Salience-based integration of redundant signals in visual pop-out search: Evidence from behavioral and electrophysiological measures

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Behavioral and electrophysiological evidence is presented suggesting that, in visual search for feature singleton targets, multidimensional signals are integrated at a preselective stage of processing. Observers searched for a target that was consistently defined by the same features, but differed from the variable context either nonredundantly by one or redundantly by two dimensionally different features. The behavioral results showed reaction time redundancy gains and evidence of coactive processing, and the electrophysiological analyses revealed the latency of the N2pc component of the event-related potential (ERP) to be expedited by redundant relative to nonredundant displays, while the response-related lateralized readiness potential (LRP) remained unaffected. These findings suggest that target signal integration in singleton search paradigms occurs pre-attentively, that is, prior to focal-attentional target selection, with observers basing their responses on the detection of featureless saliency signals, even under conditions in which the target features remain constant and are known in advance. These results have implications for theories assuming top-down influences in feature detection.

Introduction

The environment that we inhabit abounds with visual stimuli, and we largely depend on the sense of vision to plan and control goal-directed actions. One promising strategy to raise the probability that an action-relevant object is detected rapidly and reliably is to increase its conspicuity by making it differ from the context by multiple visual features. For example, road signs, by combining conspicuous colors and shapes, are designed to be detected efficiently in highly variable environments and under conditions in which little time is available to process the information and produce the appropriate action. The effect of such redundant signals on performance is usually investigated by comparing the time it takes to detect redundant relative to nonredundant (action-relevant) target stimuli. The term "redundant-signals effect" (RSE) has been introduced to describe the finding that reaction times (RTs) are expedited when redundant (i.e., two or more) targets are presented relative to the presentation of only one stimulus. Examples are the time it takes to respond

to the flashing of two compared to just one LED (e.g., Marzi et al., 1996) or the RT to a multimodal, audio-visual stimulus compared to a unimodal, visual or auditory stimulus (e.g., Miller, 1982). A characteristic common to the vast majority of RSE studies is that the to-be-detected target signals are presented within a constant context of nontarget, or distractor, elements. With reference to the scenario of steering a car, the driver would be looking for different road signs in an invariant environment.

Given that visual features such as color, orientation, size, etc., are initially encoded independently of each other, the question arises whether beneficial effects of defining a target object in a redundant fashion may arise at some pre-attentive stage(s) of processing, that is, before the object is selected by focal (spatial) attention—or whether integration of separately en-coded features is (strictly) postselective in nature, that is, dependent on the processes following the allocation of focal attention. Note that, logically, integration may occur at both pre-attentive and postselective processing stages—even though these alternatives have sometimes been discussed in exclusive, either-or terms in the literature (see, e.g., Cohen & Feintuch, 2002; Cohen & Feintuch, 2002).

The present study was designed to contribute to the identification of (a) potential loci—in particular, a pre-attentive locus—of signal integration, as well as related to this issue, (b) the nature of the integrated signals in the visual modality—by presenting observers with a constant target stimulus embedded in an environment, or context, that varied randomly across experimental trials. Applied to the above car-driving scenario, the driver would be looking for a particular road sign while navigating within a changing land-/townscape. Behavioral data—namely, manual search RTs, and electro-physiological measures, the N2pc and lateralized readiness potential (LRP) components of the event-related potential (ERP)—were examined in a pop-out search task in which the distractor context changed randomly across trials while the definition of the (to-be-detected) target remained constant. To foreshadow the results: Manual RTs were expedited on trials on which the (constant) target differed from the (variable) context in two feature dimensions—that is, redun-dantly—compared to when it differed in just one dimension. Further, the N2pc was elicited earlier in response to redundant relative to nonredundant targets, while the LRP remained unaffected. Overall, the results provide support for saliency-based accounts of visual selection (e.g., Itti & Koch, 2000; Koch & Ullman, 1985; Müller, Heller, & Ziegler, 1995; Wolfe, 1994), which postulate a pre-attentive locus of inte-gration based on dimension-specific feature contrast signals, namely, the attention-guiding overall-saliency map.

