

Perceptual Basis of Redundancy Gains in Visual Pop-out Search

Thomas Töllner^{1*}, Michael Zehetleitner^{1*}, Joseph Krummenacher²,
and Hermann J. Müller^{1,3}

Abstract

■ The redundant-signals effect (RSE) refers to a speed-up of RT when the response is triggered by two, rather than just one, response-relevant target elements. Although there is agreement that in the visual modality RSEs observed with dimensionally redundant signals originating from the same location are generated by coactive processing architectures, there has been a debate as to the exact stage(s)—preattentive versus postselective—of processing at which coactivation arises. To determine the origin(s) of redundancy gains in visual pop-out search, the present study combined mental chronometry with electrophysiological markers that reflect purely preattentive perceptual (posterior-contralateral negativity [PCN]), preattentive and postselective perceptual plus response selection-related (stimulus-locked later-

alized readiness potential [LRP]), or purely response production-related processes (response-locked LRP). As expected, there was an RSE on target detection RTs, with evidence for coactivation. At the electrophysiological level, this pattern was mirrored by an RSE in PCN latencies, whereas stimulus-locked LRP latencies showed no RSE over and above the PCN effect. Also, there was no RSE on the response-locked LRPs. This pattern demonstrates a major contribution of preattentive perceptual processing stages to the RSE in visual pop-out search, consistent with parallel-coactive coding of target signals in multiple visual dimensions [Müller, H. J., Heller, D., & Ziegler, J. Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, 57, 1–17, 1995]. ■

INTRODUCTION

The redundant-signals effect (RSE) is the shortening of RT when the response is triggered by two (or more), rather than just one, response-relevant target signal. This phenomenon is well established (e.g., Todd, 1912) and has been reported in a wide range of experimental paradigms (e.g., Koene & Zhaoping, 2007; Mohr, Endrass, Hauk, & Pulvermüller, 2007; Schroter, Ulrich, & Miller, 2007; Gondan, Lange, Rösler, & Röder, 2004; Iacoboni & Zaidel, 2003; Forster, Cavina-Pratesi, Aglioto, & Berlucchi, 2002; Lamarre, Busby, & Spidaliere, 1983). These paradigms can be classified along several criteria: (a) spatial origin of the signals (same or different locations), (b) modality of the signals (visual, auditory, or haptic), (c) number of relevant modalities (one or two), and (d) depth of signal processing necessary to determine the appropriate motor response (onset, feature contrast, or target identity). For instance, in a study by Miller (1982, Experiments 1 and 2), redundant signals were realized by presenting visual (asterisk) and auditory (tone) signals simultaneously at two separate locations relative to single signals, which could occur at one of the two locations being defined in one of the two modalities. When the task required simply the detection of any signal, both

the auditory and the visual modalities were task relevant, the spatial locations of the signals were task irrelevant, and, in terms of depth of processing, only detection of the stimulus was necessary. By contrast, in Miller's (1982) Experiment 3, observers were always presented with one letter (either "X" or "O") and one tone (either high or low) simultaneously, and they had to produce a go-response to a target letter ("X"), a target tone (high), or the combined target letter and tone. This increased the required depth of processing from onset detection to stimulus identification.

By contrast, redundant signals can also be realized by presenting two different target elements simultaneously at the same location. This was done, for instance, by Mordkoff and Miller (1993), who asked their observers to make a go-response to a stimulus letter that was either an "X," green, or a green "X" and that was always presented at the same location. Thus, to solve this task, observers had to identify the stimulus, with only one perceptual modality and one spatial location being task relevant. Similarly, Krummenacher, Müller, and Heller (2001, 2002) introduced a visual search task in which observers had to search for a feature ("pop-out") singleton that differed in color, orientation, or both from its surrounding elements. Thus, as in Mordkoff and Miller's study, the two target signals were spatially coincident and originated from the same modality. However, in contrast to Mordkoff and Yantis (1991), the target location changed unpredictably across target-present trials (rather

¹Ludwig-Maximilians-University Munich, ²Université de Fribourg, Switzerland, ³Birkbeck College London

*Contributed equally to this article.

than being fixed); that is, the task involved a component of *search*, and only simple detection (rather than identification) of a target was required to determine the appropriate motor response.

Classification of Explanatory Models

In general, models designed to explain the RSE in a specific paradigm can be classified along two lines: (i) architecture and (ii) affected processing stage. In theory, several architectures can generate RSEs: statistical facilitation in a parallel independent or an interactive race (Mordkoff & Yantis, 1991; Raab, 1962), serial architectures with an exhaustive stopping rule (Townsend & Nozawa, 1997), or coactivation models (Miller, 1986). Race models or probabilistic interpretations (e.g., Raab, 1962) assume that two simultaneously presented single signals are processed in parallel in stochastically independent afferent channels. Similar to a “horse race,” the signal that reaches a specific criterion value (e.g., activation threshold) first wins the competition and mediates further response decisions. Accordingly, given that the processing time within each channel varies randomly across trials, the mean RT for redundant (relative to single) signal trials decreases as the number of relevant channels increases, simply due to statistical facilitation. Alternatively, coactivation models (e.g., Krummenacher et al., 2001; Miller, 1982) assume that the individual signals originating from two (or more) afferent channels do not influence response decisions independently of each other; rather, there is a summation/integration of the various signals at some stage before triggering the response, which leads to violations of the so-called *race model inequality* ([RMI] Miller, 1982; for details, see Methods).

Further, the mechanisms generating RSEs (and RMI violations) can be implemented at preattentive (Zehetleitner, Krummenacher, & Müller, 2009) or postselective (Mordkoff & Miller, 1993) perceptual processing stages, at the stage of response selection (Feintuch & Cohen, 2002) or that of response production (Miller, 2007).

Preattentive versus Postselective Origins of Redundancy Gains

In the realm of visual redundant-signals paradigms (e.g., Feintuch & Cohen, 2002; Krummenacher et al., 2001, 2002; Mordkoff & Miller, 1993), it is generally agreed that coactivation rather than parallel-race models (Raab, 1962) account for observed RSEs. However, there is an ongoing debate concerning the origin(s) of the visual RSEs. Advocates of a preattentive perceptual locus (Zehetleitner et al., 2009; Koene & Zhaoping, 2007; Krummenacher et al., 2001, 2002; for a review see, Zehetleitner, Müller, & Krummenacher, 2008) assume that at least part of the RSE in pop-out search is generated at the level of early visual stimulus analysis where the relevant target attributes are coded and compared with those of nontarget

elements in dimension-specific channels (e.g., for color, orientation, etc.), without necessarily involving stages following focal-attentional target selection. By contrast, other authors have proposed that the RSE arises exclusively at stages subsequent to attentional selection (Miller, Beutinger, & Ulrich, 2009; Feintuch & Cohen, 2002; for a review see Miller & Reynolds, 2003).

Results compatible with the latter—postselective—view have been reported by Miller et al. (2009), who presented one or two target stimuli either at expected or unexpected locations. They found the RSE to be comparable in both conditions, from which they inferred that the redundancy gains arise after target elements were selected by focal attention. Using a similar logic, Feintuch and Cohen (2002) presented two bars that had one of three possible colors and one of three possible orientations, with one specific color and one orientation being defined as response-relevant target features. Observers had to produce a go-response if they discerned either the target color or the target orientation or both the target color and the orientation in the display. The target features could belong either to one bar or to two separate bars. Feintuch and Cohen found evidence for coactivation (i.e., RMI violations) only if the target features belonged to the same bar rather than to separate bars. However, when focal attention was guided to both bars simultaneously by presenting them within an outline ellipse (i.e., within an encompassing “object cue”), there was evidence for coactivation by target features belonging to separate bars. Feintuch and Cohen concluded that the coactivation mechanism is located in the processing stream after focal-attentional selection, and attentional selection is a prerequisite for the coactivation mechanism to come into play.

