

The distractor positivity (Pd) signals lowering of attentional priority: Evidence from event-related potentials and individual differences

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Abstract

We investigated the effects of task demands and individual differences on the allocation of attention. Using the same stimuli, participants indicated the orientation of a line contained in a shape singleton (identification task) or the presence of singletons (detection task). Shape singletons in the identification task elicited a contralateral negativity (N2pc) whereas shape singletons in the detection task elicited a contralateral positivity (Pd). We suggest that the reduction of attentional priority of a salient stimulus, reflected by the Pd, occurred more rapidly with the less demanding detection task. Further, fewer distractible participants showed a larger N2pc to lateral color distractors than highly distractible participants. We suggest that highly distractible participants developed compensatory mechanisms to suppress distracting stimuli.

Descriptors: Visual search, Distractibility, N2pc, Pd, EEG, Saliency, Bottom-up, Top-down, Interindividual differences

Visual attention selects objects from the overwhelming amount of sensory information for processing in capacity-limited channels. Selection may be guided by the saliency of the stimuli (e.g., Itti & Koch, 2001) or by the goals of the observer (Wolfe, Friedman-Hill, & Bilsky, 1994). Stimulus-driven attentional control receives support from the additional singleton paradigm in which reaction times (RTs) are longer when the target is shown together with a salient but irrelevant distractor (Theeuwes, 1991). Support for goal-driven attentional control comes from the contingent attentional capture paradigm, where capture of attention only occurs when distractor and target features match (Folk, Remington, & Johnston, 1992). Distractor and target are shown simultaneously in the additional singleton paradigm, whereas the distractor precedes the target in the contingent attentional capture paradigm. However, the dichotomy between top-down and bottom-up attention may be unable to accommodate all relevant findings. Most prominently, it fails to explain effects of trial history (Awh, Belopolsky, & Theeuwes, 2012).

In the present contribution, we pursued two goals to better describe top-down effects in visual search. First, we investigated how task demands affect attentional selection. We compared a demanding identification task with a less demanding detection task using the same stimuli. We predict that an electrophysiological

index of attentional selection, the N2pc, would be reduced with the less challenging task. Second, we investigated how distractibility affects attentional selection. Markers of attentional selection are expected to change for highly distractible participants. We predict larger electrophysiological responses to distracting stimuli when participants are distractible.

Electrophysiological Correlates of Attentional Capture and Inhibition

The N2pc is greatest at posterior sites in the N2 latency range, about 200–300 ms after stimulus onset. It is defined as a negative deflection in electrodes contralateral to the target compared to ipsilateral electrodes. Functionally, this component is associated with the allocation of attention to task-relevant stimuli (Eimer, 1996; Mazza, Turatto, & Caramazza, 2009) or with the resolution of competition between target and distractors (Luck & Hillyard, 1994b; Luck, Hillyard, Mouloua, & Hawkins, 1996).

Recent studies confirmed an N2pc in the direction of a lateralized distractor when the target was above or below fixation, suggesting attentional capture by salient stimuli (Hickey, McDonald, & Theeuwes, 2006). However, the N2pc to salient distractors disappears with short stimulus presentation times (Kiss, Grubert, Petersen, & Eimer, 2012) and with predictable targets (Burra & Kerzel, 2013; Jannati, Gaspar, & McDonald, 2013). In addition, the effect disappeared when the number of participant in Hickey et al.'s original data set was increased to about 40 participants (McDonald, Green, Jannati, & Di Lollo, 2013). Instead of a negative deflection, the N2pc turned into a contralateral positivity for fast responses.

A positive deflection occurring during or following the classic N2pc time window has also been reported and was initially labeled

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distractor positivity, or Pd (Burra & Kerzel, 2013; Coriveau et al., 2012; Feldmann-Wustefeld & Schubo, 2013; Hickey, Di Lollo, & McDonald, 2009; Hilimire, Mounts, Parks, & Corballis, 2011; Jannati et al., 2013; Kerzel, Schonhammer, Burra, Born, & Souto, 2011; Kiss et al., 2012; Sawaki & Luck, 2010, 2011, 2013) The Pd is considered an index of distractor suppression (Sawaki & Luck, 2010) or distractor suppression to facilitate target processing (Hilimire, Hickey, & Corballis, 2012). More recently, Sawaki, Geng, and Luck (2012) proposed that the Pd reflects modulations of attentional priority. According to this account, the Pd occurs when participants prevent the allocation of attention to distractors, but also when they terminate the allocation of attention to the target after it has been perceived.

The time intervals used to measure the Pd vary considerably between studies. Early (Sawaki et al., 2012), intermediate (Hilimire et al., 2012), and late intervals (Kiss et al., 2012; Sawaki et al., 2012; Sawaki & Luck, 2011) have been investigated such that the analysis of both early and late intervals seems relevant (for a review, see Jannati et al., 2013). In fact, an early lateralized positivity (140–190 ms) has been identified in the N1 interval and has been labeled Ppc (Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicoeur, 2012; Leblanc, Prime, & Jolicoeur, 2008). As a positive counterpart of the N1pc (Verleger, Zurawska Vel Grajewska, & Jaskowski, 2012), the Ppc is at the interface between early low-level and later top-down processing and may reflect laterally imbalanced sensory activity or the most salient item in a salience map (Jannati et al., 2013).

Cognitive Failure Questionnaire and Neural Correlates

To explore the relation between attentional capture and distractibility in everyday life, we used the Cognitive Failure Questionnaire (CFQ, Broadbent, Cooper, FitzGerald, & Parkes, 1982), which measures a person's tendency to fail on tasks that he/she is normally capable of completing (Wallace, Kass, & Stanny, 2002). The CFQ is comprised of four factors (Wallace et al., 2002): The first factor, memory, explains most of the variance and is conceptually related to memory errors or forgetfulness (e.g., "Do you find you forget what you came to the shops to buy?"). The second factor, distractibility, reflects the disturbance of internally focused attention (e.g., "Do you daydream when you ought to be listening to something?") and explains far less variance. The third factor, blunders, is related to social blunders (e.g., "Do you say something and realize afterwards that it might be taken as insulting?") and poor motor control (e.g., "Do you drop things?"). The fourth factor reflects memory for names (e.g., "Do you find you forget people's names?"). It should be noted that the four factors are not independent, but correlated (Wallace, 2004).

A number of studies have shown that CFQ scores correlate positively with the size of distractor effects in Stroop-like (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Tipper & Baylis, 1987) and visual search tasks (Forster & Lavie, 2007; Kanai, Dong, Bahrami, & Rees, 2011), suggesting that individuals with high scores on the CFQ find it harder to inhibit irrelevant stimuli. In search of a neural substrate of distractibility, Kanai et al. (2011) showed that the distractibility scores of the CFQ correlated with the volume of gray matter in the superior parietal lobe. Transmagnetic stimulation (TMS) of this brain area increased distraction by color singletons in a visual search task (Kanai et al., 2011), while repetitive pulsing (rTMS) over the right parietal cortex decreased attentional capture (Hodsoll, Mevorach, & Humphreys, 2009). Both findings suggest a causal

link between the left superior parietal cortex and inhibition of salient distractors.