Redundancy gains in visual search for feature pop-out targets

The functional architecture underlying saliency computation for target selection in visual search (specifically search for singleton feature and feature conjunction targets) has been elaborated, over the recent years, in the dimension-weighting account (DWA) of Müller and colleagues (e.g., Found & Müller, 1996; Krummenacher & Müller, 2012; Krum-menacher, Müller, & Heller, 2001, 2002; Müller et al., 1995; Weidner & Müller, 2009, 2013; Zehetleitner, Krummenacher, & Müller, 2009). Like Guided Search (GS; e.g., Wolfe, 1994), the DWA assumes that visual features are initially encoded by specialized detectors organized topographically within separable visual dimensions (such as orientation, color, motion, etc.). In the next step, feature difference, or feature contrast, signals are computed within the various dimensional modules—for instance, by local iso-feature suppression mechanisms, which modulate the activity of a given feature detector depending on the similarity of the encoded feature within its surround: the more similar the items in the surround, the greater the suppression (e.g., Li, 2002). These local feature contrast signals are then integrated, in a spatially specific fashion, by units of an overall-saliency map of the field, which guide the allocation of focal attention: Attention is allocated to that location that exhibits the highest overall saliency (or for which the overall-saliency signal reaches some threshold first) on this map.[1]

The notion of (dimension-specific) feature contrast signal integration by the units of an overall-saliency map was, arguably, first investigated systematically by Krummenacher et al. (2001, 2002), using simple pop-out target detection tasks. For instance, the to-be-detected target could differ from a homogeneous field of distractors (green vertical bars) by either color (singly defined color targets: a *red* or a *blue* vertical bar) or either orientation (singly defined orientation targets: a green *left-tilted* or a green *right-tilted* bar) or by both color and orientation (redundantly defined color-plus-orientation targets: a *red left-tilted* bar, a *red right-tilted* bar, a *blue left-tilted* bar, or a *blue right-tilted* bar). Importantly, observers had to produce a simple detection response whenever a target—whether defined singly or redundantly—was present in the search display. Krummenacher et al. reasoned that if there is indeed cross-dimensional signal integration, detection RTs to targets defined redundantly in two dimensions should violate Miller's (1982) race model inequality (RMI; for details, see the Analysis section below)—that is, essentially: The fastest RTs to such dimensionally redundant targets should be faster than the fastest RTs to targets defined in only one dimension. Restated, violations of the RMI would provide evidence in favor

of feature contrast signals generated in multiple dimensions *coactivating* a common output stage (i.e., an overall-saliency unit)—instead of there being a parallel race between the feature contrast signals computed in the various dimensions, with the winning signal solely determining the response of the output unit. Note that the latter, parallel-race model would also predict mean RT redundancy gains for dual-dimension compared to single-dimension targets, due to statistical facilitation (Raab, 1962): Comparably slower processing of one of the signals would be compensated for statistically by comparably faster processing of the other signal. However, it would not predict violations of the RMI, due to redundant targets producing more (and absolutely) faster RTs than would be expected from statistical drawing from the RT distributions generated by singly defined targets. Applying this logic to pop-out search, Krummenacher et al. (2001) found RTs to targets defined by both color and orientation to violate the RMI—consistent with dimensionally separate signals coactivating a common output stage.[2] Krummenacher et al. (2002) went on to show that dual (redundant) targets defined in different feature dimensions (e.g., a red [color] and a right-tilted [orientation] item presented at *separate* locations) also produced RMI violations as long as the two odd-one-out items were located in close proximity to each other (e.g., at neighboring display positions). By contrast, dual (redundant) targets defined in the same feature dimension (e.g., a red [color] and a blue [color] item presented at separate locations) did not produce RMI violations, but only statistical facilitation. This pattern suggests, first, that only signals from separable dimensions are integrated and that the integration is spatially specific, which is consistent with the core assumption of saliency summation models of search guidance. The evidence concerning the spatial specificity of redundant-signal integration is important, as this rules out alternative models that assume spatially nonspecific integration of target signals across dimensions, as, for example, certain versions of Feature Integration Theory (e.g., Chan & Hayward, 2009; Treisman, 1988; Treisman & Gelade, 1980; see below for details). Finally, by combining a redundant-signals (pop-out target search) paradigm with spatial-cueing manipulation, where the dimensionally singly or redundantly defined target could appear either inside or outside a region of the display pre-indicated by an arrow cue to be likely to contain the target, Krummenacher et al. (2002) showed that RMI violations do also occur outside (as well as within) the spotlight of attention. They took this finding to be indicative of a pre-attentive locus of redundant-signal integration, consistent with another core assumption of saliency summation models.