Data compatible with the former—preattentive—view have been revealed by Zehetleitner et al. (2009) and Krummenacher et al. (2001, 2002). Using a visual pop-out search task, observers had to simply discern the presence (vs. the absence) of any target, whether singly (orientation or color) or redundantly (orientation and color) defined, in the search array. Crucially, on redundant-target trials, the distance between the color and the orientation singleton could vary from zero (one bar contains both target features) to three (the two target bars were separated by two distracter bars). Krummenacher et al. found evidence of coactivation, in terms of violations of the RMI, only with small spatial separations (one to two, corresponding to 1.5°–3.6° of visual angle) but not with larger separations. This is at variance with Feintuch and Cohen (2002) who failed to find evidence of coactivation in a similar situation (with a spatial distance of one; see their Experiment 1), which led them to conclude that coactivation occurs after focal-attentional selection. In response to the challenge by Feintuch and Cohen, Krummenacher et al. (2002) attempted to strengthen the support for their hypothesis that in simple pop-out search, coactivation takes place at a level before attentional selection. In their Experiment 3, Krummenacher et al. indicated the spatial location

of an upcoming search target by an advance symbolic cue and examined for violations of the RMI at uncued (non-preselected) as well as cued (preselected) locations. They found evidence of coactivation effects in both cases (i.e., there were RMI violations even by redundant targets outside the focus of attention), arguing in favor of a preattentive rather than a postselective locus of coactivation in pop-out search. More recently, Zehetleitner et al. examined the size of the RSE and the amount of coactivation (using a geometrical measure; see Colonius & Diederich, 2006) under pop-out search conditions of high- or low-feature contrast of the target relative to the distracters; low-contrast targets were detected more slowly (by some 100 msec) than high-contrast targets, however, without search being inefficient (the slope of the function relating detection RT to the number of display elements was about 5 msec/item, that is, well below the 10-msec/item, which is considered to be the criterion for inefficient search; see Wolfe, 1998). Concerning redundancy gains, Zehetleitner et al. found both the size of the RSE (RSEs of 50 vs. 15 msec) and the amount of coactivation to be larger for low-contrast than for high-contrast redundant targets. This pattern argues against a postselective origin of coactivation effects: given that the manipulation of feature contrast affects the speed of focal-attentional selection (which is determined by preattentive coding processes), a postselective origin of coactivation effects would have predicted the RSE to be statistically comparable in both conditions (as in Miller et al., 2009) rather than to be dependent on target feature contrast.

Rationale of the Present Study

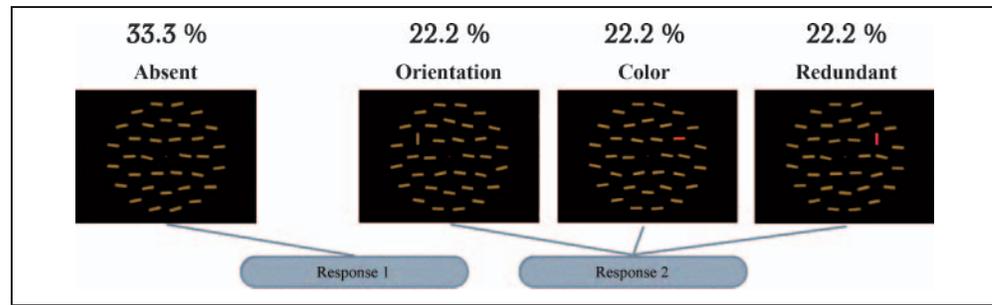
Despite these behavioral findings arguing in favor of a preselective locus of coactivation effects in pop-out search, the evidence is not unequivocal. For example, the results of the spatial-cueing experiment of Krummenacher et al. (2002), specifically the RMI violations produced by redundant targets at uncued locations, could also be explained by assuming that focal attention was attracted (away from the cued location) by a single feature of such a target (i.e., in a parallel race of the redundant features to summon attention) and that coactivation effects arose only following attentional selection of the target (which would be consistent with Feintuch & Cohen, 2002). In addition, the results from the simple pop-out search and the discrimination paradigm (e.g., Feintuch & Cohen, 2002; Mordkoff & Miller, 1993) are not necessarily incompatible because they require differential depths of stimulus processing: In pop-out search, target identification is not a prerequisite for producing a correct (simple detection) response, although it is impossible to solve the discrimination tasks without identifying the response-relevant target features.

Given this, other, nonbehavioral measures—in particular, “early” measures derived from observers’ EEG while performing a pop-out search task—may be necessary to decide between the preattentive and the postselective accounts of

redundancy gains in visual search. To our knowledge, there have been, as yet, no EEG studies of the visual redundant-signals paradigm with target signals being presented as part of one object (i.e., at the same location), as in pop-out search, although this paradigm permits a decision to be made between two or three alternative hypotheses: If coactivation occurs (at least also) at a preattentive processing stage (e.g., Krummenacher et al., 2002), electrophysiological correlates of the RSE should be observed in ERP components related to the allocation of focal attention. By contrast, if coactivation occurs only at postselective processing stages, such as perceptual target analysis for response selection (e.g., Feintuch & Cohen, 2002) or response execution (e.g., Miller, 2007), ERP components related to attentional selection should not show a redundancy gain.

Thus, in contrast to other (e.g., the divided attention or the psychological refractory period) paradigms, this approach makes it possible to focus on two specific ERP components that reflect either pure perceptual-coding or pure response-related stages of information processing. The first component, which is typically observed as a negative-going deflection over visual brain areas of the hemisphere contralateral to the location of an attended stimulus, is referred to as N2 posterior contralateral (Eimer, 1996; Luck & Hillyard, 1994) or posterior-contralateral negativity¹ ([PCN] Ansorge & Heumann, 2006; Jaskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002). This negativity has its maximum in the time range of 175–300 msec post-stimulus and has been interpreted as reflecting the allocation of focal attention on the basis of perceptual stimulus attributes (e.g., Woodman & Luck, 1999; Eimer, 1996; Luck & Hillyard, 1994). Importantly, in the visual search paradigm, single-signal targets (SSTs) and redundant-signal targets (RSTs) are typically presented at a single target location (for an exception, see Krummenacher et al., 2002).² Thus, the PCN component can be used to identify perceptual processing differences between SSTs and RSTs, unaffected by possible motor modulations. Moreover, the timing of the PCN can be used as marker of the transition from preattentive sensory coding of the whole stimulus display to the focal-attentional selection and analysis of the target item. Such latency variations have been observed in a number of studies showing that the timing of target selection does vary dependent on, for instance, stimulus intensity (Brisson, Robitaille, & Jolicoeur, 2007), set size (Wolber & Wascher, 2005), or previous target dimension (Töllner, Gramann, Müller, Kiss, & Eimer, 2008). Thus, perceptual processes can be further differentiated by using the PCN latency as an index of preattentive processing speed and the amplitude of the PCN as an index of the amount of attentional resource allocation. Finally, it should be noted that this component and thus bottom-up processing can be modulated by top-down factors such as, for instance, task set (Eimer & Kiss, 2008) or dimensional set (Töllner, Zehetleitner, Gramann, & Müller, 2010). In the present study, we analyzed the PCN to examine whether the RSE is linked to perceptual (preattentive

Figure 1. Stimulus displays used in the present visual (pop-out) search task. Participants were required to discern the presence (vs. the absence) of any singleton by pressing the corresponding response button. Two thirds of the trial displays contained a singleton target (equally likely defined within the orientation dimension,



the color dimension, or both), whereas a homogenous display was presented in one third of the trials. Actual experimental stimuli were isoluminant, with bars appearing either in yellow (as indicated by the grey bars) or red (as indicated by the white bars).

and/or attentional) stages of processing, or whether this effect is generated at later postselective stages. If the coactivation mechanism acts at the preattentive processing stage, a redundancy effect in PCN latencies would be expected (Krummenacher et al., 2001), whereas if the coactivation mechanism acts at postselective perceptual processing stages (e.g., Feintuch & Cohen, 2002), no such modulations would be expected.

To examine for possible motor contributions to the RSE in the present study, we further focused on the lateralized readiness potential (LRP). This component is typically elicited over the motor area contralateral to the side of a unimanual response and has been linked to the activation and execution of motor responses (e.g., Hackley & Valle-Inclán, 2003; Coles, 1989). As this component is extracted from the ERP by subtracting waveforms recorded from electrodes ipsilateral to the side of a response from contralateral ERPs (Eimer & Coles, 2003), perception-related processes are generally agreed to be canceled out by this procedure. Hence, the start of effector-specific motor activations, which occur after response selection processes have been completed, can be inferred by analyzing the onset of the LRP. When computed relative to stimulus onset (stimulus-locked LRP), LRP onset differences between SSTs and RSTs would reflect differential processing rates in those stages that occur before the start of selective motor activation (e.g., perceptual encoding processes, response selection). When computed relative to response onset (response-locked LRP), LRP onset differences between SSTs and RSTs would image modulated processing rates in those stages that occur after the start of selective motor activation (e.g., response execution processes; for methodological details, see also Leuthold, 2003).

In summary, different accounts of redundancy gains in visual pop-out search make distinguishable predictions: (i) If redundantly defined targets indeed facilitate focal-attentional selection relative to singly defined targets (e.g., Krummenacher et al., 2001, 2002), there should be an RSE on PCN latencies. (ii) If coactivation arises at the stage of response execution (e.g., Miller, 2007), the latencies of the response-locked LRPs should be shorter with redundantly as compared with singly defined targets. (iii) If co-

activation arises exclusively at the stage of postselective (perceptual) stimulus analysis and response selection (e.g., Feintuch & Cohen, 2002), there should be no RSE on the PCN latencies and, respectively, the onset of the response-locked LRP, whereas there should be an effect on the latencies of the stimulus-locked LRP. Importantly, the finding of an RSE on the onset of the stimulus-locked LRP would only argue in favor of the Feintuch and Cohen (2002) account if there is no RSE on the PCN latencies (reflecting faster focal-attentional selection of redundantly, compared with singly, defined targets), this effect would also show up in the latencies of the stimulus-locked LRP (which encompass both the time required for attentional stimulus selection and that for postselective stimulus-response mapping).