N2pc and Distractibility

The cortical area linked to distractibility is also associated with the N2pc. Even if the later stages of the N2pc (220–240 ms) are thought to result from processing in extrastriate areas of the occipital and inferior temporal cortex (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2011; Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004), it is interesting to note that a small contribution of the neural generators of the early N2pc (180–200 ms) are assumed to be located in the parietal lobe (Hopf et al., 2000). Further, TMS pulses over the right parietal cortex change the N2pc to a slightly positive deflection (Fuggetta, Pavone, Walsh, Kiss, & Eimer, 2006). Similarly, the process of distractor inhibition was found to reside in the left parietal lobe (Melloni, van Leeuwen, Alink, & Müller, 2012). Finally, the brain correlates of attentional processes underlying capture by additional singletons have been localized in the superior parietal cortex (de Fockert, Rees, Frith, & Lavie, 2004), which suggests an indirect but plausible link between neural activity in this region and attentional capture.

We investigated the relation between distractibility and electrophysiological correlates of attentional capture. Intuitively, distractible participants are expected to show stronger capture by distracting stimuli because their top-down control of attention is poor. This is expected to result in a larger N2pc to distractors. For the same reason, inhibition as indexed by the Pd may be weaker.

However, a less intuitive hypothesis may also be put forth. Distractible participants continuously experience their tendency to be attracted by salient stimuli and their inability to inhibit them. This experience may represent a continuous challenge that will eventually enhance their capacity to filter out irrelevant stimuli. If distractible participants had developed compensatory strategies or capacities, it may be that the N2pc to distracting stimuli would actually be smaller for highly than for less distractible participants.

Attentional Capture and Visual Short-Term Memory

The maintenance of information in visual short-term memory can be measured using the sustained posterior contralateral negativity (Jolicoeur, Brisson, & Robitaille, 2008) or the contralateral delay activity (CDA, Fukuda, Awh, & Vogel, 2010; Mazza, Turatto, Umiltà, & Eimer, 2007; McCollough, Machizawa, & Vogel, 2007; Pagano & Mazza, 2012, 2013; Vogel & Machizawa, 2004; Woodman & Vogel, 2008). Interindividual differences in visual search have been related to the amplitude of the CDA (Drew & Vogel, 2008; Luria & Vogel, 2011; Vogel, McCollough, & Machizawa, 2005), suggesting a link between visual search and working memory (Anderson, Vogel, & Awh, 2013; Anderson, Mannan, Rees, Sumner, & Kennard, 2010). It is possible that distractibility in everyday life is not so much related to early components such as the N2pc, but it could be related to later components that reflect memory processes. After all, some subscales of the CFQ refer to memory (see above).

Experiment 1

In order to characterize how the N2pc is related to CFQ scores, the following study was conducted. Participants searched for a shape singleton target and, on some trials, a color singleton distractor was presented. Figure 1 shows some sample displays. In the identifica-

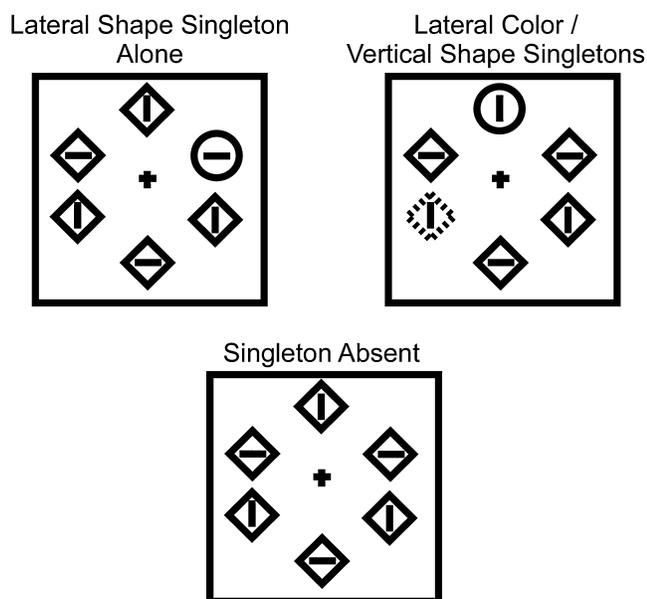


Figure 1. Example stimulus displays (not drawn to scale). In the visual search task, the target was a shape singleton (here, a circle). A color singleton distractor could also be present (here, dotted lines). In the detection task, there were displays without color or shape singleton (here, only diamonds).

tion task, observers reported the orientation of a line inside the target. We expect lateralized targets to result in an N2pc. In the critical condition, however, the target was on the vertical midline, and the distractor was lateralized. We therefore expect an N2pc to the lateralized distractor, but not to the vertical target, because the vertical target is equally represented in both hemispheres. Subsequently, the N2pc to the distractor was correlated with the CFQ scores.

In addition, we changed the task from identification to detection in order to evaluate the role of task demands on the time course of attentional priorities. In the detection task, observers were asked to indicate whether singleton elements were present in the display. Displays without singletons occurred on 20% of the trials. The singleton did not have to be identified. A similar task has been used by Luck and Hillyard (1994a), but we changed the rate of singleton-absent trials from 50% in their study to only 20%. We suggest that the detection task will use the same early processes as the identification task. Once the salient stimuli have been signaled in the saliency map, no further processing is required in the detection task, and attention, if it has been attracted by the salient stimuli, may be disengaged. According to Sawaki et al. (2012), the disengagement or lowering of attentional priority will result in a Pd.

Method

Participants. A total of 50 right-handed students (11 male, mean age of 21.6 years) at the University of Geneva without any neurological or psychiatric indications participated for course credit. Participants were naïve as to the purpose of the experiment. The local ethics committee had approved the study, and informed consent was obtained from participants prior to the experiment.

Questionnaire. All participants were asked to fill out the French version (Vom Hofe, Mainemarie, & Vannier, 1998) of the CFQ

(Broadbent et al., 1982). Participants rated the frequency of 25 common cognitive failures, with 0 indicating *never* and 4 *very often*.

Stimuli and design. We used the Cogent toolbox (www.vislab.ucl.ac.uk/Cogent2000) for MATLAB to display the stimuli. Six shapes were presented at 6° of eccentricity on a black background (see Figure 1). Diamonds (1.67° diameter) and circles (1.5° diameter) were drawn in red or green one-pixel (0.022°) lines. Inside every shape, a vertical or horizontal line (1.2° length) was drawn in gray. The luminance was ~11.6 cd/m² for red, green, and gray, and the perimeter of the squares and the diamonds was the same in order to ensure equal luminance. The shape and color of the array of stimuli varied randomly from trial to trial.

In the identification task, all displays contained one element with a shape different from the remaining elements (i.e., a shape singleton). In one third of the trials, there was only a shape singleton. In another third of the trials, the shape singleton was on the vertical midline, and a color singleton appeared at a lateral position. To counterbalance the position of the shape singleton with respect to the color singleton, we also included conditions in which the shape singleton and the color singleton were on the same or on opposite sides (one third of trials).

In the detection task, six elements with the same shape and same color were presented in singleton-absent trials (20% of the stimuli). All other stimuli were the same as in the identification task. The probabilities were 20% for displays with the same shape/color, 27% for the shape singleton alone, and 53% for shape with color singleton.

