Redundancy gains in pop-out visual search are determined by top-down task set: Behavioral and electrophysiological evidence

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We combined behavioral and electrophysiological measures to find out whether redundancy gain effects in pop-out visual search are exclusively determined by bottom-up salience or are modulated by top-down task search goals. Search arrays contained feature singletons that could be defined in a single dimension (color or shape) or redundantly in both dimensions. In the baseline condition, both color and shape were task-relevant, and behavioral redundancy gain effects were accompanied by an earlier onset of the N2pc component for redundant as compared to single-dimension targets. This demonstrates that redundancy gains are generated at an early visual–perceptual level of processing. In the color target and shape target conditions, only one dimension was task-relevant, while the other could be ignored. In these two conditions, behavioral and electrophysiological redundancy gains were eliminated. We conclude that redundant-signals effects in pop-out visual search are not driven by bottom-up salience but are instead strongly dependent on top-down task set.

Keywords: visual search, visual salience, top-down control, ERPs, N2pc, attention

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Introduction

It is a well-known fact that reaction times (RTs) in response to targets that are defined in more than one response-relevant dimension are faster than RTs to targets that are defined in just one dimension. Such RT benefits for redundantly defined targets have been termed redundantsignals effects (RSEs) or redundancy gains. They can be found during visual search for feature singletons (e.g., Krummenacher, Müller, & Heller, 2001, 2002). For example, when observers search for targets that differ from uniform distractor items either in terms of their color or their orientation (singly defined targets), or both in their color and in their orientation (redundantly defined targets), redundant targets are detected faster (Krummenacher et al., 2002). Redundancy gains in pop-out visual search are assumed to be the result of integrating the outputs of independent dimension-specific processing systems, such as color or orientation modules (e.g., Feintuch & Cohen, 2002; Krummenacher et al., 2001, 2002; Mordkoff & Miller, 1993; Mordkoff & Yantis, 1993; Zehetleitner, Krummenacher, & Müller, 2009). While some have argued that the integration of redundant signals occurs at post-selective processing stages that follow attentional target selection (e.g., Feintuch & Cohen, 2002), there is now substantial behavioral and electrophysiological evidence that redundancy gains in pop-out visual search have an early pre-attentive perceptual locus and primarily reflect the expedited attentional selection of redundant as compared to singly defined feature singleton targets (Krummenacher et al., 2002; Töllner, Zehetleitner, Krummenacher, & Müller, 2010; for a review, see Zehetleitner, Müller, & Krummenacher, 2008).

The hypothesis that redundancy gains in visual search are generated at early perceptual stages of visual processing is in line with current models of visual search that assume that target detection is guided by the integration of dimension-specific saliency signals (Cave & Wolfe, 1990; Found & Müller, 1996; Itti & Koch, 2000; Koch & Ullman, 1985; Müller, Heller, & Ziegler, 1995; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989; see Matusz & Eimer, 2011, for evidence that this integration can also operate across sensory modalities). An initial rapid visual analysis yields a number of local feature contrast maps for different feature dimensions such as color or orientation. These maps specify how similar or distinct a specific visual field location is relative to its neighboring locations. For example, a red vertical bar among green vertical bars will produce a high local feature contrast signal for color but not for orientation. Feature contrast signals are generated independently in dimension-specific modules (such as color, orientation, size, etc.; see Wolfe, 1998; Wolfe & Horowitz, 2004 for an overview of dimensions in visual search) and are then combined onto a supradimensional salience map. A particular location on this salience map will be highly activated if it receives input from more than one dimension-specific map. This will be the case if a particular item differs from adjacent items in several feature dimensions, while all other items are perceptually homogeneous (e.g., Duncan & Humphreys, 1989). A local contrast signal on the salience map reflects the presence of one or more feature differences at this location but does not specify the actual featural or dimensional identity of this difference.

The attentional selection of specific visual stimuli is guided by the current activation profile of the salience map, as attention is directed first to the most strongly activated location. This salience-based model of attentional selection provides a simple explanation for the presence of redundancy gains in singleton visual search. When targets can be selected fast and efficiently, subsequent processes that depend on selective attention (such as visual object recognition and response selection) will also be expedited. Target selection is optimal when the activation difference between the target location and that of other competing locations on the salience map is maximal. This is the case for redundant targets (e.g., targets defined by a unique color and orientation). Such targets will generate high local feature contrast signals in more than one dimensionspecific map, which will result in a stronger local contrast signal on the salience map than is produced by targets that are defined within a single feature dimension. Therefore, the attentional selection of redundant targets is more efficient, resulting in faster RTs relative to singly defined targets.