METHODS

Participants

Thirteen observers (4 women) took part in the experiment. One observer had to be excluded from the analyses due to excessive eye blink artifacts. The ages of the remaining 12 observers ranged from 20 to 30 (median 25) years. All had normal or corrected-to-normal vision and reported no history of neurological disorders. Observers were either paid or received course credit for participating.

Stimuli and Procedure

The visual search display consisted of 34 colored bar stimuli arranged along the circumferences of three imaginary circles around a white central fixation point, presented against a black background. The inner, middle, and outer circles consisted of 6, 12, and 16 items and were placed at an eccentricity of 4.5°, 8.5°, and 12.5° of visual angle, respectively (see Figure 1). In one third of the trials, a homogenous stimulus array was presented consisting only of yellow (CIE, 0.456, 0.469, 32) distractor bars. All bars were 0.6° wide and 2.7° high. They were horizontally oriented with a uniform jitter of $\pm 8^\circ$. In the remaining two thirds

of the trials, the stimulus array contained a singleton that was equally often defined in the color dimension (red; CIE, 0.544, 0.393, 32), the orientation dimension (vertical), or both (red and vertical) among 33 distracters. The position of the singleton was selected randomly from one of the six lateral positions of the middle circle. Observers were instructed to maintain central eye fixation throughout the experiment and to give a speeded forced-choice response indicating the presence versus the absence of any singleton within the search array using their left or right thumb to press a left or right mouse button, respectively.

Observers were seated in a dimly illuminated, sound-attenuated, and electrically shielded cabin. The stimuli were presented on a 17-in. computer screen placed at a viewing distance of approximately 75 cm. One experimental session consisted of 20 blocks of 72 trials each, resulting in a total of 1440 trials. Each trial started with a white fixation point for 500 msec, followed by the search array for 200 msec. A trial was terminated by the observer's response or after a maximum duration of 1000 msec. During the intertrial interval, a central white fixation point was presented for a variable duration uniformly distributed between 950 and 1050 msec. In case of an observer exceeding the maximum response time window or making an incorrect response, the word "FEHLER" (German word for "error") was centrally presented for 1000 msec before the intertrial interval, signaling incorrect behavior. Half of the observers responded "target present" using their left thumb and "target absent" using their right thumb during the first 10 blocks of the experiment and vice versa for the other half. After 10 blocks, the assignment of thumbs to mouse buttons was reversed. Before the start of each experimental half, a practice block was performed to ensure a proper stimulus-response mapping.

RT Data Analysis

Miller (1982) formalized the RMI as $P(\text{RT} < t | S_{12}) \leq P(\text{RT} < t | S_1) + P(\text{RT} < t | S_2)$, where S_i denotes a single signal presented in channel i and S_{ij} a redundant signal presented in channels i and j (where i and j can be either 1 or 2). Testing the RMI usually involves determination of the cumulative density functions (CDFs) of RTs obtained on redundant- and single-signal trials (separately for each type of single signal and for each participant). The sum of the two single-signal trial CDFs is then related to the CDF for redundant-signal trials. If the difference between the cumulative probabilities is less than zero, any observed RSE is in accordance with the race model assumption. To deal with the somewhat unintuitive property of the sum of two single-signal CDFs converging to 2 (rather than 1 as in density functions), we adopted an alternative formulation of the RMI proposed by Colonius and Diederich (2006). They demonstrated that the minimum of the sum of the two CDFs and 1, $\min(1, P(\text{RT} < t | S_1) + P(\text{RT} < t | S_2))$, is also a density function. If the CDFs are given by $P(\text{RT} < t |$

$S_1) = G_1(t)$, $P(\text{RT} < t | S_2) = G_2(t)$, and $P(\text{RT} < t | S_{12}) = F(t)$, the RMI can be formulated as $d(t) = F(t) - \min(1, G_1(t) + G_2(t)) \leq 0$, where $d(t)$ denotes the Kolmogorov distance between the two distributions $F(t)$ (i.e., the distribution based on the redundant-signal RTs) and $\min(1, G_1(t) + G_2(t))$ (i.e., the distribution corresponding to the maximum possible benefit for redundant signals compared with single signals under the race model assumption). The race model predicts the distance $d(t)$ to be smaller than zero for all times t .

To test whether $d(t)$ differs significantly from zero for a particular point in time t , we used the method of vincentization (e.g., Kiesel, Miller, & Ulrich, 2007; Miller, 1982). Accordingly, the group distribution is calculated by evaluating $d(t)$ for each observer at a defined number of quantiles. To avoid an overestimation of RMI violations due to multiple testing (if the RMI is violated at a particular quantile, violations at neighboring points are likely to occur as well; Kiesel et al., 2007; Van Zandt, 2002), we tested the RMI within a limited range of quantiles, between 0.05 and 0.20, only (for details, see Kiesel et al., 2007).

EEG Recording and Data Analysis

The EEG was recorded continuously, at a digitization rate of 500 Hz, using 64 Ag/AgCl electrodes including those corresponding to the 10–10 System (American Electroencephalographic Society, 1994). The electrodes were mounted on an elastic cap (Easy Cap, Falk Minow Services, Munich, Germany). Horizontal and vertical eye activity was monitored by means of electrodes placed at the outer canthi of the eyes and, respectively, the superior and inferior orbits. Electrophysiological signals were amplified using a 0.1- to 250-Hz band-pass filter using BrainAmp amplifiers (BrainProducts, Munich) and filtered off-line with a 1- to 40-Hz band-pass (Butterworth zero phase, 24 dB/Oct). All electrodes were referenced to Cz and re-referenced off-line to linked mastoids. Impedances were kept below 5 k Ω . Before epoching the EEGs, an independent component analysis, as implemented in the Brain Vision Analyzer software (BrainProducts, Munich), was performed to identify and backtransform blinks and horizontal eye movements from the EEGs. The EEG was then epoching into 1000-msec segments with a 200-msec pre-stimulus baseline that was used for the baseline correction. Only trials with correct responses were selected for further analysis. Trials with artifacts, such as signals exceeding $\pm 60 \mu\text{V}$, bursts of EMG activity (permitted maximal voltage steps/sampling point of 50 μV), and activity lower than 0.5 μV within intervals of 500 msec (indicating dead channels), were excluded from further analysis on an individual-channel basis before the ERPs were averaged.

The PCN component was quantified by subtracting ERPs obtained at lateral posterior electrode positions PO7/PO8 ipsilateral to the side of the singleton in the search array

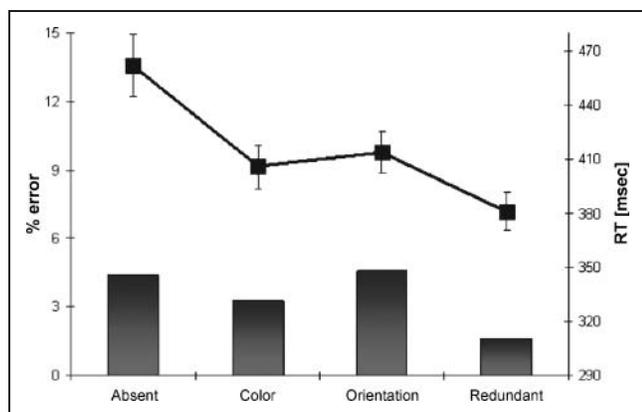


Figure 2. RTs (lines) and error rates (bars) as a function of Target Type (Absent, Color, Orientation, Redundant). Error bars indicate 95% confidence intervals based on the standard errors of the median RTs.

from contralateral ERPs. PCN latencies were determined individually as the maximum negative deflection in the 150- to 350-msec time window poststimulus. PCN amplitudes were calculated averaging five sample points before and after the maximum deflection. Latencies and amplitudes of the PCN were analyzed in one-way ANOVAs with the single factor Target Type (color, orientation, redundant).