Procedure. Subjects were seated in a sound-attenuated room at 85 cm from a 17" LCD screen refreshed at 60 Hz. The order of conditions was randomized within each block of 48 trials. Half of the participants started with the identification and the other half with the detection task. Each trial began with a gray fixation cross on a black background for a random interval between 600 and 1,600 ms. The stimulus remained on the screen until a response was given.

In the identification task, participants were instructed to report the orientation of a line inside the shape singleton. In the detection task, participants indicated whether a singleton was present or not. Participants were asked to respond as quickly as possible while maintaining accuracy better than 90%. Responses were given using two keys of a standard keyboard with one hand (counterbalanced across subjects).

Incorrect responses were indicated by a message displayed at the center of the screen. Before the experiment, participants completed 48 trials of each task in which they were trained to maintain eye fixation. Each participant performed one session of 24 blocks with 48 trials each for 1,152 trials.

To evaluate effects of switching between the identification and detection tasks, we ran two different versions of the experiment. For 21 subjects in the final sample, the identification and detection task alternated after each block of 48 trials. The other 20 participants changed tasks only once after 576 trials. The mean age of the 41 participants (9 male) in the final sample was 21.5 years.

Electroencephalogram recording and analysis. A BioSemi B.V. (Amsterdam, The Netherlands) ActiveTwo amplifier system AD-Box with 64 active Ag/AgCl electrodes sampled at 1024 Hz was used. Moreover, we used the voltage difference of two horizontal electrooculogram (HEOG) electrodes, fixed at the outer

canthi of both eyes, to detect horizontal eye movements. Using BrainVision Analyzer 2.1 (Brain Products GmbH, Gilching, Germany), we low-pass filtered our data with a Butterworth filter (zero phase shift, 40 Hz with 24 db/octave), and we used the two earlobes as reference. In order to test the validity of the reference selection, we added the mastoids and the electrode average as references for those participants who switched tasks after 576 trials. However, the selected reference (earlobes, mastoids, or average) did not change the results of the analyses of variance (ANOVAs) reported below.

Baseline correction (−100 ms to stimulus onset) was performed before artifact exclusion. Electroencephalogram (EEG) epochs started 100 ms before the onset of the display and ended after 500 ms. We excluded blinks (Fpz \pm 60 μ V), ocular movements (HEOG \pm 40 μ V) during the first 300 ms, and all other artifacts (all electrodes \pm 100 μ V) during all periods. When we had doubts about the signal, epochs were checked manually. We computed the average for left and right target conditions separately and rejected one subject whose HEOG from 0 to 300 ms was larger than \pm 3 μ V (see Woodman & Luck, 2003).

Trials with wrong responses and trials with RTs smaller than 200 ms and larger than 2,000 ms were removed. Data from 9 subjects were discarded because of the large number of incorrect responses (less than 70% correct) or because of the large number of saccades (less than 70% valid epochs). In total, data from 41 participants were retained.

Data Treatment

In both tasks, a condition with lateral color and shape singletons was added to reduce the predictability of target and distractor location. However, this condition does not respond to the experimental questions because attentional capture and inhibition may cancel each other. We therefore did not report results from this condition. Similarly, we did not report the event-related potentials (ERPs) from singleton-absent trials in the detection task.

Preliminary analysis showed that the frequency of task switching (after blocks of 48 or 576 trials) did not have a main effect and did not interact with any of the remaining factors on any of the dependent variables reported below. We therefore did not include this factor in the final analyses.

Throughout, we controlled for the familywise error of follow-up *t* tests by Bonferroni correction. For clarity, the uncorrected *p* values are reported, and tests that were nonsignificant after Bonferroni correction are mentioned.

Behavioral Results

CFQ. As suggested by the literature, most of the subtests of the CFQ are correlated. Table 1 shows the correlations and median scores.

Reaction time. Table 2 shows the mean RTs and accuracy for all conditions. A repeated measures, two-way ANOVA, 2 (Tasks: identification, detection) \times 2 (Singleton conditions: lateral shape singleton alone, lateral color/vertical shape singleton) revealed longer RTs in the identification compared to the detection task (1,091 vs. 580 ms), $F(1,40) = 539.62$, $p < .001$, $\eta_p^2 = .93$, confirming that identification was more demanding than detection. A significant interaction of singleton condition and task was observed, $F(1,40) = 130.64$, $p < .001$, $\eta_p^2 = .76$. Follow-up *t* tests were carried

Table 1. Spearman's Rank Order Correlation Between Different Subscales of the CFQ in Experiment 1

	1	2	3	4	5	Median
1. Memory	–	–	–	–	–	10
2. Distractibility	.69**	–	–	–	–	17
3. Blunders	.49*	.53**	–	–	–	10
4. Name	.167	.34*	.37*	–	–	2
5. Total	.807**	.902**	.77**	.478*	–	41

Note. $N = 41$.

* $p < .01$. ** $p < .001$.

out separately for each task. In the identification task, RTs were shorter to lateral shape singletons alone than to lateral color/vertical shape singletons (1,037 vs. 1,145 ms), $t(40) = -8.73$, $p < .001$, confirming attentional capture by the irrelevant color singletons. In contrast, RTs in the detection task were shorter to lateral color/vertical shape singletons than to lateral shape singletons alone (556 vs. 605 ms), $t(40) = 7.71$, $p < .001$, demonstrating that observers took advantage of redundantly defined singleton-present displays.

Accuracy. Analyzing accuracy with the same ANOVA as above, we found a main effect of task, $F(1,40) = 169.58$, $p < .001$, $\eta_p^2 = .80$, with lower accuracy in the identification than in the detection task (.93 vs. .99), and a main effect of display, $F(1,40) = 10.44$, $p = .002$, $\eta_p^2 = .20$, with higher accuracy for lateral shape singletons alone than for lateral color/vertical shape singletons (.96 vs. .95). Additionally, an interaction effect emerged, $F(1,40) = 18.26$, $p < .001$, $\eta_p^2 = .31$. Follow-up *t* tests revealed that accuracy was better for shape singletons alone in the identification task (.94 vs. .92), $t(40) = 3.85$, $p < .001$, but not in the detection task (.995 vs. .992), $p = .5$.

Singleton-absent trials. In singleton-absent trials of the detection task, mean RT and accuracy was 658 ms and .92, respectively. In a one-way ANOVA, we compared the singleton-absent trials to trials with lateral shape singleton alone and lateral color/vertical shape singletons (detection task only). There was a main effect of singleton condition on RTs, $F(1.44, 57.78) = 93.75$, $p < .001$, $\eta_p^2 = .7$, and accuracy, $F(1.06, 42.46) = 79.81$, $p < .001$, $\eta_p^2 = .66$, showing that singleton-absent trials were responded to more slowly, $t(40) > 7.08$, $ps < .001$, and with less precision.

