to working memory. In this case, lateral distractors presented together with midline targets should trigger N2pc and SPCN components indicative of attentional capture and working memory processing, respectively. Furthermore, distractor singletons may compete with targets for attentional selection and subsequent processing in working memory, which should result in attenuated N2pc and SPCN components to lateral targets that are accompanied by color distractors in the opposite hemifield. Visual-perceptual processing may even be completely nonselective with respect to target and distractor singletons. In this case, N2pc components of similar size should be observed for arrays with lateral targets and midline distractors and for arrays with lateral distractors and midline targets. Furthermore, no N2pc should be present at all for arrays where targets and distractors appear in opposite hemifields. If the efficiency of voluntary attentional selection was impaired in the absence of feature-specific top-down task sets, one of these patterns of ERP results should be observed in the free color-choice task. Overall, differences in the efficiency of selective processing between this task and the fixed color task, as reflected by task-dependent N2pc and SPCN differences, would provide new insights into the role of feature-specific anticipatory preparation in visual attention.

Method

Participants

Twenty-three volunteers took part in the experiment. Three participants were excluded from further analysis because of excessive eye movements. Two others were excluded because their error rate on same-parity trials in the free color-choice task exceeded 10% (see below). All remaining 18 participants (mean age 26.7 years, seven male) had normal or corrected vision.

Stimuli and Procedure

Stimuli were presented on a CRT monitor with a 60 Hz refresh rate. Search arrays consisted of eight different digits (digits 2 to 9) arranged at equidistant positions around a central fixation cross at a radial distance of 2.75° visual angle. Each digit subtended 0.6° × 0.8°. Two of these digits had two different colors (red, blue, or green; CIE x/y values .634/.350, .143/.070, and .302/.576), and the other six digits were gray (CIE .319/.360). Displays with a red and a green, a red and a blue, or a green and a blue digit were presented in random order and with equal probability across trials. The location of one color digit was randomly chosen on each trial, and the second color digit was always separated by two gray distractor items from the other color singleton. All colors were equiluminant

(4.5 cd/m^2). Search arrays were presented for 150 ms and followed by a 1650 ms empty interval. A central fixation point was continuously present throughout each block.

There were two search tasks. In the *fixed color task*, one color was designated as target color, and the other two colors were nontarget colors. Participants had to detect the target-color digit and report whether it was odd or even by pressing one of two vertically arranged response keys (even digit: top key; odd digit: bottom key) with their left or right hand. A target-color item was present in two thirds of all trials and was randomly and equiprobably an odd or an even digit. In the remaining trials, the two nontarget-color digits were presented, and no response was required. In the *free color-choice task*, participants were instructed to select one of the two colored digits in the search display on each trial, and to respond according to the parity (odd or even) of this chosen target item. They were informed that each of the three possible target colors was equally likely to appear in each search array, and that they could, therefore, not select one specific target color in advance. Digit/color assignments were arranged such that on two thirds of all trials, the two colored digits differed in their parity, so that participants' response choice could be used to determine which of these two digits they had selected. In the remaining one third of all trials, both colored digits were either odd or even, and thus required the same response. These trials were used to determine the accuracy of participants' response selection in the free color-choice task. Task order, target color in the fixed color task, and assignment of hands to response keys were counterbalanced across participants. Eight successive blocks of 96 trials each were run for each search task, resulting in a total of 768 trials per task.

EEG Recording and Data Analysis

EEG was DC-recorded from 23 scalp electrodes at standard positions of the extended 10/20 system (500 Hz sampling rate; 40 Hz low-pass filter) against a left-earlobe reference, and rereferenced offline to averaged earlobes. The continuous EEG was segmented from 100 ms prior to 600 ms after search array onset. Trials with artifacts (HEOG exceeding $\pm$ 25 μV, VEOG exceeding $\pm$ 60 μV, all other channels exceeding $\pm$ 80 μV) were removed prior to analysis. Averaged waveforms were computed for the fixed color task and the free color-choice task. Separate averages were computed for different spatial target-distractor arrangements in the search display: (a) Target on the left or right side and distractor on the vertical meridian (top or bottom position); (b) Target and distractor in opposite hemifields (target left/distractor right, or vice versa); and (c) Target on the vertical meridian and distractor on the left or right side. The N2pc component was measured on the basis of ERP mean amplitudes obtained between 210 and 260 ms after search array onset at lateral posterior electrodes PO7 and PO8 where this component is maximal. The SPCN component was quantified on the basis of ERP mean amplitudes measured in the 400–600 ms poststimulus time window at PO7/8.