For the LRP analysis, stimulus- and response-locked waveforms were extracted from the EEG data. Stimulus-locked waveforms were computed within an 800-msec period after the onset of the search display, relative to a 200-msec prestimulus baseline. To obtain the response-locked LRP, the first step involved the extraction of stimulus-locked LRP waveforms epoching the EEGs into 4000-msec segments ranging from 2000 msec before and after stimulus onset. Next, a baseline correction was applied based on a prestimulus interval (−200 to 0 msec) before the data were then re-epoched into response-locked LRP waveforms ranging from 800 msec before to 200 msec after response onset. Both LRP waveforms were computed separately for all three (color, orientation, redundant) trial

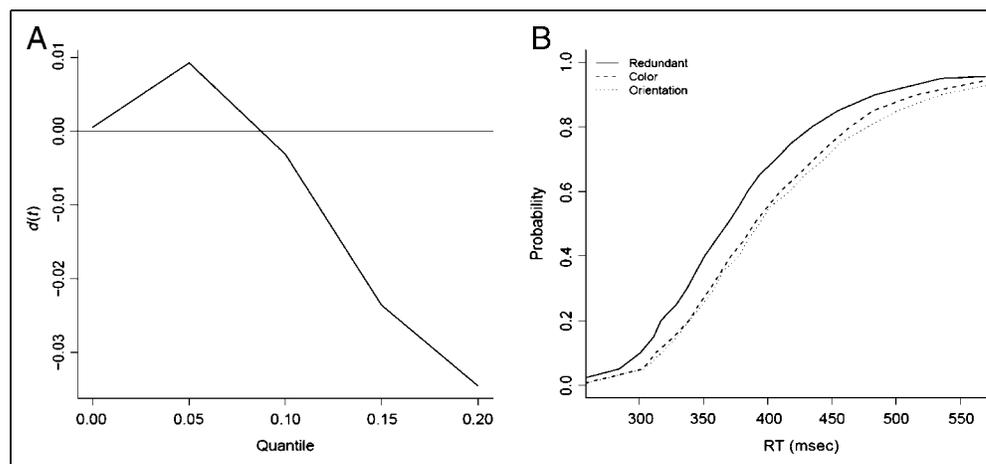
conditions by subtracting ERPs at electrodes C3/C4 ipsilateral to the side of uni-manual hand responses from contralateral ERPs using the following formula: $(C4[\text{left}] - C3[\text{left}] + C3[\text{right}] - C4[\text{right}]) / 2$. All other postprocessing steps before averaging the LRP were kept identical (to the PCN analysis). Determination of stimulus- and response-locked LRP onset latencies was based on Ulrich and Miller's (2001; see also Miller, Patterson, & Ulrich, 1998) jackknife-based scoring method, which defines the LRP onset as the point in time when the LRP amplitudes reaches a specific criterion relative to the prestimulus baseline. As suggested by Miller et al. (1998), we used 50% and 90% of maximum LRP amplitude as an optimal criterion for determining stimulus- and response-locked LRP onset latencies, respectively. Statistical analyses were conducted on onset latencies and amplitudes (using five sample points before and after the maximum deflection obtained in the time window 100–20 msec before response onset for the response locked and in the time window 200–600 msec after stimulus onset for the stimulus-locked LRP) of both LRP waveforms. As for the PCN component, onset latencies and amplitudes of the LRP waveforms were analyzed by one-way ANOVAs with the factor Target Type (color, orientation, redundant).

RESULTS

Behavioral Data

RTs and error rates were analyzed using one-way ANOVAs with the factor Target Type, including target absence as an additional level (absent, color, orientation, redundant). Trials with RTs longer than 1000 msec and shorter than 150 msec were excluded from the analysis (less than 1% of the data). Although error rates were low overall (3.5%), the main effect of Target Type was significant, $F(3, 33) = 9.3, p < .001$: fewer errors were made on redundant-target trials (1.6%) compared with color target (3.3%; Tukey HSD post hoc comparison: $p < .04$), orientation target (4.6%; $p < .003$), and target-absent trials (4.4%; $p < .006$) (Figure 2).

Figure 3. (A) Test for violations of the RMI. RMI violations occur if the distance $d(t)$ between the redundant signal and the sum of both single-signal distributions is positive (represented by the area above the horizontal line). The distance $d(t)$ is depicted for the 0.05, 0.10, 0.15, and 0.20 quantiles. (B) Cumulative RT distributions for each of the three Target Type conditions (Color, Orientation, and Redundant).



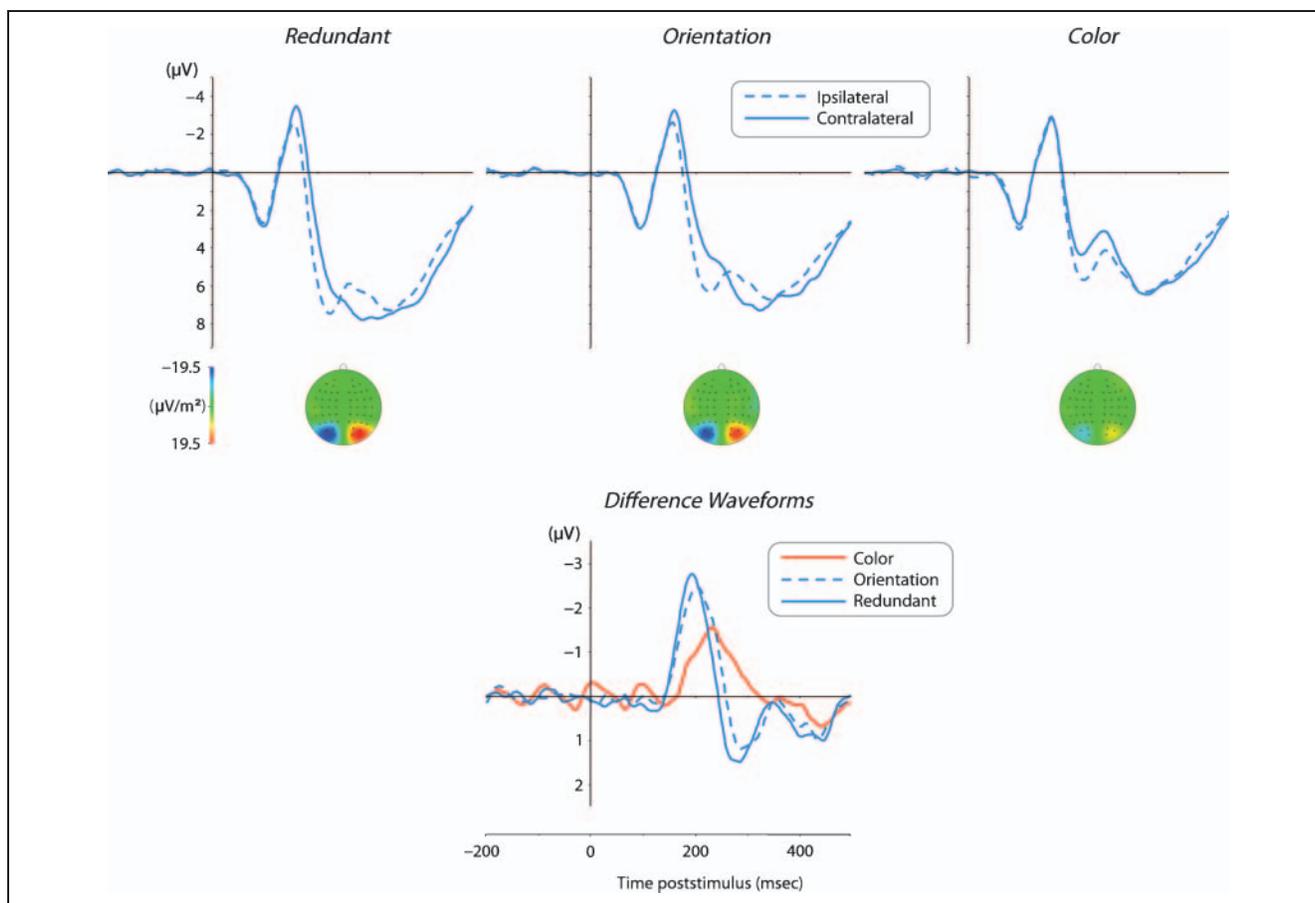


Figure 4. Upper panel: Grand averaged event-related brain potentials elicited in the 500-msec interval following stimulus onset at electrode positions PO7/PO8 contralateral (solid line) and ipsilateral (dashed line) to the target location. Central panel: Topographical maps of PCN scalp distributions for each of the three Target Type conditions (Color, Orientation, and Redundant) at the point in time when the difference between contra- and ipsilateral waveforms was maximal. These maps were computed by mirroring the contra-ipsilateral difference waves to obtain symmetrical voltage values for both hemispheres (using spherical spline interpolation). Bottom panel: PCN difference waveforms obtained by subtracting ipsilateral from contralateral activity for each of the three Target Type conditions.

Trials with erroneous responses were excluded from the RT analysis. The same ANOVA as for the error rates revealed RTs to vary significantly as a function of Target Type, $F(3, 33) = 47.7, p < .001$. Target-absent responses (462 ± 17.4 msec) were slower than responses to orientation (414 ± 11.3 msec, $p < .001$), color (406 ± 12.1 msec, $p < .001$), and redundant targets (381 ± 10.9 msec, $p < .001$). Furthermore, RTs to singly defined orientation and color targets were statistically equivalent ($p > .7$), whereas redundant targets were responded to faster than both orientation ($p < .003$) and color ($p < .007$) targets.

To examine whether this redundancy gain could be accounted for by coactivation rather than parallel-race models, we tested the RMI. First, we corrected for fast guesses using a “kill-the-twin” procedure (Eriksen, 1988; Grice, Nullmeyer, & Spiker, 1977; see also Krummenacher et al., 2001, 2002). As the target-present-to-absent ratio was 2:1, a random fast guess was correct in two of three cases. Therefore, for every false alarm, we selected two trials on which the RTs were in an interval of ± 3 msec of the false alarm RT and excluded them from further analysis. As can be seen from Figure 3A, there was a significant violation of the RMI at

the 0.05 quantile, $d(t) = 0.009, t(11) = 2.2, p < .025$, which rules out parallel-race models. $d(t)$ at the other three quantiles tested was $-0.003, -0.024,$ and -0.035 , respectively.