The findings of Krummenacher et al. (2001, 2002) have been replicated and extended in a series of follow-up studies (e.g., Krummenacher, Grubert, & Müller, 2010; Töllner, Zehetleitner, Krummenacher, & Müller, 2011; Zehetleitner et al., 2009). Importantly, Zehetleitner et al. (2009) showed that the RMI violations reported by Krummenacher et al. indeed reflect a signal summation, rather than a serial-exhaustive- or interactive-race-type, processing architecture. Furthermore, Töllner, Zehetleitner, Krummenacher et al. (2011; see also Grubert, Krummenacher, & Eimer, 2011) showed that dimensionally redundant (vs. nonredundant) target definition,[3] in addition to producing mean RT redundancy gains and violations of Miller's (1982) RMI (cf. Krummenacher et al., 2001, 2002), speeds up the emergence of a particular component of the electroencephalogram (EEG), which has been interpreted as reflecting the time demands of pre-attentive coding processes determining the target for focal-attentional selection: the ERP component referred to as N2pc (or PCN; Töllner, Müller, & Zehetleitner, 2012). The N2pc, usually triggered at around 200 ms after stimulus onset, is an enhanced negativity over parieto-occipital electrode sites contralateral to the side of an attended item. In search-type paradigms, the N2pc is thought to reflect the allocation of focal attention to a candidate target amongst distractor items (Eimer, 1996; Luck & Hillyard, 1994). Evidence that the timing of this component is (a) sensitive to target saliency but (b) independent of postselective processing demands associated with the task (e.g., postselective stimulus analysis and stimulus-response [S-R] mapping in detection vs. localization vs. feature discrimination vs. compound search tasks) has recently been provided by Töllner and colleagues (Töllner, Rangelov, & Müller, 2012; Töllner, Zehetleitner, Gramann, & Müller, 2011). Another component examined by Töllner, Zehetleitner, Krummenacher et al. (2011) is the LRP, which serves as a marker for processes of response selection (stimulus-locked or sLRP) or, respectively, response production (response-locked or rLRP; Eimer, 1998; Eimer & Coles, 2003; Hackley & Valle-Inclán, 2003). The LRP is an enhanced negativity over central electrode sites above areas of the motor cortex contralateral to the side of the hand with which a unimanual response is executed. In the study of Töllner, Zehetleitner, Krummenacher et al. (2011), the rLRP timing, in contrast to the N2pc timing, did not differ between conditions with singly and redundantly defined targets. On this basis, Töllner, Zehetleitner, Krummenacher et al. (2011) concluded that the redundant-signals effect in visual pop-out search arises at a perceptual coding stage that mediates the allocation of focal attention.

Thus, taken together, the available evidence argues in favor of a saliency summation architecture, in which feature signals are integrated in a spatially specific
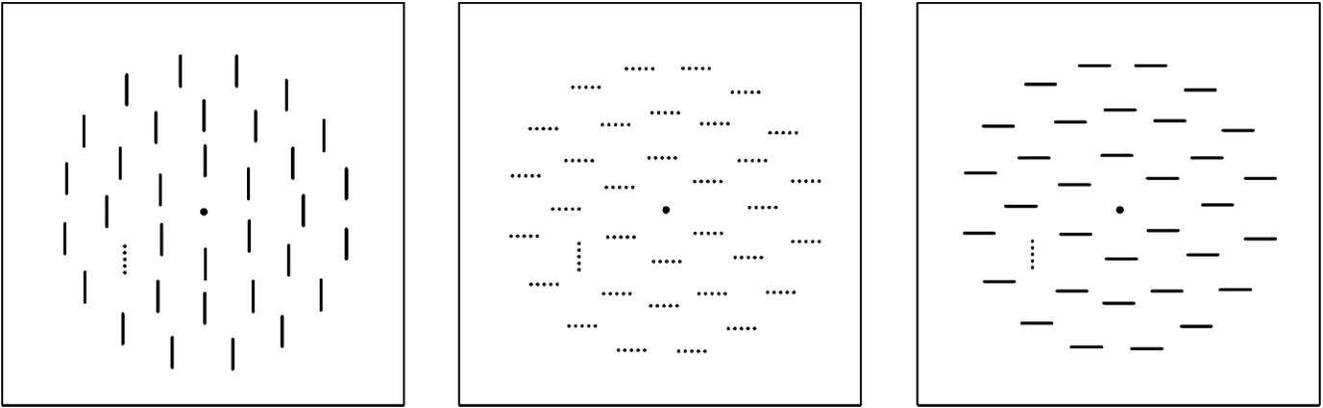
Figure 1. Schematic illustration of the three stimulus displays used in the present experiment. Target identity was kept constant across conditions while distractor identity changed in order to differentiate the target from distractors in the color (left-hand panel), orientation (middle panel), and, redundantly, in the color and orientation (right-hand panel) dimensions. Stimuli were colored red (solid lines) and yellow (dotted lines).