Reaction times (RTs) and response accuracy were determined for each trial. In the free color-choice task, participants' ability to correctly base response selection on the parity of the chosen target digit was estimated on the basis of response accuracy on those trials where both colored digits had the same parity. Two partici-

pants whose error rate exceeded 10% on these trials were excluded from further analyses.

Results

Behavioral Results

Figure 2 shows mean correct RTs in the fixed color task and in the free color-choice task, separately for trials where the two colored digits had the same or a different parity. A main effect of task was obtained, $F(1, 17) = 42.84$, $p < .001$, $\eta_p^2 = .716$, as RTs were faster in the fixed color task than in the free color-choice task (657 ms vs. 731 ms). There was also a main effect of distractor compatibility (same vs. different parity as the target), $F(1, 17) = 22.97$, $p < .001$, $\eta_p^2 = .575$, and, more importantly, an interaction between task and distractor compatibility, $F(1, 17) = 13.43$, $p < .01$, $\eta_p^2 = .441$. In the free color-choice task, participants responded faster on trials where both color singletons had the same parity than on trials where one color digit was odd and the other was even, 716 vs. 739 ms; $t(17) = 5.01$, $p < .001$. In contrast, the identity of the nontarget-color digit (same or different parity) did not affect RTs to targets in the fixed color task, 654 vs. 658 ms; $t(17) = 1.38$, $p = .186$. In the fixed color task, incorrect responses occurred on 2.1% of all target-present trials, and there were no False Alarms on target-absent trials. In the free color-choice task, participants chose the incorrect response on 4.8% of all trials where both colored digits had the same parity.

ERP Results

Figure 3 shows ERPs triggered at electrodes PO7/8 contralateral and ipsilateral to the visual field of a target color digit in trials where the distractor color digit was located on the vertical meridian (top panel) or in the opposite visual field (middle panel), separately for the fixed color task (left) and the free color-choice task (right). In Figure 3 (bottom panel), ERP waveforms obtained at PO7/8 contralateral and ipsilateral to distractor color digits are shown for trials where these were accompanied by a target color
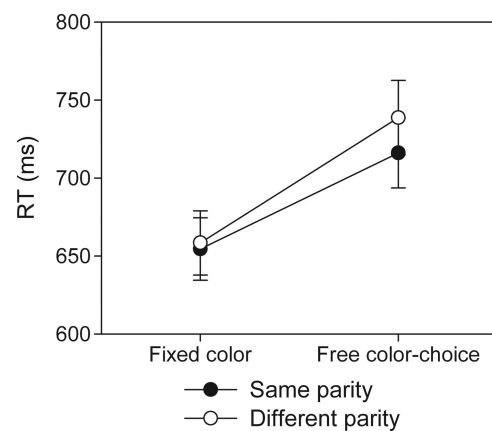