ERP Results

N2pc (270–320 ms). Figure 2 shows that the N2pc and the Pd were maximal between 270–320 ms. A repeated measures, two-way ANOVA, 2 (Tasks: identification, detection) \times 2 (Singleton conditions: lateral shape singleton alone, lateral color/vertical shape singleton) was conducted on the mean amplitudes. The main effect of task reached significance, $F(1,40) = 19.38$, $p < .001$, $\eta_p^2 = .32$, with a more negative mean amplitude in the identification than in the detection task (−0.31 vs. 0.35 μ V). There was an interaction of task and singleton condition, $F(1,40) = 26.22$, $p < .001$, $\eta_p^2 = .40$. For the lateral shape singleton alone, there was a difference between identification and detection tasks (−0.59 vs. 0.71 μ V), $t(40) = -6.15$, $p < .001$. For the lateral color/vertical shape singleton, the difference between identification and detection task was not significant (−0.04 vs. −0.008 μ V), $p > .8$.

Table 2. Mean Response Time (RT) and Accuracy for Identification and Detection Tasks in Experiment 1

Singleton position	Identification task		Detection task	
	RT	Accuracy	RT	Accuracy
Lateral shape singleton, no color singleton	1,037 (22)	.95 (.005)	605 (21)	.99 (.001)
Lateral color singleton, vertical shape singleton	1,145 (25)	.92 (.007)	556 (23)	.99 (.001)
Singleton absent			658 (9)	.92 (.008)

Note. Standard error of the mean is given in parenthesis. The shape singleton was the target in the visual search task.

We tested the reliability of the lateralized components by t test against zero. The lateral shape singleton alone evoked a significant N2pc component in the identification task ($-0.59 \mu\text{V}$), $t(40) = 4.17$, $p < .001$, and a significant positivity in the detection

task ($0.71 \mu\text{V}$), $t(40) = 4.78$, $p < .001$. In contrast, the lateral color/vertical shape singleton did not result in a significant lateralized component in the identification ($-0.04 \mu\text{V}$), $p = .822$, and detection tasks ($-0.008 \mu\text{V}$), $p = .93$.

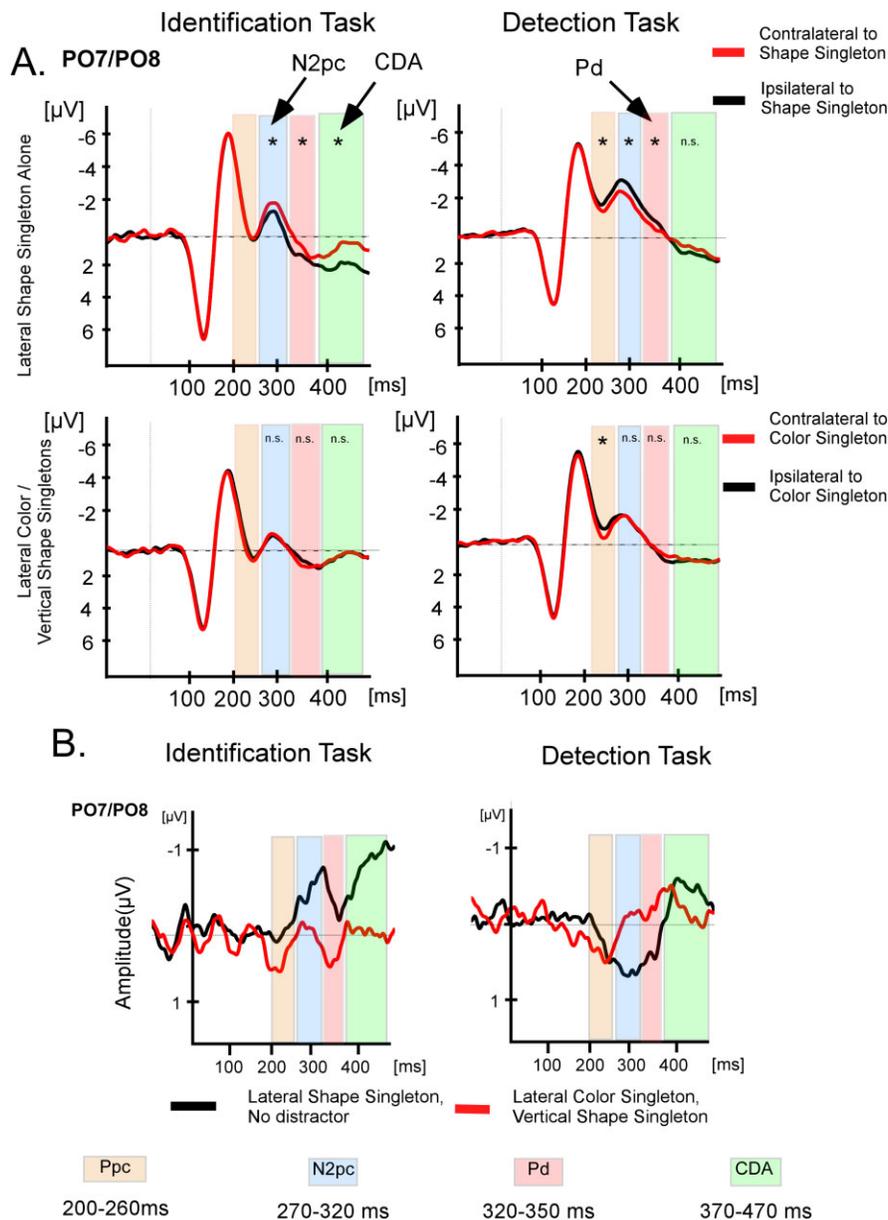


Figure 2. Results of Experiment 1. A: Grand averages for ipsi- and contralateral PO7/PO8 electrodes for lateral shape singletons alone (first row) and lateral color/vertical shape singletons (second row). B: The difference waveforms were obtained by subtracting the ipsilateral from the contralateral waveforms (PO7/PO8). Note the difference in scale between panels A and B. * $p < .05$ (uncorrected).

Pd (320–350 ms). Further, we ran the same ANOVA as above on the interval from 320–350 ms, which is typically associated with the Pd. In addition to a main effect of task, $F(1,40) = 7.63, p = .009, \eta_p^2 = .16$, there was an interaction, $F(1,40) = 24.89, p < .001, \eta_p^2 = .38$. For the lateral shape target alone, there was a negative lateralized component in the identification task ($-0.62 \mu\text{V}$), and a positive component in the detection task ($0.52 \mu\text{V}$). The two means were significantly different, $t(40) = -4.99, p < .001$, and the negative component in the identification task ($-0.62 \mu\text{V}$), $t(40) = -4.1, p < .001$, and the Pd in the detection task ($0.52 \mu\text{V}$), $t(40) = 3.12, p = .003$, were significantly different from zero. For the lateral color singleton/vertical shape singletons, we did not find a significant difference between the identification and detection tasks (0.31 vs. $-0.1 \mu\text{V}$), $p > .08$.