It is often assumed that local feature contrast signals in dimension-specific maps and their integration in salience maps are determined solely by the physical properties of visual search displays and are independent of the search intentions of an observer (e.g., Itti & Koch, 2000). In this case, redundancy gains in singleton visual search should depend exclusively on the relative bottom-up salience of target stimuli, and should not be affected at all by top-down task sets. However, others have argued that salience-driven object selection is often modulated by topdown attentional priorities (e.g., Fecteau & Munoz, 2006). For example, the dimension weighting account (Found & Müller, 1996; Müller et al., 1995) assumes that feature contrast signals from different dimension-specific modules are integrated in a weighted fashion and that their weights do not only depend on bottom-up factors such as intertrial priming but also on top-down biases induced by instructional cues (e.g., Krummenacher et al., 2001; Müller, Reimann, & Krummenacher, 2003).

Along very similar lines, the relative roles of bottom-up salience and top-down task set for attentional capture by feature singletons in visual search are still contested. While bottom-up salience can play a role (e.g., Theeuwes, 1991, 2010), there is also abundant evidence that capture is primarily determined by top-down task sets. In experiments where search displays are preceded by spatially uninformative feature singleton cues, spatial cuing effects indicative of attentional capture by the cues (i.e., faster RTs to cued compared to uncued target locations) are only observed when cues possess target-defining features (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). For example, during search for red color singleton targets, red cues capture attention, but blue cues (or singleton cues defined in a dimension other than color) do not, demonstrating that attentional capture by salient visual feature singletons is contingent on top-down task set. Even highly salient stimuli can be successfully ignored when they do not share features with the current search target.

In summary, some accounts of visual search propose that attentional capture and redundancy gain effects in singleton visual search are bottom-up phenomena that are solely determined by physical stimulus salience, while others suggest that these effects are modulated by top-down task sets. Until now, the question whether redundancy gains are affected by top-down search intentions has not been investigated directly. The aim of the present experiment was to study the relative roles of bottom-up salience and top-down task set during search for redundant targets. If the integration of local feature contrast signals in salience maps is a purely bottom-up phenomenon, redundancy gains in singleton visual search should not be affected by manipulations of dimension-specific task sets. In contrast, if this integration is sensitive to intentional search strategies, benefits for redundant relative to singly defined targets should be modulated by the task relevance of specific target dimensions and should not depend entirely on bottom-up salience.

To test these alternative predictions, we measured the relative impact of top-down task set and bottom-up salience on behavioral and electrophysiological correlates of redundancy gains in visual search for feature singleton targets. As such redundancy gains are attributed to the expedited attentional selection of redundantly defined targets (see above), our particular focus was on an event-related brain potential (ERP) index of the speed of attentional selectivity: The N2pc component is an enhanced negativity over posterior electrode sites contralateral to the side of an attended stimulus that is typically triggered around 200 ms after stimulus onset during the attentional selection of a candidate target stimulus among distractors in visual search (Eimer, 1996; Luck & Hillyard, 1994). Because the N2pc



Figure 1. Illustration of the different search displays used in this study (left: pure color singletons; middle: pure shape singletons; right: redundant color and shape singletons).

can serve as a precise temporal marker for the allocation of focal attention to visual feature singletons (e.g., Eimer & Kiss, 2008; Kiss & Eimer, 2011; Lien, Ruthruff, Goodin, & Remington, 2008), it is particularly useful to track the time course of redundancy gain effects on attentional target selection and their modulation by topdown control.

Participants viewed search displays that could contain one feature singleton that was defined in terms of its unique color (red or green, varied across participants), its unique shape (diamond), or both, among distractors (green or red squares; see Figure 1). On other trials, only uniform distractors were present. Behavioral performance and N2pc components were measured in three task conditions that were identical in terms of the physical properties of the search arrays but differed with respect to task instructions. In the baseline condition, participants were instructed to respond to the presence of any feature singleton (pure color, pure shape, redundant color and shape). In this task, benefits for the attentional selection of redundantly defined targets should be observed, and this should be reflected by faster target-present RTs relative to trials with pure color or pure shape singletons, as well as an earlier onset of the N2pc component to redundant targets.