manner across dimensions by some overall-saliency map of the field, which in turn guides visual selection and, if required by the task, postselective processes extracting (via feedback connections; Töllner, Conci, Rusch, & Müller, 2013) target identity information for choosing the correct response. However, there are alternative takes of the available data, for instance, Chan and Hayward's (2009) proposal of detection decisions in pop-out search being based on a nonspatial route of processing (as originally envisaged in Feature Integration Theory) and strict notions of signal integration occurring only post selection, that is, within the spotlight of attention (e.g., Cohen & Feintuch, 2002; Feintuch & Cohen, 2002). Related to this debate, the exact nature of the signals that are integrated (e.g., at the stage of search guidance) remains also unclear. Crucially, saliency summation models assume that the signals that are integrated, as well as the integrated signals themselves, are actually featureless in nature, that is: Feature contrast signals do not carry information as to the exact feature values, and overall-saliency activations do not carry information as to the exact dimensions that originally generated the contrasts (Bisley & Goldberg, 2010; Gottlieb, 2007; Müller, Humphreys, & Donnelly, 1994). On the other hand, it is possible that, given that the observers know exactly which targets—including (redundant) combinations of target features—are possible, they may actually operate a top-down strategy of enhancing (biasing) the coding of all those features that are potentially target-defining. For instance, if observers know that the target is likely, say, a red and/or right-tilted bar, they may pre-activate detectors tuned to red in the color dimensions and to right tilt in the orientation dimension. Accordingly, when a target encountered on a trial is actually defined by being both red and right-tilted, the respective feature detectors would more rapidly accumulate evidence for

the presence of their feature and may thus coactivate a common output unit faster compared to when the target is defined by only one or the other feature. In essence, this is the detection route in Chan and Hayward's (2009) dual-route account of visual search performance, and it would also be consistent with a GS-type model which allows for the top-down biasing of known target features (see, e.g., Wolfe, Butcher, Lee, & Hyle, 2003), even though in GS, these feature biases would ultimately operate via a spatial processing route determining the allocation of focal attention.[4]

Thus, importantly, models assuming that feature pop-out search involves the top-down biasing of multiple, known (because across trials reoccurring) target features in separate dimensions in parallel would explain the coactivation effects reported by Krummenacher et al. (2001, 2002) in terms of redundant targets activating multiple pre-activated feature detectors, as compared to only one such detector being activated by singly defined targets, with their activations converging on a common output stage, whether this stage is conceived of as nonspatial or spatial in nature. In other words, such models would predict coactivation effects to be largely based on feature-specific signals, rather than on (featureless) feature contrast signals. Note that GS-type models, which inherently assume a spatial route of overall-saliency coding, would also allow for a role of feature contrast computations in singling out the target. Arguably, however, owing to the top-down enhanced coding of target-defining features, any role of feature contrast computations in signaling the odd-one-out item would be severely diminished: Given the competitive advantage conferred to the detectors encoding target features, their signaling would be rapidly driven to threshold by an appropriate feature in the field without feature contrast mechanisms, such as iso-feature suppression (which, after all, requires the

operation of lateral interactions among dimensionally organized detectors), contributing significantly to their activation.

Rationale of the present study

Accordingly, models that assume feature-specific coding for target selection and detection decisions would predict coactivation effects whenever dual (or by extension, multiple) target features are known in advance, relatively independently of the display context within which these features are embedded. Conversely, models assuming featureless coding of target saliency would predict the feature-context relations to be of paramount importance. The present study was designed to compare and contrast these models by examining RT performance and electrophysiological measures of processing in a pop-out search task in which the target (and thus its feature description) was always the same on target-present trials, but in which, critically, the distractor context was variable such that, relative to the context, the target was singly defined in either one or the other dimension, or redundantly in two dimensions. In more detail, for some of the participants, the target was invariably a *yellow horizontal* bar which differed from the background in either the color dimension (in which case the distractors were *red* horizontal bars), or in the orientation dimension (in which case the distractors were yellow *vertical* bars), or redundantly in both the color and orientation dimensions (in which case the distractors were *red vertical* bars)—see Figure 1 for an illustration. (Note that this experimental situation is exactly the reverse to that employed by Töllner, Zehetleitner, Krummenacher et al., 2011.) If the target, whose features are invariable, is detected via top-down biasing of its features, RT performance should be little affected by the variation of the distractor context (in a sense, in terms of its feature description, the target is always redundantly defined). By contrast, if the target is singled out by feature contrast computations, then there should be a mean RT gain and violations of the RMI when the target is redundantly defined relative to the variable background (i.e., when there is feature contrast in two dimensions) compared to when it is only singly defined (i.e., when there is feature contrast in only one dimension). Evidence in line with the latter pattern would provide strong support for saliency summation models that assume featureless signaling of odd-one-out items in the various dimensions and summation of these signals by an overall-saliency map.