Late Ppc (200–260 ms). Inspection of Figure 2B suggests that there was a positive deflection for all singleton conditions in the interval before the classic N2pc but later than the classic Ppc (140–190 ms) interval, very close to the Pd interval thought to represent suppression of the “attend-to-me signal” (Sawaki & Luck, 2010). The same two-way ANOVA as above showed an effect of task, $F(1,40) = 9.69, p = .003, \eta_p^2 = .19$, with a more positive amplitude for the detection than for the identification task (0.41 vs. $0.1 \mu\text{V}$), and an effect of color singleton condition, $F(1,40) = 4.25, p = .046, \eta_p^2 = .096$, with a more positive amplitude for the lateral color/vertical shape singleton ($0.36 \mu\text{V}$) than the lateral shape target alone ($0.15 \mu\text{V}$). The interaction was not significant, $p = .32$. In the detection task, the Ppc was significantly larger than zero for lateral shape singletons alone ($0.37 \mu\text{V}$), $t(40) = 3.6, p = .001$, and for lateral color/vertical shape singletons ($0.46 \mu\text{V}$), $t(40) = 4.26, p < .001$.

CDA (370–470 ms). The CDA was more negative with lateral shape singletons alone than with lateral color and vertical shape singletons (-0.89 vs. $-0.53 \mu\text{V}$), $F(1,40) = 9.94, p = .003, \eta_p^2 = .19$. The interaction between task and singleton condition was significant, $F(1,40) = 5.07, p = .03, \eta_p^2 = .11$. In the identification task, the CDA was larger with lateral shape singletons alone than with lateral color/vertical shape singletons (-0.77 vs. $-0.44 \mu\text{V}$), $t(40) = -3.35, p = .001$. There was no difference between the two singleton conditions in the detection task, $p = .36$. Further, the CDA was only significantly larger than zero in the identification task with lateral shape singletons alone ($-0.77 \mu\text{V}$), $t(40) = 4.35, p < .001$.

Nonparametric analyses. Following Sawaki et al. (2012), we used a nonparametric permutation method to test for the presence of the Pd in an extended time window from 150 to 350 ms. Because there is considerable variability between studies with respect to the time interval that was analyzed, it seems necessary to show that a positive deflection was significant regardless of the exact time window. To this end, we randomly recoded ipsi- and contralateral target positions in 1,000 permutations and calculated the positive area under the resulting grand-average waveforms from 150 to 350 ms. The resulting distributions are shown in Figure 3 and provide an estimate of the variability in the data. Then, we determined how many percent of the values in the noise distribution were smaller than the positive area of the actual grand-average waveform. The test was significant if the observed value was in the extreme 5% of the simulated values. We focused on the condition that yielded a significant Pd in the analyses above (i.e., the condition with lateral shape singleton alone). For the detection task, we

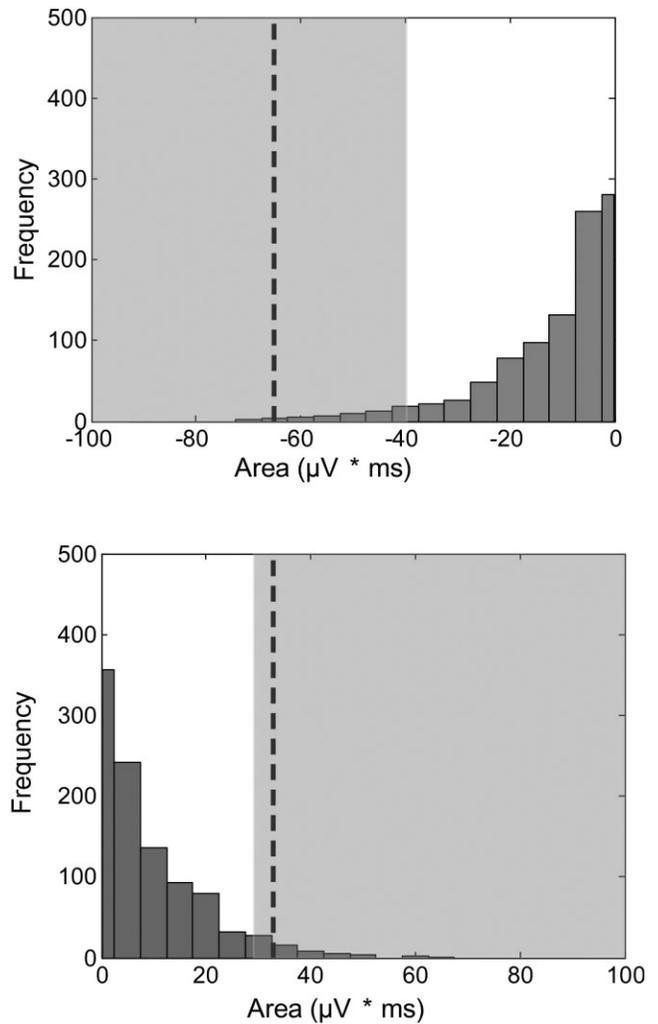


Figure 3. Permutation tests of the negative and positive areas under the grand-average waveforms from 150 to 350 ms in the identification task (top panel) and the detection task (bottom panel). For both tasks, the condition with a lateral shape singleton without color singleton was analyzed. The gray bars show the estimated noise distribution after 1,000 permutations. The black dotted lines represent the observed negative and positive areas (N2pc and Pd, respectively) in the grand-average waveforms. The gray areas indicate the extreme 5% of the distribution. Because the black dotted lines fall inside the gray regions, the observed values are significantly greater than would be expected by chance.

found that the positive area was significant, $p < .001$. By analogy, we ran the same analysis on the N2pc in the identification task and confirmed a significant negative area, $p < .05$. The test on the conditions with lateral color/vertical shape singletons did not reach the level of significance in either task.

Correlations between CFQ and behavioral data. As in Kanai et al. (2011), we correlated the capture effect with the CFQ subscales. A significant Spearman rank order correlation between the subscale memory and the capture effect was confirmed, $r_s(39) = -.41, p = .007$, and is shown in the top panel of Figure 4. Surprisingly, participants that are more distractible showed a smaller attentional capture effect.

Correlations between CFQ and electrophysiological data. The bottom panel of Figure 4 shows a scatter plot of CFQ scores and

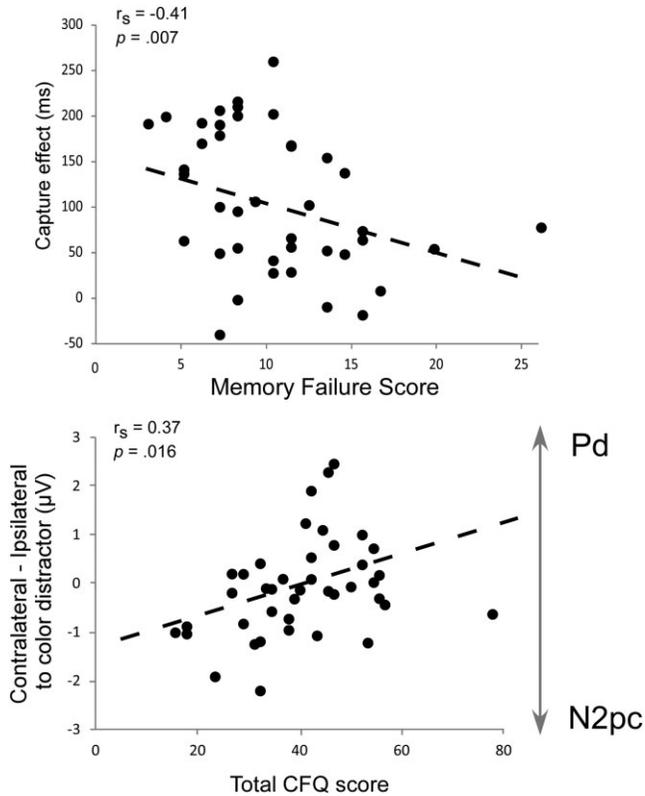


Figure 4. The top panel shows the scattergram of the behavioral capture effect and the memory failure score of the Cognitive Failure Questionnaire (CFQ). The bottom panel shows the scattergram of the N2pc/Pd to the irrelevant color singleton and the total CFQ score. Even without the outliers (surrounded points), the correlations are significant.