Figure 2. Mean correct response times to targets in the fixed color task and in the free color-choice task, shown separately for trials where the parity of the two color singleton digits was the same or different. Error bars represent standard errors of the mean.
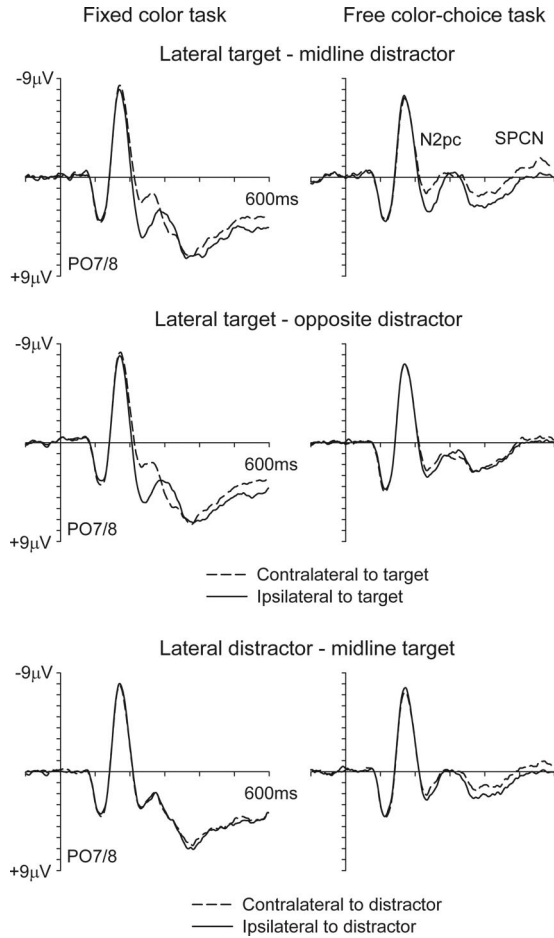
Figure 3. ERPs elicited in the 600 ms interval after search array onset at posterior electrode sites PO7/8 in the fixed color task (left) and in the free color-choice task (right). Top panel: ERPs for search arrays containing a lateral target and a color digit distractor on the vertical midline, shown separately for electrodes contralateral (dashed lines) and ipsilateral (solid lines) to the visual hemifield where the target was presented. Middle panel: ERPs for search arrays containing a lateral target and a color digit distractor in the opposite hemifield, for electrodes contralateral and ipsilateral to the target. Bottom panel: ERPs for search arrays containing a lateral color digit distractor and a target on the vertical midline, for electrodes contralateral and ipsilateral to the distractor.

color task for lateral distractor digits accompanied by midline targets. A different pattern of results was observed in the free color-choice task. Selected target color digits on the left or right side that were accompanied by a midline distractor triggered successive N2pc and SPCN components. However, the N2pc was delayed and attenuated relative to the N2pc obtained in response to the same type of search array in the fixed color task. On trials where lateral target digits were accompanied by a distractor color digit in the opposite hemifield, target-elicited N2pc and SPCN
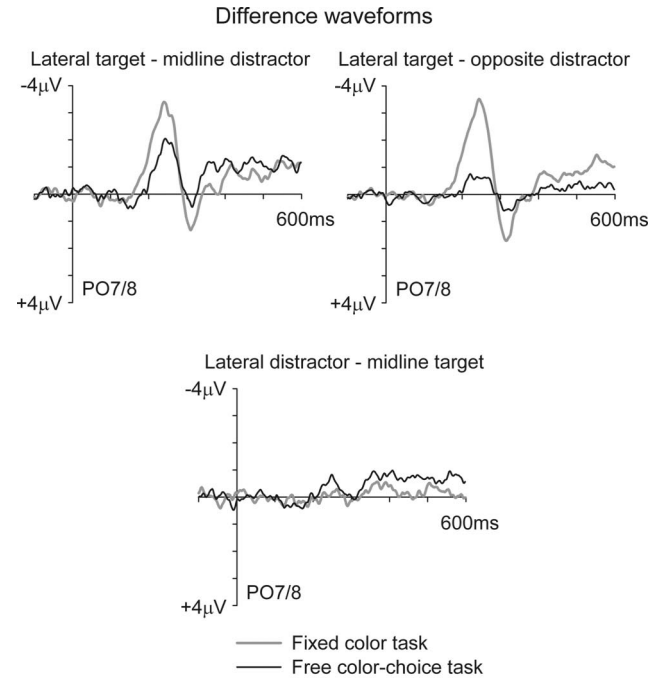

Figure 4. Difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in the fixed color task (gray lines) and the free color-choice task (black lines), shown separately for search arrays with lateral targets and midline distractors, arrays with targets and distractors in opposite hemifields, and arrays with lateral distractors and midline targets. Bottom panel: Topographic maps (back views) of N2pc and SPCN scalp distributions observed during the 210–260 ms poststimulus time window (N2pc) and during the 400–600 ms time window (SPCN) in response to arrays with lateral targets and midline distractors, shown separately for the fixed color task and the free color-choice task. Maps were constructed by spherical spline interpolation (see Perrin, Pernier, Bertrand, & Echallier, 1989) after mirroring the ipsilateral-contralateral difference waveforms to obtain symmetrical voltage values for both hemispheres.

digit on the vertical midline. Figure 4 presents difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for the three different search array types and the two tasks. Figure 4 also shows scalp distribution maps for N2pc and SPCN components obtained during their respective time windows (210–260 ms and 400–600 ms poststimulus) for trials with lateral targets and midline distractors, separately for the fixed color task and the free color-choice task.