Electroencephalographic Data

Posterior-Contralateral Negativity

Figure 4 (top panel) presents the ERPs obtained at PO7/PO8 contralateral and ipsilateral to the side of the singleton, separately for orientation, color, and redundant targets as well as the difference waveforms (contralateral activity minus ipsilateral activity) for each of the three experimental conditions (bottom panel). As can be seen, a solid PCN component was elicited in all three conditions, with PCN latencies and amplitudes substantially differing among the Target Type conditions. Numerically, the fastest latencies and the largest amplitudes were observed for redundant-signal trials (208 msec; $-3.61 \mu\text{V}$), followed by the two single-signal trials: orientation (223 msec; $-3.11 \mu\text{V}$) and color (240 msec; $-2.09 \mu\text{V}$).

This pattern of effects was substantiated by repeated measure ANOVAs of the PCN latencies and amplitudes

with the factor Target Type (color, orientation, redundant). For PCN latencies, a significant main effect was revealed, $F(2, 22) = 20.176, p < .001$. Subsequent (Tukey HSD) post hoc testing confirmed that redundant targets were significantly faster relative to color ($p < .001$) and orientation targets ($p < .019$), thus demonstrating differential

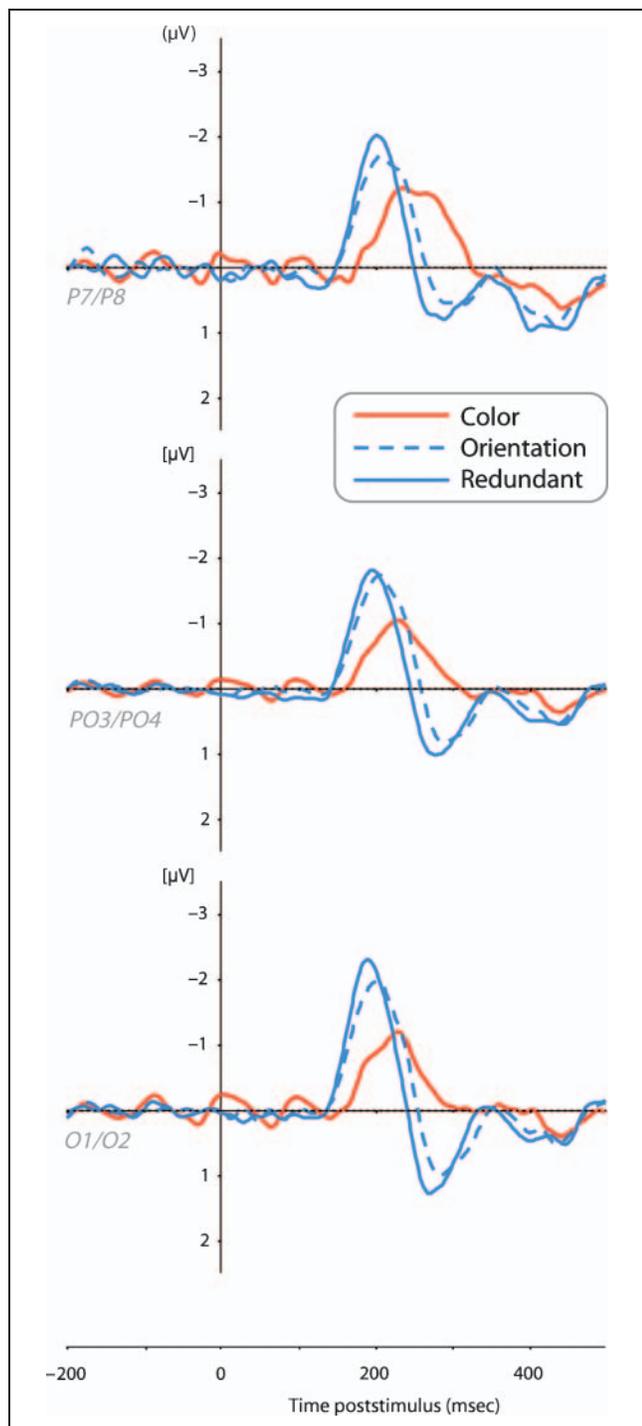


Figure 5. PCN difference waves obtained by subtracting ipsilateral from contralateral activity for each of the three Target Type conditions (Color, Orientation, and Redundant) at electrode sites (P7/P8, PO3/PO4, and O1/O2) adjacent to PO7/PO8.

processing rates within preattentive processing stages depending on the coding (redundant versus single) of the target.³ In addition, the latency difference between both singly defined targets was found to reach statistical significance ($p < .007$).

As with the PCN latencies, there was also a significant effect of Target Type on the PCN amplitudes, $F(2, 22) = 12.662, p < .001$. Further analysis (Tukey HSD post hoc contrasts) revealed the amplitudes to differ significantly between redundant and color targets ($p < .001$) and between orientation and color targets ($p < .008$), but not between redundant and orientation targets ($p > .265$). Thus, although there was a statistically clear-cut effect of redundant target coding on the PCN latencies, the (numerical) enhancement of the PCN amplitudes in response to redundantly coded targets failed to receive unequivocal statistical support.

To examine whether the pattern of target-dependent PCN (latency and amplitude) effects revealed above generalizes across neighboring electrode sites (see Figure 5), two further repeated measures ANOVAs were carried out, each with the factors Target Type (color, orientation, redundant) and Electrode Site (O1/O2, PO7/PO8, PO3/PO4, P7/P8). For PCN latencies, this ANOVA replicated the main effect of Target Type, $F(2, 22) = 23.707, p < .001$: latencies were faster for redundantly defined targets (208 msec), intermediate for singly defined orientation targets (223 msec), and slowest for color targets (240 msec); all comparisons were significant (Tukey HSD: $p < .001$). In addition, the main effect of Electrode Site was significant, $F(3, 33) = 6.377, p < .002$, with faster PCN latencies at O1/O2 as compared with P7/P8 (220 vs. 227 msec; Tukey HSD: $p < .001$). Importantly, the Target Type \times Electrode Site interaction was nonsignificant ($p > .574$); that is, the timing of the PCN did not differ reliably as a function of target type across electrode sites. For the PCN amplitudes, all effects were revealed to be significant, Target Type, $F(2, 22) = 15.088, p < .001$; Electrode Site, $F(3, 33) = 5.894, p < .002$; interaction, $F(2, 22) = 3.637, p < .004$. As expected, the strongest (PCN) activations were elicited at PO7/PO8, with significant RSEs evident at all ($p < .002$) but one (PO3/PO4, $p > .47$) electrode site.

Lateralized Readiness Potential

Figure 6 (left side) displays the stimulus-locked LRP waveform obtained at C3/C4 for all three experimental conditions. As can be seen, redundantly defined targets were accompanied by markedly faster onsets of the stimulus-locked LRP wave as compared with singly defined targets, however, without amplitude modulations across conditions. This was corroborated by the jackknife-based scoring method (Miller et al., 1998), which yielded the fastest stimulus-locked LRP onset latencies for RSTs (241 msec), followed by color (261 msec) and orientation SSTs (268 msec). Statistically, this was validated by a main effect of Target Type, $F_c(2, 22) = 9.571, p_c < .001$.⁴ Subsequent (Tukey

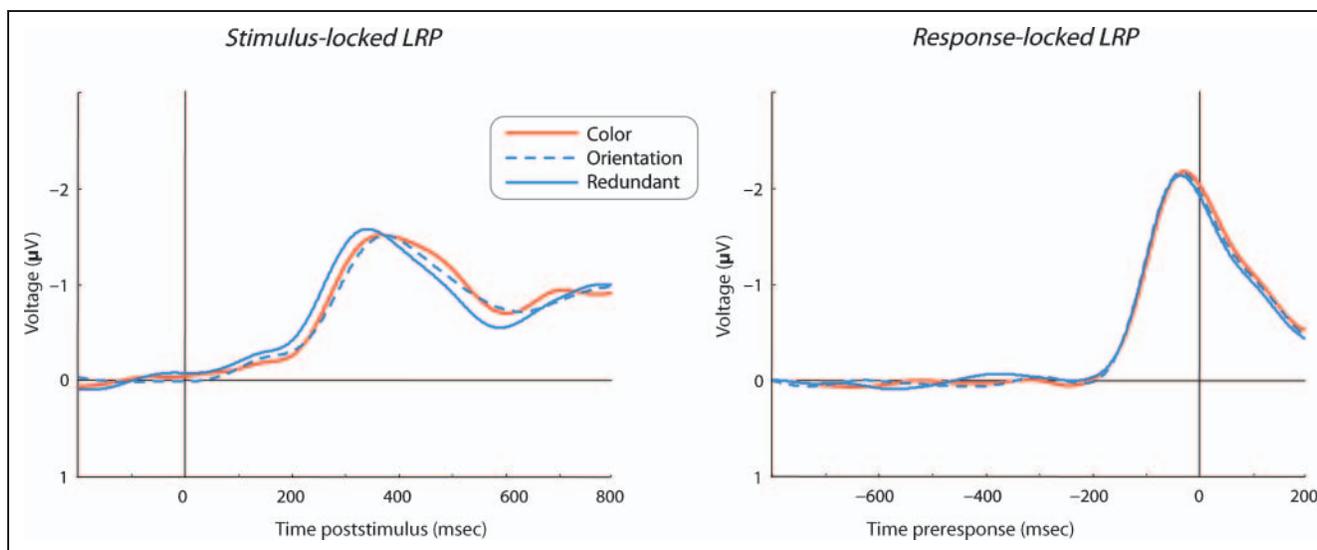


Figure 6. Left side: LRPs elicited in the 800-msec interval following stimulus onset at electrode positions C3/C4, separately for each Target Type condition (Color, Orientation, and Redundant). Right side: LRPs elicited in the 800-msec interval before response onset at electrode positions C3/C4, separately for each of the three Target Type conditions.