mean ERPs to lateral distractors in the identification task from 270–320 ms. Less distractible participants showed larger N2pc components to distractors than highly distractible participants. This counterintuitive result was confirmed by the significant Spearman rank order correlation between N2pc amplitude and CFQ scores, $r_s(39) = .37, p = .016$. When looking at the different scales of the CFQ, we found only small variations between the subscales distractibility, $r_s(39) = .31, p = .046$, and names, $r_s(39) = .45, p = .003$, but no correlation with the subscale memory, $r_s(39) = .13, p = .42$. No further correlations were observed between the total CFQ scores and the N2pc, Pd, or the Ppc in the other conditions.

Figure 5 shows a scatter plot of CFQ scores and the mean ERPs to lateral shape targets alone in the identification task from 370–470 ms. Participants with low CFQ scores had a large CDA, while participants with high scores had a small CDA close to zero. This impression was confirmed by a significant Spearman rank order correlation between the CDA to the lateral shape target alone and the total score of the CFQ, $r_s(39) = .402, p = .009$. The correlation was also significant with the memory scale, $r_s(39) = .421, p = .006$, and the distractibility scale, $r_s(39) = .320, p = .042$.

Median split by CFQ. In order to confirm the correlation between the ERP components and the CFQ, we created two groups of 20 participants with CFQ scores below and above the median CFQ score. The subject with the median value was excluded. Mean ERPs are shown in Figure 6.

In the identification task, components from 270–320 ms to lateral color singletons and vertical shape singletons differed between subjects with high and low CFQ scores (-0.59 vs. $0.44 \mu\text{V}$), $t(38) = -3.6, p = .001$. The N2pc was significant for participants with low CFQ scores, $t(19) = -3.59, p = .002$, and the positive difference for subjects with high CFQ scores approached significance, $t(19) = 1.89, p = .074$. In the following interval from 320–350 ms, the positive difference also approached significance for participants with high CFQ scores ($0.61 \mu\text{V}$), $t(19) = 2.11, p = .04$. The Bonferroni-adjusted critical p value for three tests is .0167.

The component from 370–470 ms to a lateral shape singleton alone in the identification task differed between subjects with high and low CFQ (-1.34 vs. $-0.2 \mu\text{V}$), $t(38) = -3.52, p = .001$. The CDA was significant for participants with low CFQ scores, $t(19) = -6, p < .001$, but not for participants with high CFQ scores, $p = .35$.

Experiment 2

In order to rule out the possibility that the Pd or the N2pc were caused by luminance differences in the stimuli, we ran a control experiment with the same displays. Participants performed a categorization task at central fixation instead of the identification and detection tasks used in Experiment 1. Thus, the peripheral stimuli were completely task irrelevant. Figure 7A shows a sample stimulus.

Method

The same displays as in the identification task of Experiment 1 were shown. Observers were asked to judge whether a stimulus presented at central fixation was a number or a letter by key press. The letters appeared at the same time as the peripheral stimuli and subtended 0.25° vertically. Observers worked through 6 blocks of 96 trials. Thirteen students (4 male, mean age of 23.1 years) participated for pay.

Results

Behaviorally, the presence of a color distractor did not change RTs (557 vs. 559 ms) or accuracy (.96 vs. .96), $ps > .35$. The grand-average waveforms are shown in Figure 7B. Data treatment

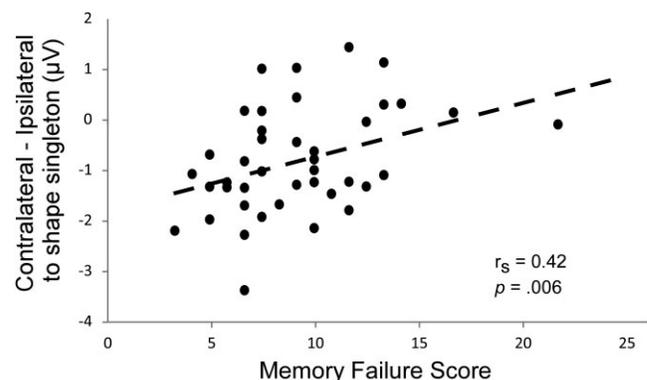


Figure 5. Scattergram of amplitude of the CDA and the memory subscale of the CFQ. Even without the outliers (surrounded points), the correlation is significant.