In the other two conditions, only one of the two feature dimensions was task-relevant. In the color target condition, participants had to respond to all color singletons, regardless of whether or not they were also singletons in the shape domain, but had to ignore pure shape singletons. In the shape target condition, they had to respond to all shape singletons, regardless of whether or not they were also singletons in the color domain, but had to ignore pure color singletons. If redundancy gains in singleton visual search are a bottomup phenomenon that is driven exclusively by the stronger salience of redundantly defined singletons as compared to pure color or shape singletons, the difference in task instruction between the baseline condition and the color or shape target condition should have no effect. In other words, redundancy gains of similar size should be observed in all three task conditions, both for RT and N2pc measures. In contrast, if redundancy gains are modulated by the task relevance of a specific feature dimension, the pattern of results observed in the color and shape target conditions should be very different from the results found in the baseline condition. Any benefits for attentionally selecting redundantly defined targets as compared to pure color or shape targets should be much smaller than in the baseline condition, or perhaps even be completely absent. This pattern of results would suggest that currently taskirrelevant stimulus dimensions can be effectively excluded from guiding visual search for feature singletons.

Methods

Participants

Twelve paid observers (5 females; age range = 21-37 years, median age = 26.8 years) took part in the experiment. All participants were right-handed, had normal or corrected-to-normal vision, and normal color vision by self-report.

Stimuli and procedure

Participants were seated in a sound attenuated, electrically shielded, and dimly illuminated cabin. Stimulus presentation, timing, and response recording were controlled by an LG Pentium PC running under Windows XP and using the "Cogent 2000" toolbox (http://www.vislab. ucl.ac.uk/cogent.php) for MATLAB (Mathworks). Stimuli were presented at 100 Hz on a 22" LCD monitor (Samsung wide SyncMaster 2233), at a screen resolution of 1280×1024 pixels. Viewing distance was approximately 100 cm. All visual search displays consisted of twelve items that were located at equidistant positions along the circumference of an imaginary circle, at an angular distance of 3.7° from a central fixation point (Figure 1). Stimuli were red (CIE 0.636, 0.335) or green (CIE 0.259, 0.546) outline squares or diamonds (angular size: $0.7^{\circ} \times 0.7^{\circ}$). Feature singletons, when present, always appeared randomly and with equal probability at one of the six most lateral locations (corresponding to the 2, 3, and 4 o'clock positions on the right side and the 8, 9, and 10 o'clock positions on the left side). All color stimuli were equiluminant (7.4 cd/m^2) and were presented against a black background. Feature singletons were either defined in one dimension only (color or shape) or redundantly in both dimensions (color and shape). Shape singletons were always diamonds among squares. Singleton color was counterbalanced across participants. Half of them were presented with red singletons among green distractors and the other half with green singletons among red distractors. Each trial started with a 500-ms fixation point display, which was followed by the presentation of the search array (200-ms duration). The intertrial interval was 1000 ms.

There were three task conditions that were identical in terms of physical stimulus properties but differed with respect to task instructions. They were delivered in successive blocks, with task order counterbalanced across observers. In the baseline condition, participants were instructed to detect and respond to the presence of any singleton, regardless of whether it was defined redundantly (color and shape singleton) or just within one dimension (pure color or shape singletons). On targetabsent trials without feature singleton, no response was required. The baseline condition consisted of 12 successively delivered blocks with 60 trials per block. Thirty trials per block were target-absent trials. Redundant singleton targets, pure color singletons, or pure shape singletons were each presented on 10 trials per block. In the *color target* condition, participants had to detect and respond only to color singletons (regardless of whether or not they were also shape singletons). Trials with pure shape singletons and trials without feature singletons were both non-target trials and required no response. In the shape target condition, participants had to detect and respond only to shape singletons (regardless of whether or not they were also color singletons). Here, pure color singleton trials and trials without any feature singleton were non-target trials and required no response. The color and shape target conditions both contained 6 successively delivered blocks, with 96 trials per block. Trials with redundantly defined singletons, pure color singletons, pure shape singletons, and singleton-absent trials were equiprobable (24 trials per block). Button-press responses were required on target-present trials only. Response hand was swapped after half of the blocks in each task condition. Accuracy rates and mean RTs were fed back to the participant at the end of each block. Brief training blocks of 32 trials were run prior to the start of each task condition and prior to the first block after swapping the response hand.