HSD) post hoc comparisons confirmed all experimental conditions to be significantly different from each other ($p < .05$). The ANOVA investigating the stimulus-locked LRP amplitudes confirmed the informal impression that, statistically, LRP activations time locked to the stimulus onset were comparable between target conditions, $F(2, 22) = 1.698$.

Finally, no differences between RSTs and SSTs were evident in the response-locked LRP waveforms. As can be seen from Figure 6 (right side) and the outcome of the same ANOVA as for stimulus-locked LRPs, the onset latencies and amplitudes of the response-locked LRP were independent of the definition of the target, nonsignificant Target Type main effect for onset latencies, $F_c(2, 22) = 0.878$, as well as amplitudes, $F(2, 22) = 0.353$. This pattern indicates that redundant target coding did not affect the stages of response activation and execution in the present (visual search) task.

DISCUSSION

Redundancy gains refer to the phenomenon of speeded RTs when the response is triggered by two, rather than just one, response-relevant target signals. Depending on the experimental paradigm, redundant signals can be realized by presenting the same target element simultaneously at two separate locations (e.g., divided attention paradigm), or two different target elements can be presented simultaneously at the same location (e.g., visual search paradigm). For the latter, it is generally agreed that the RSE results from a coactive mechanism that acts within the visual modality (e.g., Feintuch & Cohen, 2002; Krummenacher et al., 2001). However, at what level of processing—preattentive

and/or postselective—coactivation arises is currently under debate: Krummenacher et al. (2002) argue for a preattentive locus, in contrast to Feintuch and Cohen (2002) who favor a postselective, but still perceptual origin of coactivation. Theoretically, response-related processing stages are also possible (e.g., Miller, 2007). To permit a clear-cut differentiation between these processing stages in a given task, the present study used the visual search paradigm, which lends itself to the analysis of two specific electrophysiological markers that reflect either purely (preattentive) perceptual (PCN) or purely response-related processing (LRP). More specifically, the study was designed to identify the locus, or loci, of behaviorally measured redundancy gains in visual pop-out search across the processing cycle from the perceptual encoding of the stimulus through the selection of the required response to the activation and execution of the selected motor action.

Behaviorally, observers performed as expected: RTs were markedly faster and more accurate in response to redundantly defined compared with singly defined pop-out targets, replicating previous (search) results (Zehetleitner et al., 2009; Krummenacher et al., 2001, 2002). In addition, the RMI (Miller, 1982) was significantly violated, which has been taken to argue in favor of coactivation models (Krummenacher et al., 2001, 2002; Miller, 1982).

Electrocortical Correlates of Redundancy Gains in Visual Pop-out Search

At the electrophysiological level, this speeding-up of RTs to redundantly, relative to singly, defined pop-out targets was associated with systematic modulations of the PCN component, in particular: Latencies were shorter to redundantly

defined targets relative singly defined orientation and color targets (RSEs of 15 and 32 msec, respectively).⁵ The latency of the PCN can be regarded as marking the transition from preattentive to focal-attentional processing; that is, it reflects the preattentive stimulus encoding rate (e.g., Töllner et al., 2008). Thus, the PCN latency modulation observed in the present study demonstrates the involvement of preattentive perceptual processes in the generation of the RSE. The fact that the behavioral RT advantages for redundantly relative to singly defined targets were of a similar order of magnitude (RSEs of 33 and 25 msec relative to orientation and color targets, respectively) suggests that the largest portion of the behaviorally measured RSE in visual pop-out search originates from preattentive perceptual processes that operate before, and provide the basis for, focal-attentional target selection.

Besides the main finding that the (mean) PCN latencies on RSTs were significantly shorter than the shortest (mean) latencies on SSTs, the data also revealed a difference between singly defined color and orientation targets, namely, delayed PCN latencies and reduced amplitudes for color targets. This closely resembles the pattern reported in one of the earliest and most influential studies of the PCN component: Eimer (1996), which also reported the PCN to be delayed and reduced in amplitude in response to color (vs. form) processing. However, in Eimer's study, behavioral RTs were faster for color than for form targets, which he took as evidence that the elicitation of the PCN is dependent on the efficiency of processing within the respective dimensions. Because the behavioral performance did not differ (significantly) between color and orientation targets in the present study, one other reason for the differential PCNs between the two dimensions might lie in the neuroanatomical architecture of the human visual system: neural populations mostly concerned with color processing reside in V4 (extrastriate visual cortex), whereas the processing of (preferred) orientation information starts already in V1 (striate cortex).⁶ Thus, coding of the relevant attributes at different levels in the visual system might account for the observed PCN difference between orientation and color targets.⁷ However, although the PCN latencies were longer for color (than for orientation) targets in the present study, they were associated with (significantly) earlier stimulus-locked LRP onsets and (nonsignificantly) faster overt RTs (see below). This may be taken to suggest that color targets were somewhat more efficiently processed at the stages of postselective stimulus analysis and/or response selection (compared with orientation targets).

In addition to the PCN modulation, redundant coding of pop-out signals was also revealed to significantly reduce the stimulus-locked LRP onset latencies as compared with singly defined orientation and color targets (reductions of 27 and 21 msec, respectively). However, because these latencies inherently include any preselective processing differences between conditions, the PCN latencies would need to be subtracted from the stimulus-locked LRP laten-

cies to examine for any redundancy gains arising at the stages of postselective stimulus analysis and response selection before the stage of response production (cf. Töllner et al., 2008).⁸ The stimulus-locked LRP latencies were only little longer than the PCN latencies: The average difference was 33 msec and showed little systematic variation among the three target type conditions (33, 21, and 45 msec for redundant, color, and orientation targets, respectively). In particular, there was no evidence of a redundancy gain relative to color targets (the dimension processed fastest) or to the average of the two types of singly defined targets, at this postselective processing stage—suggesting that postselective stimulus analysis and response selection processes did not contribute to the behavioral redundancy gains. This short latency difference between the stimulus-locked LRP and the PCN (of 33 msec, on average) in the present pop-out search task is also noteworthy, as it contrasts with the much larger difference seen in compound-search tasks (e.g., of 126 msec in the study of Töllner et al., 2008), where the response-defining visual attribute is dissociated from the target-defining feature(s). This suggests that simple detection responses in pop-out search require very little postselective processing—consistent with the notion that the (overall saliency) signal that triggers the allocation of focal attention to the target (i.e., a covert “orienting response”) also more or less directly triggers the instructed motor response (for discussions, see Müller & Krummenacher, 2006; Müller, Krummenacher, & Heller, 2004).

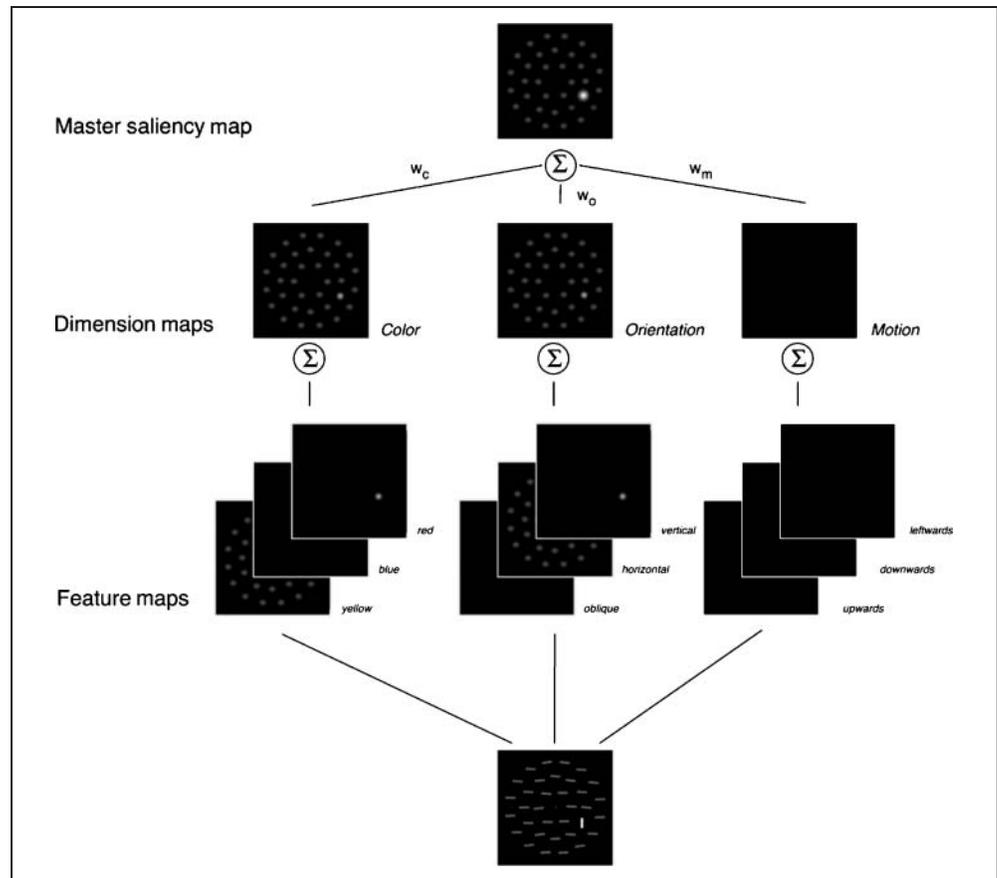
Finally, there was no effect of target signal redundancy on the onset latencies and amplitudes of the response-locked LRP. Thus, in marked contrast to, for instance, the divided attention paradigm—for which a response-locked LRP onset latency shift of about 11 msec has been reported, accounting for over half of a behavioral RSE of 20 msec (see Miller, 2007)—we found no indication of modulated processing rates at the level of response production.