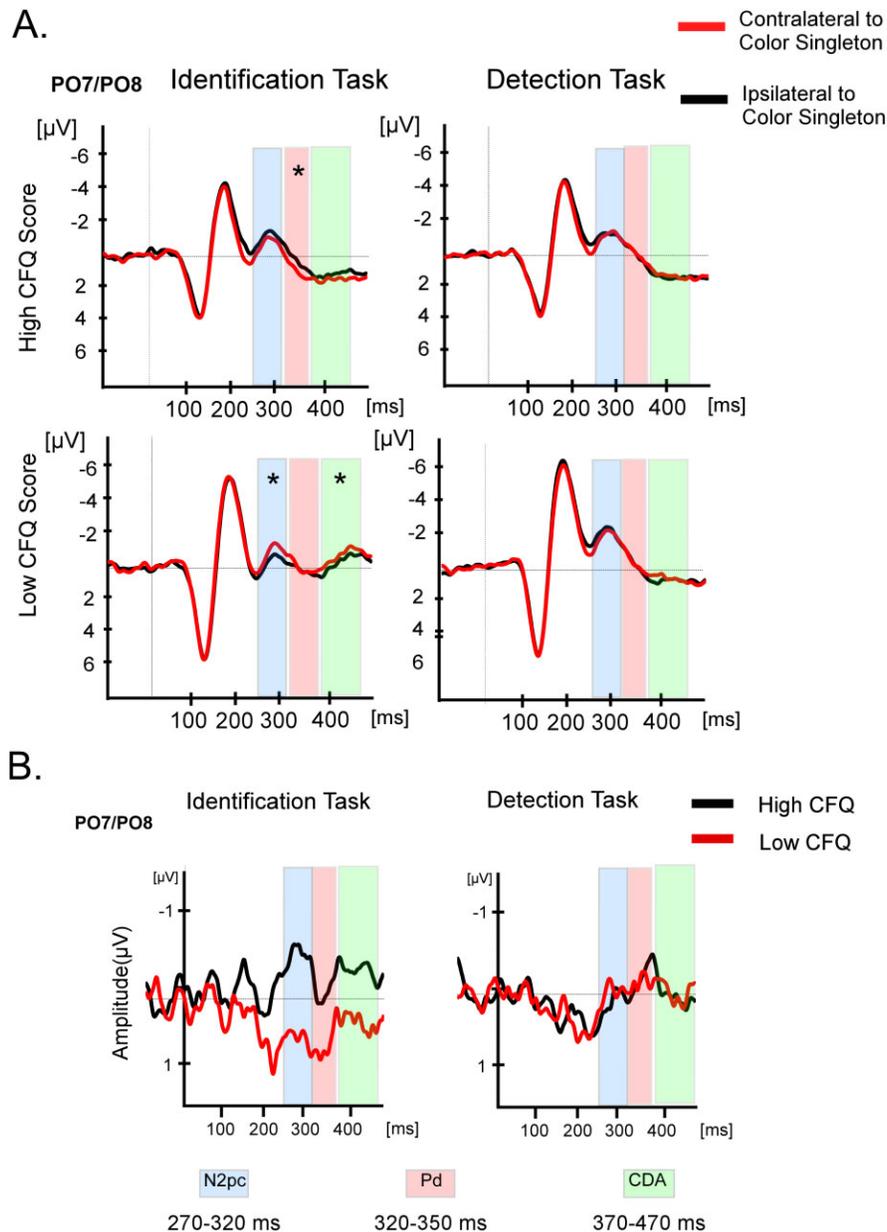


Figure 6. Results of Experiment 1 as a function of the score on the Cognitive Failure Questionnaire (CFQ). A: Grand averages for ipsi- and contralateral electrodes in the condition with lateral color and vertical shape singletons as a function of task and CFQ score. B: The difference waveforms obtained by subtracting the ipsilateral from the contralateral waveforms (PO7/PO9). Note the difference in scale between panels A and B. * $p < .05$ (uncorrected).

was as in Experiment 1, and 7% of the data were removed due to errors or artifacts. In the two early time intervals identified in Experiment 1, from 200–260 ms and from 270–320 ms, we failed to find significant lateralized ERPs, $ps > .09$. We did not find any correlation between the 270–320 ms time intervals and the CFQ. The permutation test failed to indicate the presence of a Pd in the interval from 150–350 ms. Because the N2pc and Pd were not observed with a task at central fixation, we conclude that search-related processes and not luminance differences account for the results of Experiment 1.

Discussion

Based on recent discussions on the functional significance of the Pd and reports on the neural substrate of interindividual differences in

distractibility, we measured event-related potentials in two tasks that involved either identification or detection of singletons, sometimes in the presence of distracting stimuli. Additionally, we measured the frequency of cognitive failures in everyday life by means of the CFQ and correlated CFQ scores with an electrophysiological measure of attentional deployment to distracting stimuli.

Effects of Task Requirements

Our results show that the N2pc can be reversed by task requirements even if the physical stimulus is the same. The identification task required the localization of a shape singleton, and attention had to be allocated to its location in order to discriminate the orientation of the line. Using the same stimuli, we asked observers to report the presence of a singleton in the detection task. We

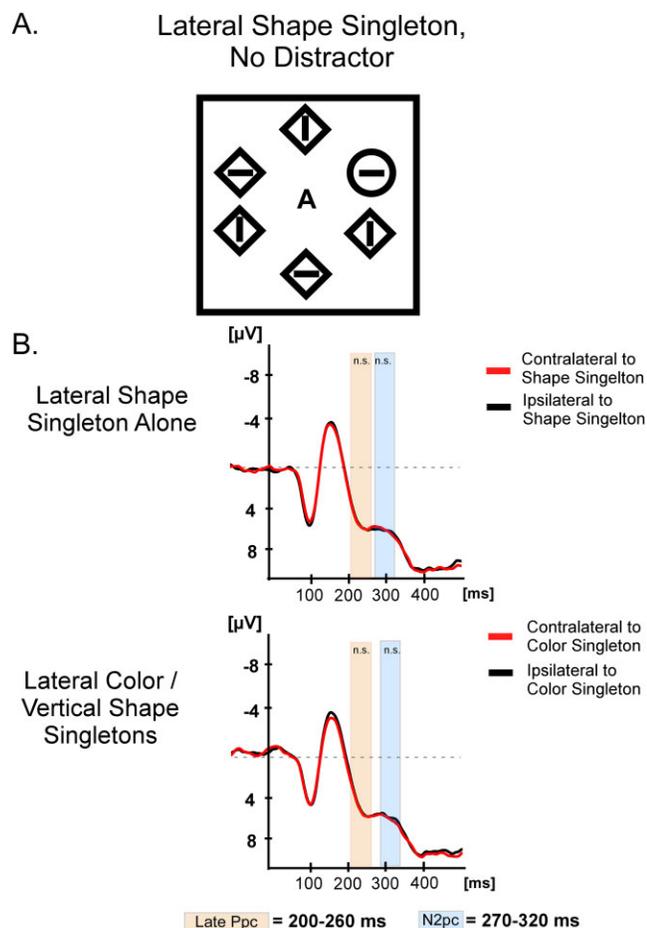


Figure 7. Stimuli and results from Experiment 2. A: Example display (not drawn to scale). The center item could be a letter or a number. B: Grand averages for ipsi- and contralateral electrodes in the condition with lateral shape singleton alone and in the condition with vertical shape and lateral color singleton.

observed that the N2pc to the shape singleton targets in the identification task turned into a Pd in the detection task. Thus, depending on the task of the observer, the same shape singleton produced opposite lateralization of ERP components.

The attenuation of the N2pc by task demands is consistent with a previous study by Luck and Hillyard (1994a). They confirmed an N2pc to salient pop-out targets, but only when they were task relevant. They also used a detection task, but, contrary to the present study, observers had to indicate whether a specific singleton was present. On half of the trials, singletons were absent, and on the remaining trials, color, orientation, or size singletons were presented. Only one of those singletons was the target, so that target-present trials had a probability of 17% and were therefore rather rare. In contrast, singleton-present trials in our detection task had a probability of 80% and were therefore frequent. The shape singleton was present in all singleton-present trials, whereas the color singleton only in 66.2% of those trials (or 53% of total trials). Thus, participants expected to see shape singletons more often than color singletons or singleton-absent trials. In contrast, Luck and Hillyard's (1994a) subjects expected to see no singleton trials (50%) and irrelevant singletons (33%) more often than the target singleton (17%). The different expectancies may have called for

some in-depth examination of a weak search template in Luck and Hillyard ("Is this really the target?"), whereas there was rapid verification of a strong search template in our study ("Is this a shape singleton that I saw before?"). Thus, it is not only the detection task itself that determines whether singletons are attended or inhibited, but the trial context and the resulting expectancies have to be taken into account (cf. Töllner, Müller, & Zehetleitner, 2012). As a case in point, we observed shorter RTs when singletons were present than when they were absent. This pattern was reversed in Luck and Hillyard (1994a) with the slowest RTs to the target singletons.