Note that such evidence would also be at variance with models that posit signal integration to occur *exclusively* at a postselective stage of processing (e.g., the dimension-action model [DAM] of Cohen &

Feintuch, 2002; Feintuch & Cohen, 2002): At this stage, the signals that are (thought to be integrated) are feature-specific in nature, with focal attention making the exact features available to be compared against a range of target templates. Templates may be set up based on knowledge of the (limited number) of exact features that the target can take on, and if encoded features can be checked in parallel against such templates, multiple templates may be activated at the same time, with their output converging on (or coactivating) a common detection response (see Krummenacher et al., 2010, for an elaboration of this account). Thus, exclusive postselective integration accounts would encounter a difficulty explaining how processing of a target with an invariant feature description can be expedited by variation of the distractor context within which it is embedded. Consequently, such accounts would have to concede the possibility of pre-attentive integration, which (as already stated above) does not necessarily exclude the possibility of an additional, postselective integration stage.

Methods

Participants

Twelve observers took part in the experiment. Participants' ages ranged from 20 to 28 years (median age 23.8 years); 10 observers were female, and 11 were right-handed. All participants had normal or corrected-to-normal vision, including color vision. Participants were paid at an hourly rate of CHF 20 (approximately $20) or received course credits.

Stimuli, procedure, and apparatus

Observers were presented with search displays consisting of 34 items (see Figure 1). Six, 12, and 16 search items were arranged on three imaginary (concentric) circles with radii of 4.5°, 8.5°, and 12.5° of visual angle, respectively. A white fixation point was presented at the center of the screen, which participants were asked to fixate on during the whole experiment. Search items were rectangular bars (subtending 2.7° × 0.6° of visual angle), oriented vertically or horizontally. The orientation of individual search items was randomly jittered within a range of ±8.0° of visual angle relative to the vertical or horizontal. The target item was presented at one randomly selected location on the three left or right lateral locations of the middle circle. In half of the (target-present) trials, the target appeared

in the left visual hemifield and in the right hemifield in the other half.

The feature that defined the target singleton was counterbalanced across participants and remained constant during the whole experiment for each individual observer. Color features were red/orange (CIE 0.544, 0.393; luminance 3.0 cd/m^2) and yellow (CIE 0.456, 0.469; luminance 3.0 cd/m^2); orientation features were horizontal and vertical. The identity of the distractor items could be changed (or repeated) randomly across trials. As a consequence, the target item differed from distractors (the search context) either on a single dimension, color or orientation, or on both the color and the orientation dimensions. In other words, the target was defined either by a nonredundant single-dimension or a redundant dual-dimension feature difference. As an example, the target item was red (color) and vertical (orientation) while the distracters were either red and horizontal (single-dimension orientation condition), or yellow and vertical (single-dimension color condition), or yellow and horizontal (dual-dimension redundant condition). The other combinations of target and distractors were: red and horizontal (target), red and vertical, yellow and horizontal, and yellow and vertical (distractors); yellow and vertical (target), yellow and horizontal, red and vertical, or red and horizontal (distractors); yellow and horizontal (target), yellow and vertical, red and horizontal, or yellow and vertical (distractors). One out of the four target and distractor definition conditions was randomly assigned to each participant, with each of the four conditions being completed by 3 of the 12 participants.

Participants indicated the presence or absence of a target item by pressing one of two predefined response keys (of a custom-built response pad placed on the armrest of the armchair in which participant were seated). Participants were instructed to respond as quickly and accurately as possible. Half of the observers started the experiment by signaling target presence and absence by pressing, respectively, the right-hand key with the right index finger and the left-hand key with the left index finger; the reverse initial trial type to response assignment was used for the other half of the participants. The assignment was reversed in all participants after they had completed half of the trials.