In the fixed color task, target color digits elicited a large N2pc component that was followed by a sustained posterior contralateral negativity (SPCN). These two components were triggered in a very similar fashion regardless of whether distractor color digits appeared on the vertical meridian or in the opposite visual field. In contrast, no N2pc or SPCN components were apparent in the fixed

components were strongly attenuated relative to the fixed color task. Whereas no lateralised ERP components were elicited by lateral distractor color digits accompanied by midline targets in the fixed color task, lateral distractors triggered a small N2pc and a substantial subsequent SPCN in the free color-choice task. These informal observations were confirmed by the statistical analyses described below.

N2pc component. In the fixed color task, a main effect of contralaterality (electrode contralateral vs. ipsilateral to the target), $F(1, 17) = 27.59, p < .001, \eta_p^2 = .619$, was obtained for trials with lateral targets, reflecting an N2pc to these stimuli. There was no interaction between contralaterality and distractor location (midline vs. opposite hemifield), $F < 1$, demonstrating that an N2pc of similar amplitude was triggered for both search array types. There was no N2pc in response to lateral distractor color digits accompanied by targets on the vertical meridian, $F < 1$. In the free color-choice task, a main effect of contralaterality for trials with lateral targets, $F(1, 17) = 22.11, p < .001, \eta_p^2 = .565$, indicative of an N2pc, was accompanied by an interaction between contralaterality and distractor location, $F(1, 17) = 16.28, p < .001, \eta_p^2 = .489$, confirming that the target N2pc was strongly reduced on trials where the nontarget color digit was in the opposite hemifield relative to trials where it was on the vertical midline. However, follow-up analyses revealed that the N2pc was reliably present for both types of trials, both $F(1, 17) > 7.45$, both $p < .05$, both $\eta_p^2 > .305$. In marked contrast to the fixed color task, a significant N2pc was triggered in the free color-choice task by lateral distractor color digits that were presented together with midline targets, $F(1, 17) = 7.27, p < .05, \eta_p^2 = .300$.

Further analyses were conducted to directly compare N2pc components triggered by each of the three search array types in the fixed color and free color-choice tasks, with task as additional factor. N2pc amplitude for lateral targets accompanied by midline distractors was smaller in the free choice task than in the fixed color task, as demonstrated by an interaction between task and contralaterality, $F(1, 17) = 6.6, p < .05, \eta_p^2 = .280$. For lateral targets presented together with color digit distractors in the opposite hemifield, the N2pc was much smaller in the free color-choice task as compared to the fixed color task, $F(1, 17) = 16.72, p < .001, \eta_p^2 = .496$, and this N2pc attenuation was even more pronounced than for displays with lateral targets and midline distractors.[1] For search arrays with lateral distractors and midline targets, the analysis of N2pc mean amplitudes obtained a significant interaction between task and contralaterality, $F(1, 17) = 4.73, p < .05, \eta_p^2 = .218$, due to the fact that color digit distractors triggered a small but reliable N2pc in the free color-choice task, but not in the fixed color task.

The N2pc to lateral target stimuli was not just smaller, but was also delayed in the free color-choice task relative to the fixed color task (see Figure 4). Jackknife-based analyses were conducted for the onset latency of the N2pc to lateral target stimuli (using the method described by Miller, Patterson, & Ulrich, 1998, with N2pc onset defined as the time-point where the voltage in N2pc difference waveforms exceeded -0.5 μV).[2] For search arrays with lateral targets and midline distractors, target N2pc onset was reliably delayed by 28 ms in the free color-choice task relative to the fixed color task, corrected t-value $t_c(17) = 4.8, p < .001$. An N2pc onset difference of 32 ms was found between the two tasks

for search arrays with lateral targets and distractors in the opposite hemifield, $t_c(17) = 3.4, p < .01$.