EEG recording and data analysis

The continuous electroencephalogram (EEG) was DC-recorded with a digitization rate of 500 Hz, using a BrainAmps DC amplifier (BrainProducts, Munich, Germany) and 23 scalp electrodes embedded in elastic caps (easyCAP) at standard positions of the extended 10/20 system (American Electroencephalographic Society, 1994). The horizontal electrooculogram (HEOG) was measured from two electrodes placed at the outer canthus of each eye. The online EEG was 40 Hz low-pass and 50 Hz notch filtered, and no additional offline filters were applied. All electrodes were referenced to the left earlobe and offline re-referenced to averaged earlobes. Impedances were kept below 5 k Ω . The EEG was epoched into 600-ms segments from 100 ms prior to 500 ms after search array onset. Trials containing saccades (voltage exceeding $\pm 30 \ \mu V$ in the HEOG channel; 1.7% of all trials), eye blinks (voltage exceeding $\pm 60 \ \mu V$ at Fpz; 3.3% of all trials), and muscular artifacts (voltage exceeding $\pm 80 \ \mu V$ at all channels; 0.6% of all trials) were removed from the analysis. Event-related potentials (ERPs) were computed relative to the 100-ms pre-stimulus baseline for each combination of task condition (baseline, color target, shape target) and singleton type (redundant color and shape singleton, color singleton, shape singleton). N2pc mean amplitudes were quantified within a 180-280 ms post-stimulus latency window at lateral posterior electrode sites PO7/8. N2pc onset latency values were measured on the basis of difference waveforms computed by subtracting ERPs at PO7/8 ipsilateral to the hemifield where a feature singleton was located from contralateral ERPs. To determine N2pc onset, the jackknife-based procedure as described by Ulrich and Miller (2001) was used. This procedure estimates onset latencies on the basis of grand averages computed from subsamples of averaged ERP difference waveforms obtained by successively excluding one participant from the original sample. N2pc onset latencies were computed separately for each combination of task condition and singleton type and were defined as the point in time where the difference waveform for each subsample exceeded an absolute threshold value of $-1 \mu V$. In statistical analyses of N2pc onset latencies,



Figure 2. (Top) Response times (RTs, left) and N2pc onset latencies (right) in response to pure color singleton targets, pure shape singleton targets, and redundant color and shape singleton targets, shown separately for all three task conditions. (Bottom) Redundancy gain effects observed for RTs (left) and N2pc onset latencies (right), computed by subtracting values for pure feature singleton targets from values measured for redundant targets. Redundancy gains associated with singleton shape (differences between trials with redundant color and shape singleton targets and trials with pure color singleton targets) and redundancy gains associated with singleton targets) are shown color (differences between trials with redundant color and shape singleton targets and trials significant differences are indicated by brackets.

F and *t*-values were corrected (indicated with the label F_c) according to the formula described by Ulrich and Miller. Analyses of N2pc mean amplitudes and onset latencies were conducted separately for each task condition. Mean RTs were analyzed for each task condition, including the factor singleton type. For both RT and N2pc onset latency data, redundancy gains observed in the baseline condition were statistically compared to redundancy gains observed in the color and shape target conditions, and Bonferroni correction was applied where appropriate.

Results

Behavioral performance

Reaction times

Anticipatory or exceedingly slow responses (RTs faster than 200 ms or slower than 1000 ms) were removed from analysis, resulting in the exclusion of 0.1% of all trials.

Figure 2 (left) shows mean RTs in response to search arrays containing different types of singletons, separately for all three task conditions, as well as RT redundancy gains observed for redundantly defined singleton targets relative to pure color or shape singleton targets. As expected, RT redundancy gains were present in the baseline condition. In the color and shape target conditions, these gains appear to be strongly attenuated if not entirely absent.