Pd Reflects Lowering of Attentional Priority

In the present study, the different requirements of identification and detection tasks turned the N2pc into a Pd (cf. Figure 2A, top row). Because the stimuli were the same, we assume that the saliency signal (Sawaki et al., 2012; Sawaki & Luck, 2010) that was generated by the singletons was the same in the two tasks. How did the different task sets produce the different patterns of ERPs? The identification task required the allocation of attention to the shape singleton to allow for fine discrimination of the line orientation. The detection task was less demanding because only the presence of the singleton had to be signaled and the shape singleton was extremely frequent, which may have induced a stable search template. Neither its location nor its identity was important. Because there was no singleton to be identified, it seems unlikely that the Pd to the shape singleton in the detection task served target resolution as hypothesized by Hilimire, Hickey, and Corballis (2012). Rather, it seems likely that it was possible to lower the attentional priority of the shape singleton rapidly after its detection based on the saliency signal. Actually, the Pd was already visible in an early interval (late Ppc from 200–260 ms), which is consistent with the succession of saliency perception and the early suppression of the resulting attend-to-me signal (Jannati et al., 2013; Sawaki et al., 2012; Sawaki & Luck, 2010). Because singletons did not have to be distinguished, it made no sense to stay focused on the singletons.

Additional evidence for low-priority processing in the detection task is the lack of a CDA in this condition. In the identification task, a CDA occurred showing that the target was efficiently maintained in visual working memory (Vogel & Machizawa, 2004; Vogel et al., 2005) or that detailed object identity was retrieved from visual working memory (Töllner et al., 2012). In the detection task, no CDA was detected, which is consistent with the assumption that no in-depth processing occurred and that the target's attentional priority was rapidly lowered.

In contrast to lateral shape singletons, there was no Pd to lateral color singletons in the detection task. Possibly, the lower frequency of color singletons resulted in search templates that were less stable than for the shape singletons or participants simply focused on the shape singleton because only the shape singleton reliably signaled singleton-present trials.

Distractibility Correlates with the N2pc to Distractors

We observed that the amplitude of the N2pc to the lateral distractors in the identification task was correlated with cognitive failures in everyday life as measured by the CFQ. Surprisingly, the

distractor-related N2pc was larger when participants had low CFQ scores than when they had high CFQ scores. Under the typical interpretation that CFQ scores reflect distractibility (e.g., Forster & Lavie, 2007; Kanai et al., 2011), our results suggest that less distractible participants allocate more attention to the distractor than highly distractible participants do. Intuitively, one would have predicted the opposite. However, the RT data confirm the counterintuitive result. Subjects with high scores on the memory failure subscale show smaller attentional capture in the RT data and are therefore better at inhibiting distracting stimuli than subjects with fewer memory failures.

Even if this effect is counterintuitive, some past results validate our data. Action video game players and media multitaskers show less attentional capture by a salient distractor in the additional singleton paradigm (Cain & Mitroff, 2011; Chisholm, Hickey, Theeuwes, & Kingstone, 2010). Both populations deal more frequently with distracting stimuli in everyday life. Therefore, they may have developed a higher proficiency to suppress distracting stimuli. The idea is that these populations have developed compensatory behavioral capacities to deal with situations that overload attentional and cognitive systems.

Kanai et al. (2011) developed a similar argument to explain the larger volume in the left superior parietal lobule of distractible subjects. Kanai et al. speculated that structural changes in the left superior parietal cortex provide distractible subjects with the necessary top-down control to function normally in daily life. According to this account, the source of distractibility would be elsewhere in the cortex, but structural changes compensate for high distractibility.

A similar logic may be applied to our results. When confronted with distracting stimuli, highly distractible participants compensate by inhibiting salient stimuli more vigorously. Therefore, the N2pc to lateral color distractors was absent and the median split analysis showed that there were some hints of a Pd, which is associated with inhibition. The question arises as to what degree conscious strategies of participants with low and high distractibility differed. Because the CFQ is a self-assessed questionnaire, it is plausible that participants were aware of their own distractibility and absent-mindedness. Because metacognition of the visual search strategy has been associated with a decrease of the attentional capture effect (Proulx, 2011), it is possible that knowledge about their distractibility contributed to reducing attentional capture and the associated N2pc.

While highly distractible participants showed more inhibition than less distractible participants did, less distractible participants showed stronger indices of active maintenance of the stimuli in working memory (cf. correlation CFQ–CDA). We speculate that highly distractible participants have learned to compensate for their distractibility at the level of attentional selection, which explains why they showed less attentional capture. However, the correlation between CDA and CFQ shows that transfer into working memory was poor in highly distractible participants, but this aspect did not disrupt performance in the present task.

When does the CFQ Correlate with Inhibition?

We found that attentional capture in RTs was negatively correlated with the memory failure subtest of the CFQ. In contrast, Kanai et al. (2011) reported a positive correlation. As a behavioral index of attentional capture, they calculated the RT differences between a condition in which target shape and color singleton distractor were

separate objects and a condition with a target shape that was also a color singleton. That is, the color singleton could appear on the target (i.e., a combined color and shape singleton), which radically changes the strategy used during the task. In our experiments, observers knew that the shape target would never occur on the color singleton and the color singleton could therefore be ignored, whereas participants in Kanai et al.'s experiment could not exclude the color singleton from search.

Further, the target shape was fixed in Kanai et al.'s (2011) study. We recently reported that the predictability of the target shape strongly modulated the N2pc in response to distractors (Burra & Kerzel, 2013), and we therefore speculate that differences in target predictability may account for the discrepancy between our results and those of Kanai et al. In fact, Broadbent et al. (1982) suggested that participants with low CFQ scores are better able to take advantage of advance information about the target location. This claim is corroborated by less distraction for participants with low CFQ scores when the location of the distracting stimuli is fixed (e.g., above or below the target word, Tipper & Baylis, 1987).

Overall, a mixed picture of the relationship between inhibition and CFQ scores emerges. Better inhibition in participants with low CFQ scores has been reported for conditions with predictable location or shape of the distractor. In the present experiment, neither location nor shape was known in advance, which may explain why we observed better inhibition in participants with high CFQ scores.

Finally, our data constrain the reliability of the N2pc as a marker of attentional capture. Recently, it was suggested that the N2pc toward distractors is simply the result of a noisy signal (McDonald et al., 2013). Our study shows that the noise may be reduced by considering interindividual differences in distractibility. The median split by CFQ score showed that attentional capture by color distractors occurs in participants with low CFQ scores. For low-CFQ participants, the N2pc to visual distractors was significant. In a previous study, we found the N2pc to distractors significant for the complete sample (Burra & Kerzel, 2013), but this result may have to be taken with caution because distractibility was not measured. Future research needs to consider interindividual differences in order to arrive at reliable conclusions as to attentional capture.

Conclusions

Overall, our results suggest that the Pd is related to the lowering of attentional priority. Initially, singleton stimuli generate a saliency signal, which was also referred to as "attend-to-me signal" (Sawaki & Luck, 2010). When the task demands were low, such as in our detection task, the attentional priority of the shape singletons was rapidly decreased, which resulted in a Pd. Target processing in the identification task made it necessary to keep the attentional priority high, which resulted in an N2pc. Further, interindividual differences suggest that highly distractible participants activate more neural resources to suppress salient distractors than less distractible participants do. When pooling less distractible and highly distractible participants, the N2pc toward the salient distractor may seem unreliable. We suggest that interindividual differences modulate the level of distractor inhibition and therefore dramatically change the behavioral and electrophysiological results in the additional singleton paradigm.

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