SPCN component. The SPCN (measured in the 400–600 ms time window after search array onset) was reliably elicited by lateral target stimuli in the fixed color task, as confirmed by a main effect of contralaterality, $F(1, 17) = 8.21, p < .05, \eta_p^2 = .326$. Target SPCN amplitudes did not differ between search arrays with midline distractors and arrays with distractors in the opposite hemifield, $F < 1$. No reliable SPCN was triggered in the fixed color task by search arrays containing a lateral distractor and a midline target, $F(1, 17) = 2.8, p = .113$. A different SPCN pattern was found for the free color-choice task. For lateral targets, a main effect of contralaterality, $F(1, 17) = 18.5, p < .001, \eta_p^2 = .521$, reflecting the presence of an SPCN, was accompanied by a significant interaction between contralaterality and distractor location (midline vs. opposite hemifield), $F(1, 17) = 19.55, p < .001, \eta_p^2 = .535$, confirming that SPCN components triggered by selected color digit targets on the left or right side were strongly reduced when a color digit distractor was present on the opposite side. Follow-up analyses demonstrated that a reliable SPCN was elicited by lateral targets accompanied by midline distractors, $F(1, 17) = 24.12, p < .001, \eta_p^2 = .587$, whereas the SPCN in response to targets presented together with a colored digit distractor in the opposite hemifield was only marginally significant, $F(1, 17) = 4.3, p = .054, \eta_p^2 = .202$. In contrast to the fixed color task, lateral color digit distractors that were presented together with midline targets triggered a reliable SPCN component, $F(1, 17) = 16.0, p < .001, \eta_p^2 = .485$.

Additional analyses were conducted to directly compare SPCN components triggered by each of the three different search array types in the fixed color and free color-choice tasks, with task as additional factor. For lateral targets presented together with midline distractors, no interaction between task and contralaterality was present, $F < 1$, as SPCN components were of similar amplitude in both tasks. In contrast, a significant task x contralaterality interaction was observed for arrays with targets and distractors in opposite hemifields, $F(1, 17) = 5.91, p < .05, \eta_p^2 = .258$, reflecting the strong attenuation of the SPCN in the free color-choice task. This interaction was also reliable for search arrays with lateral distractors and midline targets, $F(1, 17) = 9.54, p < .01, \eta_p^2 = .359$, due to the presence of a significant SPCN in the free color-choice task, and its absence in the fixed color task.

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[1] The observation that the target N2pc amplitude difference between the fixed colour task and the free colour-choice task was larger for trials with distractor singletons in the opposite hemifield than for trials with midline distractors was confirmed in an additional analysis across these two display types that included the additional factor distractor location (opposite side vs. midline). This analysis revealed a significant task x distractor location x contralaterality interaction, $F(1, 17) = 9.41, p < .01, \eta_p^2 = .356$.

[2] N2pc onset was quantified on the basis of an absolute rather than a relative amplitude criterion because the large N2pc amplitude difference between the two tasks for trials with targets and distractors in opposite hemifields prevented a meaningful application of the more commonly used relative criterion. For trials with lateral targets and midline distractors, an additional jackknife analysis where N2pc onset was defined as 50% of its peak amplitude confirmed the presence of a reliable N2pc onset delay in the free colour-choice task, $t_c(17) = 4.1, p < .01$.

Discussion

To study how intentional target selection in visual search operates in the absence of advance information about target-defining features, and to identify the benefits for attentional selectivity that are conveyed by the availability of preparatory top-down task sets, behavioral and electrophysiological indicators of attentional processing were compared between two search tasks that were performed in response to identical visual displays, but with different instructions. In the fixed color task, participants had to select a digit defined by a known target color in order to report its parity, while ignoring another task-irrelevant color singleton digit, or both color digits if neither matched the target color. In the free color-choice task, no target color was specified in advance, and two of the three possible singleton colors were randomly chosen on each trial. Participants had to select one of the two color singleton digits and report its parity. In the former task, attentional target selection was guided by advance knowledge about the target-defining color, whereas no such feature-specific top-down task set was available in the latter task.