These observations were confirmed by statistical analyses. In the baseline condition, a highly significant effect of singleton type was present (F(2, 22) = 65.2, p < 0.001). RTs to redundant color and shape singleton targets (322 ms) were reliably faster than RTs to color targets (340 ms) and to shape targets (372 ms). The presence of these redundancy gains was confirmed by two-tailed paired *t*-tests (both t(11) > 6.5; both p < 0.001). In addition, RTs to color targets were faster than RTs to shape targets (t(11) = 5.6, p < 0.001). In marked contrast to the baseline condition, there were no reliable RT redundancy gains in the two single-feature target conditions. In the color target condition, mean RTs were identical for redundant color and shape singleton targets and pure color singleton targets (both 327 ms; F(1, 11) < 1). Likewise, in the shape target condition, RTs for redundant targets and pure shape singleton targets did not differ reliably (381 ms versus 386 ms; F(1, 11) = 1.8, p = 0.212). To confirm that the presence versus absence of RT redundancy gains was determined by task set, redundancy



Figure 3. Grand-average ERPs at posterior electrodes PO7/8 contralateral and ipsilateral to the location of a feature singleton stimulus, shown separately for each combination of task condition and singleton type.

gains measured in the baseline condition and the two single-feature target conditions were compared via onetailed paired *t*-tests. The redundancy gain associated with singleton shape (i.e., the RT benefit for redundant color and shape singleton targets compared to pure color singleton targets) observed in the baseline condition (18 ms) differed reliably from the RT difference found in the color target condition (0 ms; t(11) = 6.3, p < 0.001). Likewise, the redundancy gain associated with a singleton color (i.e., the RT benefit for redundant singleton targets relative to pure shape singleton targets) was reliably larger in the baseline condition (50 ms) than in the shape target condition (4 ms; t(11) = 8.1, p < 0.001).

Error rates

Accuracy was generally high. False alarms occurred on 1.1% of all target-absent trials, and participants failed to respond on 0.1% of all target-present trials. Miss rates did not differ reliably between the three task conditions. False alarms were less frequent in the color target condition (0.4%) than in the shape target and baseline conditions (1.5% and 1.3%, respectively, both t(11) > 4.9; both p < 0.001).

Event-related potentials—N2pc component

Figure 3 shows the ERPs obtained at PO7/8 contralateral and ipsilateral to the side of a feature singleton, separately for all three singleton types and all the three task conditions.

In Figure 4, difference waveforms obtained by subtracting ipsilateral from contralateral ERPs are shown for each task condition, separately for the three types of singletons. N2pc components were triggered in response to all feature singleton stimuli in all three task conditions, but these components differed substantially in terms of their amplitudes and onset latencies. N2pc onset latencies determined by the jackknife-based method (see Methods section), and N2pc mean amplitudes obtained in the 180– 280 ms post-stimulus time window on trials with redundantly defined singleton targets, pure color singletons, and pure shape singletons, were analyzed separately for each of the three task conditions.

N2pc onset latencies

In the baseline condition, the analysis of N2pc onset latencies revealed a main effect of singleton type



Figure 4. Difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in response to pure color singletons, pure shape singletons, and redundant color and shape singletons, shown separately for all three task conditions. These ERP data are the basis for the N2pc onset latency and redundancy gain estimates shown in Figure 2 (right panels).

 $[F_{c}(2, 22) = 7.4, p = 0.003]$. As shown in Figure 4 (left panel), the N2pc to redundantly defined target singletons emerged earlier than the N2pc to pure color or shape singletons, as predicted. Statistical analyses using onetailed paired t-tests confirmed that the N2pc onset to redundant color and shape singleton targets (171 ms) was reliably earlier than the N2pc onset for pure color targets (184 ms; $t_c(11) = 3.0$, p = 0.017) and pure shape targets $(196 \text{ ms}; t_c(11) = 3.5, p = 0.008)$. There was no significant N2pc onset difference between pure color and shape targets $(t_c(11) = 1.6, p = 0.198)$. In the color target condition, a main effect of singleton type was observed $[F_c(2, 22) = 72.8, p < 0.001]$, which was due to the fact that the N2pc to search arrays with task-irrelevant shape singletons (231 ms) was strongly delayed relative to the N2pc onset in response to task-relevant redundant targets (171 ms) and pure color targets (174 ms; t_c (11) = 11.9 and 8.0, respectively, both p < 0.001; see Figure 4, middle panel). Critically, N2pc onset latencies did not differ between redundantly defined color and shape singleton targets and pure color targets ($t_c(11) < 1$). A main effect of singleton type on N2pc onset latency was also found in the shape task $[F_{c}(2, 22) = 4.0, p = 0.033]$, as the N2pc to task-irrelevant color singletons (203 ms) emerged later than the N2pc to redundant color and shape singleton targets (176 ms; $t_c(11) = 2.6$, p = 0.038). The N2pc latency difference between irrelevant color singletons and pure shape targets (190 ms) was not reliable ($t_c(11) =$ 1.2, p = 0.384). Importantly, the N2pc onset difference between redundant targets and pure shape targets (Figure 4, right panel) was not statistically reliable $(t_c(11) = 2.1, p = 0.096).$