In summary, the present electrophysiological results provide a clear-cut picture: In visual pop-out search, redundancy gains originate entirely from processes that operate at the processing stage(s) of preattentive perceptual encoding, consistent with, for example, Krummenacher et al. (2002); by contrast, there did not appear to be any (additional) contribution from postselective stages of stimulus analysis and stimulus-response mapping (e.g., Feintuch & Cohen, 2002) and of response execution (e.g., Miller, 2007).

Coactivation of Visual Dimensions

The present findings have important theoretical implications as to the nature of redundant-signal integration in pop-out search (and perhaps more generally in paradigms in which the two target signals originate from the same location and signal detection is sufficient for responding). That redundant signals were found to have a strong impact

Figure 7. Parallel-coactive processing of multiple visual dimensions as assumed by a saliency-based processing architecture (see also Itti & Koch, 2000). The stimulus display is initially decomposed by a set of basic analyzer units (e.g., for color, orientation, motion, etc.), which compute the presence of feature contrast (i.e., saliency) for all locations across the visual scene. On this account, targets redundantly defined within the color and orientation dimensions generate feature contrast signals simultaneously in both dimensional maps, thus generating a stronger (summed) saliency signal at the level of the master map (resulting in faster PCN latencies and thus faster behavioral reactions) compared with targets defined by color or orientation only.



on PCN latencies provides strong support for the proposal of Krummenacher et al. (2001, 2002) that RSEs are essentially preattentive in nature. This is consistent with salience summation models (Gao, Mahadevan, & Vasconcelos, 2007; Itti & Koch, 2000; Koch & Ullmann, 1985), such as the dimension-weighting account (e.g., Müller, Heller, & Ziegler, 1995; see also Töllner, Gramann, Müller, & Eimer, 2009, for a modality-weighting account). According to these models, a visual scene is initially decomposed by a set of basic visual analyzer units in separate dimensions (color, orientation, etc.), where each dimension-specific input module computes a map of feature contrast signals across all locations in the visual field. These signals are then transmitted to a supra-dimensional master map of activations, which integrates (sums) the dimensional signals separately for each location. The most active location on this overall-saliency map determines the deployment of focal attention. On this account, redundancy gains in visual pop-out search originate from the integration of target signals encoded in separate visual dimensions before the allocation of spatial attention. As illustrated in Figure 7, dimensionally redundant targets lead to two simultaneous activations in the respective (dimension-specific) input modules. Thus, because both activations (at the same spatial location) are projected to a common master map unit, evidence for the presence of a pop-out target is accumulated faster (against a fixed threshold) due to the summation⁹ of the

two single dimensional signals. By contrast, on single-signal trials, the shift of focal attention is determined solely by a single dimension-specific activation, prolonging the time required to activate the master map unit above threshold. This model is further supported by the observation that searching for (dual) redundant targets defined in the same dimension (e.g., a red and a blue vertical bar among green vertical distracters) produces mean RT redundancy gains, but no violations of the RMI (even if closely spaced). By contrast, if dual targets are defined in different dimensions (e.g., red vertical and green tilted bar among green vertical distracters), RT redundancy gains and violations of the RMI are observed (Krummenacher et al., 2002). Thus, generation of activity in different dimensions might be a further prerequisite for coactive processing at the preattentive level of perceptual coding to occur.

This is not to say that the RSEs in the same-object identification paradigms of Feintuch and Cohen (2002) and, respectively, Mordkoff and Miller (1993) are likewise generated at a preattentive level of processing. Although there are several commonalities between their paradigms and the present pop-out search task (in particular, spatially coincident signals defined within the visual modality), they differ in two crucial respects: First, the target location is always fixed, that is, no search is necessary; second, the required depth of processing is greater in the identification task than in the simple detection task (in the latter,

the mere presence of a featural inhomogeneity in the field is sufficient to determine the required response whereas the target's featural identity is task irrelevant). Instead of a preattentive locus, redundancy gains in such identification paradigms might arise at a later level of perceptual stimulus analysis for response selection. For example, according to the dimension-action model of Feintuch and Cohen (2002) and Cohen and Shoup (1997), coactivation occurs at the level of response selection if an attentionally selected and analyzed stimulus possesses two response-relevant features in different dimensions (i.e., redundant signal). The present data, however, suggest that coactive processing in simple pop-out search tasks does not involve coactivation of responses at this postselective level of processing—presumably because a detection response can be initiated directly on the basis of the master map saliency signal, without requiring any deeper, postselective stimulus analysis (see also Müller & Krummenacher, 2006; Müller et al., 2004).

Conclusion

In summary, the present study has revealed new insights into the mechanisms underlying redundancy gains in visual pop-out search. On the basis of lateralized event-related brain potentials (PCN and LRP), a preattentive perceptual basis of redundancy gains can be proposed in situations where dual (dimensionally separate) target signals originate from identical spatial locations amongst distracters. These results provide new evidence in favor of saliency summation models (such as the dimension-weighting account) and appear inconsistent with models that envisage the RSE to be generated exclusively at postselective stages of processing (e.g., Feintuch & Cohen, 2002).

Acknowledgments

This research was supported by German Research Foundation (DFG) grants FOR480 and EC142 (Excellence Cluster "Cognition for Technical Systems"). The authors thank Nick Myers for technical assistance.

Reprint requests should be sent to Thomas Töllner, Department Psychology, General and Experimental Psychology, Ludwig-Maximilians-University Munich, Leopoldstr. 13, D-80802 Munich, Germany, or via e-mail: toellner@psy.uni-muenchen.de.

Notes

1. As it has been demonstrated by Shedden and Nordgaard (2001), both amplitude and latency of this component are independent of the timing and activation of the nonlateralized N2 component. We thus prefer to use the term PCN (instead of N2pc) to preclude misleading interpretations.
2. Note that at least two visual stimuli, presented simultaneously in both visual hemifields, are necessary to elicit a PCN component.
3. When comparing redundant and orientation targets in Figure 4, the PCN offsets appear to differ, whereas the onsets are indistinguishable. To examine this, we additionally computed separate jackknife-based analyses for the on- and the offsets of the PCN (using 50% of the maximum amplitude). However, these

analyses failed to reveal significant differences (at an alpha level of 5%) weakening the possibility that the presence of some slower trials with orientation-defined targets shifted the (orientation-) PCN toward a longer latency. We thank Pierre Jolicoeur for suggesting these additional analyses.

4. F values of all LRP onset latencies are corrected according to the formula: $F_c = F / (n - 1)^2$ (see also Ulrich & Miller, 2001).
5. Note that, due to temporal "smearing," peak latency differences should not be regarded as representing the "true" extent of underlying processing differences.
6. It should be noted that orientation-selective V1 cells may also code some aspects of stimulus color, as indicated by conjunction cells in (monkey) V1 (Leventhal, Thompson, Liu, Zhou, & Ault, 1995).
7. Theoretically, the shape of the color PCN may be consistent with some component jitter, which should be reflected in greater RT variance for color (relative to orientation) targets. However, as can be seen in Figure 3B, there was no apparent difference between both types of singly defined target.
8. Although subtracting PCN latencies from stimulus-locked LRP latencies may be problematic (due to the different ways in which these latencies are estimated; see above), the resulting differences would have at least illustrative value.
9. Note that for redundant targets, the resulting overall saliency is not equal to the summed saliency signals from the single target dimensions (Nothdurft, 2000). Rather, dimensional signals seem to be integrated in a subadditive fashion. Nothdurft (2000) attributed the amount of subadditivity for different combinations of dimensions to the amount of overlap of the underlying saliency mechanisms. The subadditivity is likely due to the fact that saliency increases asymptotically, rather than to infinity. That is, it is impossible to raise saliency above a certain level by increasing feature contrast or by presenting redundant targets (Gao et al., 2007; Nothdurft, 1993).