RTs were 74 ms faster in the fixed color task relative to the free color-choice task, which provides initial evidence that anticipatory preparation did indeed facilitate attentional target selection. Furthermore, the identity of the ignored color singleton digit (same vs. different parity as the target) had no effect on RTs in the fixed color task, suggesting that these distractors were not processed sufficiently deeply to affect response selection. In contrast, a significant behavioral distractor compatibility effect was present in the free color-choice task, with slower RTs on trials where targets and distractors differed in parity. This indicates that even though targets were selected on the basis of color, nonselected distractor digits were processed up to a level where their identity was available, which affected the selection of responses to targets. Overall, these behavioral findings show that the availability of a feature-specific top-down task set had a strong impact on the efficiency of attentional target selection. The ERP results obtained in this study provide new and more specific insights into the mechanisms that produce these behavioral effects of advance preparation on selective attention.

In the fixed color task, attentional target selection was indeed very efficient, as expected. Lateral targets accompanied by distractors on the vertical midline elicited a large N2pc component, reflecting the spatial selection of target-color digits, followed by an SPCN component indicative of the subsequent processing of these targets in working memory. In contrast, no reliable N2pc or SPCN components were triggered by lateral nontarget-color digits that were presented together with midline targets, demonstrating that the preparatory top-down color task set prevented attentional capture by salient nontarget stimuli, and also prevented access of these distractors to working memory. N2pc and SPCN components to lateral targets were equal in size for trials where distractors appeared on the vertical meridian (and thus could not trigger lateralised posterior components) and trials where distractors were located in the opposite hemifield, which further supports the conclusion that color singleton distractors in the fixed color task were effectively excluded from competition with targets for attentional selection and access to working memory. This is perfectly consistent with the observation that no RT distractor compatibility effects were observed in this task (see above). Overall, the ERP

results observed in the fixed color task are in line with the biased competition model of selective attention (Desimone & Duncan, 1995) and its central claim that preparatory top-down attentional templates bias competition between simultaneous stimuli in visual processing in favor of those stimuli that match currently task-relevant features. The presence of an N2pc component to lateral targets, and the absence of an N2pc to equally salient lateral distractors in the fixed color task suggest that this competition is largely resolved within 200 ms after search array onset.

The ERP results obtained in the free color-choice task demonstrate that when a preparatory top-down task set is absent at search display onset, and participants have to make an online choice between two color singletons, the efficiency of attentional selection is impaired. They do, however, also show that early selectivity of visual-perceptual processing is by no means abolished when anticipatory ideational preparation is not possible, and participants have to choose between two equally salient candidate target events after the onset of a visual search array. On trials with lateral targets and midline distractors, the N2pc component emerged within about 200 ms after stimulus onset. This observation is interesting, as it demonstrates that online attentional selection processes can operate rapidly even when there is no advance information about target-defining features (see also Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004, for behavioral evidence for rapid top-down control of cued target selection with short cue-target intervals). However, N2pc onset was delayed by about 30 ms in the free color-choice task relative to the fixed color task (Figure 4, top left panel). This finding suggests one first benefit of the anticipatory ideational preparation process postulated by William James (1890/1981): Feature-specific top-down task sets increase the speed of attentional target selection. It should be noted that the magnitude of this speed benefit, as inferred from target N2pc onset differences between the two tasks (about 30 ms), was considerably smaller than the overall RT difference between the fixed color and free color-choice task (74 ms), which suggests that additional processes beyond attentional selection speed also contributed to this behavioral difference. As discussed below, the SPCN results observed in the free color-choice task provide evidence about the nature of these additional processes.

The most obvious qualitative difference in the pattern of ERP results between the two tasks was found for search arrays with lateral distractors and midline targets. While no N2pc and SPCN components were triggered by these arrays in the fixed color task, these components were reliably present in the free color-choice task (Figure 3, bottom panel). The emergence of an N2pc to lateral distractors suggests that these distractors captured attention on at least some trials, even though the other color digit on the midline was eventually chosen as target. Again, this does not imply that visual processing was completely nonselective in the free color-choice task: Although reliable, the N2pc to lateral distractor/midline target search arrays was much smaller than the N2pc in response to lateral target/midline distractor arrays, which further underlines the early emergence of attentional selectivity in this task. Nevertheless, the presence of an N2pc to lateral distractors in the free color-choice task, and its absence in the fixed color task points to a second benefit of anticipatory ideational preparation: Anticipatory top-down task sets prevent attentional capture by salient but currently irrelevant visual stimuli.