Figure 2 (right panel) shows that redundancy gains on N2pc onset latencies observed in the baseline condition were much larger than any redundancy gains found in the

two single-feature target conditions, in line with the pattern of RT redundancy gains shown in the left panel. To confirm that just like the RT effects, redundancy gains on N2pc onset latencies were determined by top-down task set, redundancy gains observed in the baseline condition were compared to effects found in the color and shape target conditions, respectively, with one-tailed paired t-tests. The N2pc onset redundancy gain associated with singleton shape (i.e., the earlier N2pc latency for redundant color and shape targets relative to pure color targets) in the baseline condition (13 ms) was reliably larger than the non-significant redundancy gain in the color target condition (4 ms; $t_c(11) = 2.2, p < 0.027$). The redundancy gain associated with singleton color (i.e., the earlier N2pc latency for redundant color and shape targets relative to pure shape targets) was also numerically larger in the baseline condition (25 ms) than in the shape target condition (14 ms), but this difference failed to reach statistical significance ($t_c(11) = 1.1, p < 0.151$).

N2pc amplitudes

In the baseline condition, a highly significant main effect of contralaterality [F(1, 11) = 102.0, p < 0.001] confirmed that a reliable N2pc was indeed triggered by feature singletons. A contralaterality × singleton type interaction [F(2, 22) = 8.4, p = 0.002] indicated that N2pc amplitudes differed between singleton types, but paired *t*-tests confirmed that reliable N2pc components were present for all three feature singleton types (all t(11) > 6.9; all p <0.001). In the color target condition, a main effect of contralaterality [F(1, 11) = 54.7, p < 0.001] was accompanied by an interaction between contralaterality and singleton type [F(2, 22) = 11.6, p < 0.001]. As shown in Figures 3 and 4, the N2pc to task-irrelevant pure shape singletons was strongly attenuated relative to the N2pc to task-relevant redundant targets and pure color targets. However, a reliable N2pc was present not just for target singletons (both t(11) > 6.2; both p < 0.001) but also for irrelevant pure shape singletons (t(11) = 4.4, p = 0.001). In the shape target condition, there was again a main effect of contralaterality [F(1, 11) = 146.8, p < 0.001] and a contralaterality × singleton type interaction [F(2, 22) = 31.5, p < 0.001]. The N2pc to task-irrelevant pure color singletons was attenuated relative to the N2pc to redundant targets and pure shape targets but remained reliably present not just for target singletons (both t(11) > 9.1; both p < 0.001) but also for irrelevant pure color singletons (t(11) = 5.6, p < 0.001).

Follow-up analyses confirmed that the task relevance of a specific stimulus dimension did indeed modulate N2pc amplitudes. The N2pc to pure color singletons was reliably reduced in the shape target condition relative to the color target and baseline conditions (both t(11) > 2.5, both p < 0.05). Likewise the N2pc to pure shape singletons was smaller in the color target condition than in the shape target and baseline conditions (both t(11) > 6.5, both p < 0.001).