REFERENCES

- American Electroencephalographic Society. (1994). Guideline for standard electrode position nomenclature. *Journal of Clinical Neurophysiology*, *11*, 111–113.
- Ansgore, U., & Heumann, M. (2006). Shifts of visuospatial attention to invisible (metacontrast-masked) singletons: Clues from reaction times and event-related potential. *Advances in Cognitive Psychology*, *2*, 61–76.
- Brisson, B., Robitaille, N., & Jolicoeur, P. (2007). Stimulus intensity affects the latency but not the amplitude of the N2pc. *NeuroReport*, *18*, 1627–1630.
- Cohen, A., & Shoup, R. (1997). Perceptual dimensional constraints in response selection processes. *Cognitive Psychology*, *32*, 2, 128–181.
- Coles, M. G. H. (1989). Modern mind-brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology*, *26*, 251–269.
- Colonius, H., & Diederich, A. (2006). The race model inequality: Interpreting a geometric measure of the amount of violation. *Psychological Review*, *113*, 148–154.
- Eimer, M. (1996). The N2pc as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.
- Eimer, M., & Coles, M. G. H. (2003). The lateralized readiness potential. In M. Jahanshahi & M. Hallett (Eds.), *The Bereitschaftspotential: In honour of Professors Deecke and Kornhuber* (pp. 229–248). New York: Kluwer Academic.
- Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related

- brain potentials. *Journal of Cognitive Neuroscience*, *20*, 1423–1433.
- Eriksen, C. W. (1988). A source of error in attempts to distinguish coactivation from separate activation in the perception of redundant targets. *Perception & Psychophysics*, *44*, 191–193.
- Feintuch, U., & Cohen, A. (2002). Visual attention and coactivation of response decisions for features from different dimensions. *Psychological Science*, *13*, 362–370.
- Forster, B., Cavina-Pratesi, C., Aglioti, S. M., & Berlucchi, G. (2002). Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time. *Experimental Brain Research*, *143*, 480–487.
- Gao, D., Mahadevan, V., & Vasconcelos, N. (2007). On the plausibility of the discriminant center-surround hypothesis for visual saliency. *Journal of Vision*, *8*, 1–18.
- Gondan, M., Lange, K., Rösler, F., & Röder, B. (2004). The redundant target effect is affected by modality switch costs. *Psychonomic Bulletin & Review*, *11*, 307–313.
- Grice, G. R., Nullmeyer, R., & Spiker, V. A. (1977). Application of variable criterion theory to choice reaction time. *Perception & Psychophysics*, *22*, 431–449.
- Hackley, S. A., & Valle-Inclán, F. (2003). Which stages of processing are speeded by a warning signal? *Biological Psychology*, *64*, 27–45.
- Iacoboni, M., & Zaidel, E. (2003). Interhemispheric visuo-motor integration in humans: The effect of redundant targets. *European Journal of Neuroscience*, *17*, 1981–1986.
- Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, *40*, 1489–1506.
- Jaskowski, P., van der Lubbe, R. H. J., Schlotterbeck, E., & Verleger, R. (2002). Traces left on visual selective attention by stimuli that are not consciously identified. *Psychological Science*, *13*, 48–54.
- Kiesel, A., Müller, J., & Ulrich, R. (2007). Systematic biases and type II error accumulation in tests of the race model inequality. *Behavior Research Methods*, *39*, 539–551.
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, *4*, 219–227.
- Koene, A. R., & Zhaoping, L. (2007). Feature-specific interactions in salience from combined feature contrasts: Evidence for a bottom-up saliency map in V1. *Journal of Vision*, *7*, 1–14.
- Krummenacher, J., Müller, H. J., & Heller, D. (2001). Visual search for dimensionally redundant pop-out targets: Evidence for parallel-coactive processing of dimensions. *Perception & Psychophysics*, *63*, 901–917.
- Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: Parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 1303–1322.
- Lamarre, Y., Busby, L., & Spidalieri, G. (1983). Fast ballistic arm movements triggered by visual, auditory, and somesthetic stimuli in the monkey. I. Activity of precentral cortical neurons. *Journal of Neurophysiology*, *50*, 1343–1358.
- Leuthold, H. (2003). Programming of expected and unexpected movements: Effects on the onset of the lateralized readiness potential. *Acta Psychologica*, *114*, 83–100.
- Leventhal, A. G., Thompson, K. G., Liu, D., Zhou, Y., & Ault, S. J. (1995). Concomitant sensitivity to orientation, direction, and color of cells in layers 2, 3, and 4 of monkey striate cortex. *Journal Neuroscience*, *15*, 1808–1818.
- Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*, 291–308.
- Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*, 247–279.
- Miller, J., Beutinger, D., & Ulrich, R. (2009). Visuospatial attention and redundancy gain. *Psychological Research*, *73*, 254–262.
- Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology*, *35*, 99–115.
- Miller, J., & Reynolds, A. (2003). The locus of redundant-targets and nontargets effects: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 1126–1142.
- Miller, J. O. (2007). Contralateral and ipsilateral motor activation in visual simple reaction time: A test of the hemispheric coactivation model. *Experimental Brain Research*, *176*, 539–558.
- Mohr, B., Endrass, T., Hauk, O., & Pulvermüller, F. (2007). ERP correlates of the bilateral redundancy gain for words. *Neuropsychologia*, *45*, 2114–2124.
- Mordkoff, J. T., & Miller, J. (1993). Redundancy gains and coactivation with two different targets: The problem of target preferences and the effects of display frequency. *Perception & Psychophysics*, *53*, 527–535.
- Mordkoff, J. T., & Yantis, S. (1991). An interactive race model of divided attention. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 520–538.
- Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*, 1–17.
- Müller, H. J., & Krummenacher, J. (2006). Locus of dimension weighting: Pre-attentive or post-selective? *Visual Cognition*, *14*, 490–513.
- Müller, H. J., Krummenacher, J., & Heller, D. (2004). Dimension-specific intertrial facilitation in visual search for pop-out targets: Evidence for a top-down modifiable visual short-term memory effect. *Visual Cognition*, *11*, 577–602.
- Nothdurft, H. C. (1993). Saliency effects across dimensions in visual search. *Vision Research*, *33*, 839–844.
- Nothdurft, H. C. (2000). Saliency from feature contrast: Additivity across dimensions. *Vision Research*, *40*, 1183–1201.
- Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, *24*, 574–590.
- Schroter, H., Ulrich, R., & Miller, J. O. (2007). Effects of redundant auditory stimuli on reaction time. *Psychonomic Bulletin & Review*, *14*, 39–44.
- Shedden, J. M., & Nordgaard, C. L. (2001). ERP time course of perceptual and post-perceptual mechanisms of spatial selection. *Cognitive Brain Research*, *11*, 59–75.
- Todd, J. W. (1912). *Reaction to multiple stimuli*. New York: Science Press.
- Töllner, T., Gramann, K., Müller, H. J., & Eimer, M. (2009). The anterior N1 component as an index of modality shifting. *Journal of Cognitive Neuroscience*, *21*, 1653–1669.
- Töllner, T., Gramann, K., Müller, H. J., Kiss, M., & Eimer, M. (2008). Electrophysiological markers of visual dimension changes and response changes. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 531–542.

- Töllner, T., Zehetleitner, M., Gramann, K., & Müller, H. J. (2010). Top-down weighting of visual dimensions: Behavioural and electrophysiological evidence. *Vision Research*, *50*, 1372–1381.
- Townsend, J. T., & Nozawa, G. (1997). Serial exhaustive models can violate the race model inequality: Implications for architecture and capacity. *Psychological Review*, *104*, 595–602.
- Ulrich, R., & Müller, J. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology*, *38*, 816–827.
- Van Zandt, T. (2002). Analysis of response time distributions. In J. T. Wixted (Vol. Ed.) & H. Pashler (Series Ed.), *Stevens' handbook of experimental psychology (3rd ed.)*. Volume 4: *Methodology in Experimental Psychology* (pp. 461–516). New York: Wiley.
- Wolber, M., & Wascher, E. (2005). The posterior contralateral negativity as a temporal indicator of visuo-spatial processing. *Journal of Psychophysiology*, *19*, 182–194.
- Wolfe, J. M. (1998). What can 1,000,000 trials tell us about visual search? *Psychological Science*, *9*, 33–39.
- Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*, 867–869.
- Zehetleitner, M., Krummenacher, J., & Müller, H. J. (2009). Co-activation—neither serial exhaustive nor interactive—models can explain violations of the race model in visual pop-out search. *Attention, Perception, & Psychophysics*, *71*, 1739–1759.
- Zehetleitner, M., Müller, H. J., & Krummenacher, J. (2008). What the redundant-signal paradigm reveals about preattentive visual processing. *Frontiers in Biology*, *14*, 5279–5293.