As important as the presence of a small distractor-elicited N2pc in the free color-choice task is the fact that lateral distractors elicited a substantial and highly significant SPCN component when they were accompanied by targets on the vertical midline. This finding demonstrates that in the absence of a preparatory feature-specific task set, nonselected color digits gained access to processing in working memory. This conclusion is perfectly consistent with the presence of substantial behavioral distractor compatibility effects in the free color-choice task, which provides converging evidence for the processing of distractor identity in this task. The presence of reliable SPCN components triggered by distractors in the free color-choice task, and their absence in the fixed color task suggest a third benefit of anticipatory ideational preparation: Preparatory top-down task sets prevent access of salient but currently task-irrelevant stimuli to working memory. This function of top-down attentional preparation was already anticipated by William James in his claim that "an object attended to will remain in the memory, while one inattentively allowed to pass will leave no traces behind" (James, 1890/1981, p. 403f.). The observation that lateral distractors elicited an SPCN component in the free color-choice task points to another cause for the RT delay observed in this task relative to the fixed color task: When target selection is not guided by anticipatory attentional templates, the resulting competition between target and distractor items for working memory processing will interfere with the speed and efficiency of target identification.

The ERP results observed in the free color-choice task for search arrays where targets and distractors appeared in opposite hemifields provides further evidence for impaired attentional selectivity in this task. N2pc and SPCN components to lateral target stimuli were both strongly attenuated relative to arrays with lateral targets and midline distractors, and the SPCN was only marginally significant. In other words, distractors in the opposite hemifield acted as strong competitors for attentional selection and access to working memory when no advance feature-specific top-down task set was available to guide attentional target selection. This is of course perfectly consistent with the observation that color digit distractors triggered reliable N2pc and SPCN components in the free color-choice task when they were paired with targets on the vertical midline. If N2pc and SPCN components are elicited simultaneously by stimuli in the left and right hemifield, this will result in an attenuation or (if component amplitudes are equal in size) elimination of the net effect observed for the whole search array. The fact that residual N2pc and SPCN components remained present in the free color-choice task for arrays with targets and distractors on opposite sides provides further evidence that even though attentional selectivity in this task was impaired, it was not completely abolished. Nevertheless, there was a marked contrast with the pattern of ERP effects obtained in the fixed color task, where the presence of contralateral distractors had no impact whatsoever on N2pc and SPCN components. This difference between the two tasks demonstrates that in the absence of a preparatory feature-specific task set, voluntary online target selection is insufficient to rapidly resolve the competition between salient visual events, and provides further evidence that advance information does indeed play a decisive role in biasing this competition in favor of currently task-relevant stimuli (Desimone & Duncan, 1995). This constitutes a fourth benefit of anticipatory ideational preparation: Preparatory top-down task sets are critical for the fast resolution of attentional competition between simultaneously present candidate target stimuli.

Before these conclusions can be accepted, two methodological issues need to be considered. In the free color-choice task, partic-