Discussion

To investigate whether redundancy gains in pop-out visual search are a bottom-up phenomenon that is driven by physical stimulus salience, or a top-down effect that is contingent upon observers' current search goals, we compared RTs and N2pc components in response to singleton targets that were either defined in one dimension (color or shape) or redundantly in both dimensions, in three conditions that differed in terms of task instructions. In the baseline condition, color and shape were equally taskrelevant. In the two other task conditions, only color singletons or only shape singletons were designated as targets. In the baseline condition, RT redundancy gains were observed, in line with previous behavioral studies (e.g., Krummenacher et al., 2001, 2002). Importantly, these behavioral redundancy gains were accompanied by N2pc onset latency differences: The N2pc component emerged earlier in response to redundant color and shape targets relative to pure color or pure shape targets. The N2pc is an electrophysiological marker of the spatially selective visual processing of target events in extrastriate visual cortical areas (e.g., Hopf et al., 2000). The observation that the onset latency of this component mirrors behavioral redundancy gains in pop-out visual search thus provides strong evidence in support of the view that these effects are generated at early stages of visual-perceptual processing (Krummenacher et al., 2002; Töllner et al., 2010) and against the hypothesis that they are primarily associated with post-perceptual stages (Feintuch & Cohen, 2002).

A very different pattern of effects was observed in the two single-target conditions where only color or only shape singletons were designated as targets. The behavioral redundancy gain effects observed in the baseline condition were no longer present, as RTs in response to redundantly defined color and shape targets were not reliably faster than RTs to pure color or shape targets. This was further confirmed by the analyses of N2pc onset latencies, which also did not reveal significant benefits for redundant as compared to pure targets. The absence of reliable redundancy gains in both behavioral and ERP measures in the color and shape target conditions demonstrates that bottomup salience differences are not sufficient to produce these effects and that top-down search intentions play a decisive role. This is further illustrated in Figure 2 (bottom panel), which compares redundancy gains for RTs and N2pc onset latencies observed in the baseline condition and in the single-target conditions. Redundancy gains associated with singleton color were generally larger than the redundancy gains associated with singleton shape. More importantly, these redundancy gains were consistently and reliably larger in the baseline condition than in the singletarget conditions. This was the case for redundancy gains associated with singleton color and with singleton shape and for RTs as well as for N2pc onset latencies. As the physical differences between redundant targets and pure color or pure shape targets were identical in all three task conditions, the observed differences in redundancy gains between the baseline condition and the two single-target conditions cannot be attributed to bottom-up salience and can thus only be accounted for by the different top-down goals that guided search in these tasks.

These findings are clearly inconsistent with models that emphasize the critical role of bottom-up salience for target selection in visual search (e.g., Itti & Koch, 2000). Such models would predict that redundancy gain effects are driven exclusively by the current activation profile on a salience map that is determined by integrated local stimulus contrast values obtained from different dimension-specific maps. If this was correct, very similar redundancy gain effects on RTs and N2pc onset latencies should have been observed in all three task conditions, which was clearly not the case. What the current results suggest instead is that local feature contrast signals do not automatically result in corresponding activations on the salience map, but that their contribution is weighted by the task relevance of a particular dimension. They are in line with the assumptions of the dimension weighting model as proposed by Müller et al. (e.g., Krummenacher et al., 2001; Müller et al., 2003). When one dimension is made response-irrelevant, its top-down weight is reduced, which will strongly attenuate its impact during the integration stage at the level of the salience map. As a result, attentional target selection is driven primarily by local contrast signals from the response-relevant dimension, thus reducing or eliminating any redundancy gain effects on behavioral end electrophysiological measures. However, signals from the irrelevant dimension may not be completely suppressed: On trials with task-irrelevant singletons (pure shape singletons in the color target condition or pure color singletons in the shape target condition), the N2pc was delayed and attenuated relative to trials with target singletons (Figure 4), but it was still reliably present, suggesting that these singletons were still able to attract attention to some degree. Furthermore, although redundancy gain effects were small and nonsignificant in the two single-target conditions, they were at least numerically present for most comparisons (Figure 2, bottom panel).

Previous work has shown that attentional capture by salient but task-irrelevant visual singletons can be prevented, both when these stimuli precede target arrays (e.g., Folk et al., 1992) and also when they appear at the same time but at a different location than the target (Müller, Krummenacher, Gever, & Zehetleitner, 2009). These observations are in line with the hypothesis that taskdependent top-down control strongly attenuates the impact of local feature contrast signals from irrelevant dimensions on the activation profile of the salience map. The novel contribution of the current study is to demonstrate that this is even the case when task-relevant and taskirrelevant stimulus features appear at the same location and are part of the same visual object. Redundantly defined target singletons are selected faster than pure color or pure shape singletons when both feature dimensions are task-relevant but not when only one of these dimensions is included in the currently active task set.

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