ipants' responses on trials where the two colored digits differed in parity were used to determine which of these two digits was attentionally selected. To interpret these responses as reliable indicators of target selection, it has to be assumed that participants committed few response selection errors on these trials. An erroneous response to a selected color digit (e.g., an "even" response to an odd digit) would result in the selected item being incorrectly classified as distractor, and the ignored digit as target. To measure the frequency of such response selection errors, one third of all free color-choice trials contained two colored digits with the same parity, and therefore required a known correct response. On 4.8% of these trials, participants' response was incorrect, demonstrating that response selection errors did indeed occur, and that the resulting possibility of an incorrect classification of targets and distractors on a subset of trials needs to be seriously considered. One could even argue that the critical ERP differences between the free color-choice task and the fixed color task (i.e., the presence vs. absence of distractor-elicited N2pc and SPCN components, and the attenuation of target N2pc and SPCN components for arrays with contralateral distractors) that were interpreted in terms of impaired attentional selectivity in the former task, and as evidence for benefits of ideational preparation in the latter task, may be an artifact of such incorrect classifications in the free color-choice task. To investigate this possibility, ERPs obtained for different search array types in this task were averaged separately for participants whose response error rate in same-parity trials was either above or below the median. If the ERP evidence for impaired attentional selectivity in perception (N2pc) and working memory (SPCN) in the free color-choice task was due to incorrect target/distractor classifications linked to response selection errors, this evidence should be stronger for those participants who are more likely to commit such errors. However, the median-split analysis provided no support for this prediction. In fact, distractor-elicited N2pc and SPCN components were numerically (albeit not significantly) larger for those nine participants with fewer response selection errors in same-parity trials (average error rate: 2.9%) than for participants with above-median error rates (average error rate: 6.8%). N2pc and SPCN components to lateral targets were numerically larger for participants who committed more response errors than for the more accurate subgroup, which is again inconsistent with the hypothesis that the ERP evidence for an impairment of target-selective attentional processing in the free color-choice task was due to an imperfect method of determining the identity of freely selected targets in this task.

A second methodological concern also requires consideration. One could argue that in spite of the instruction to do otherwise, participants may have prepared either explicitly or implicitly for one specific target color in the free color-choice task, as the probability of each of the three colors being present in the next search array was 67%. With this strategy, an online selection between the two color singleton digits would only have been required in those trials where the anticipated color did not appear. In other words, the free color-choice task may have included a majority of trials where advance preparation guided attentional target selection just as fast and efficiently as in the fixed color task, and a minority of trials where target selection was less efficient because of the absence of any explicit or implicit advance preparation. The pattern of N2pc results in the free color-choice task does not support this hypothesis. If the target N2pc in this task

reflected the joint contribution of two types of trials with efficient and inefficient target selection, respectively, N2pc onset should have been similar to the fixed color task, because it would be determined by the former type of trials. Furthermore, trials with less efficient target selection would have contributed to the average N2pc waveforms only at longer latencies. Therefore, the ascending flank of the N2pc in the free color-choice task should be less steep than in the fixed color task, but the N2pc should be more sustained, resulting in a delayed offset. An inspection of Figure 4 demonstrates that this predicted pattern for the time course of N2pc components in the two tasks was not observed. Target N2pc onset was clearly delayed in the free color-choice task, and there was no evidence for a more gradual rise or a delayed offset of the N2pc in this task relative to the fixed color task. These observations suggest that there was no explicit or implicit advance preparation for a specific color in the free color-choice task.

If participants did not choose a target color prior to search array presentation in the free color-choice task, how did targets get selected in this task? It was assumed that this selection was based on an intentional decision in favor of one of the two color singletons. However, one could argue that target color selection in the free color-choice task did not proceed in such an explicit top-down fashion, but was instead the outcome of bottom-up attentional competition between the two singletons (e.g., Desimone & Duncan, 1995), where random fluctuations in activation strength should eventually produce a winner even when top-down guidance is absent. Although this possibility cannot be decisively ruled out, it does not fit well with the observation that spatially selective ERP modulations in the free color-choice task were delayed by only 30 ms relative to the fixed color task. It seems plausible to assume that an exclusively bottom-up driven resolution of attentional competition between two equally salient singletons will develop gradually, and should therefore result in a substantially longer N2pc onset delay.

In summary, the present study investigated attentional selectivity in a task where target selection is voluntary, but is not guided by advance information about the target-defining feature, and contrasted this task with the more commonly studied situation where such advance information is available. Results demonstrated that even in the absence of preparatory attentional templates, intentional target selection produces spatially selective modulations of visual processing that emerge within 200 ms after stimulus onset. However, the speed and efficiency of target selection is considerably reduced relative to a situation where selection is guided by a preparatory feature-specific task set. William James (1890/1981) was the first to point to the critical role of anticipatory ideational preparation in selective attention, and the current study has demonstrated four general (and interlinked) benefits of this type of preparation: It speeds up attentional target selection, rapidly resolves attentional competition in favor of currently task-relevant visual stimuli, eliminates attentional capture by salient but irrelevant events, and prevents the entry of such events into working memory.

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