The whole experiment comprised a total of 1,296 trials, divided into 18 blocks of 72 trials each; a target was present in 50% of the trials, and absent in the other 50%. Within each block, each of the three possible target-distractor definitions (color, orientation, redundant) was presented equally often; target-present and -absent trials were presented in random order. Each trial started with the presentation, for 500 ms, of a white fixation point at the center of the screen, followed by the search array, which was presented for 200 ms and then extinguished. The trial was terminated by the observer's response. In the case of a response error, a feedback screen displaying the word "error" was shown for 1000 ms before the start of the next trial, which began with the presentation of a blank screen for a variable intertrial interval of 1950 to 2050 ms. Accuracy and RT performance were fed back to the participant at the end of each block. Prior to the experiment proper and before the change of the trial type to response key assignment, participants completed a practice block of 34 trials to (re)familiarize them with the task.

Participants were comfortably seated in a dimly illuminated testing booth. Their arms rested on the armrests of a chair, onto which the response keys were fixed. Stimulus presentation, timing, and response recording were controlled by a Pentium PC running the Windows XP operating system, using the Psychophysics Toolbox (Brainard, 1997) library for Matlab (MathWorks, Inc., Natick, MA). Stimuli were presented on a 19-in. CRT monitor (Philips Brilliance P202, Philips N.V., Eindhoven, The Netherlands) at a screen refresh rate of 100 Hz and a screen resolution of 1280 × 1024 pixels. Observers viewed the display from a distance of approximately 75 cm.

Data registration and analysis

Behavioral measures

The RT data of the four target-distractor conditions were pooled. To examine for mean RT redundancy gains, mean RTs from the two nonredundant single-dimension (color, orientation) target/distractor trials were compared to RTs from the dual-dimension redundant (color and orientation) target/distractor trials. RTs were subjected to a repeated-measures analysis of variance (ANOVA) with the single factor context (color, orientation, redundant). Furthermore, the cumulative RT distributions of the nonredundant single-dimension (color, orientation) and redundant dual-dimension (color and orientation) trials were tested for violations of Miller's (1982) RMI, in order to determine whether redundant signals (dual-dimension color and orientation targets) were processed in a parallel race or a parallel coactive fashion. The RMI tests whether the fast part of the RT distribution to redundant target signals is significantly faster than the RTs in the fastest single target (color, orientation) trials. Formally, the RMI states that $P(RT < t \mid CO) \leq P(RT < t \mid C) + P(RT < t \mid O)$, that is: The summed probability—$P(RT < t \mid C) + P(RT < t \mid O)$—of a response to a single signal (C: color; O: orientation) occurring before time t must not be smaller than the probability $P(RT < t) \mid CO)$ of a response to a redundant (CO) target occurring before time t for the assumption of a parallel race to be satisfied. Violations

q	p_c	p_o	$p_c + p_o$	$t(11)$	p
5	1.3	2.3	3.6	2.6	0.013
10	3.4	4.8	8.1	2.0	0.036
15	6.3	7.4	13.7	0.8	0.218
20	9.7	11.0	20.7	0.4	0.366

Table 1. Test for violations of the RMI for all (12) observers. *Note*: q: quantile of the RT distribution; $p_c(p_o)$: probability of RTs to color (orientation) signals; $p_c + p_o$: sum of single signal probabilities.

of the RMI indicate that the race model assumption does not hold and that the two (color and orientation) signals contribute jointly, that is, coactively, to the activation of a subsequent module. All t-tests were two-tailed, and Bonferroni corrections were applied where necessary.

EEG recording and data analysis

The continuous EEG was DC-recorded at a digitization rate of 1000 Hz, using 64 Ag/AgCl active electrodes embedded in elastic caps (actiCAP, Brain-Products, Munich, Germany) and placed according to the international 10-10 System (American Electroencephalographic Society, 1994). Horizontal (HEOG) and vertical (VEOG) eye activity was monitored and recorded at electrode positions F9/10 and Fp1/inferior orbit of the eye, respectively. Electrophysiological signals were amplified with a 0.1–250-Hz band-pass filter using BrainAmp amplifiers (BrainProducts, Munich, Germany), and were filtered offline with a 1–40-Hz band-pass (Butterworth zero phase, 24 dB/oct). All electrodes were referenced to FCz and offline re-referenced to averaged mastoids (corresponding to electrode sites TP9/TP10). Impedances were kept below 5 kΩ. The EEG was epoched into 700-ms segments from 100-ms prior (used for baseline correction) to 600-ms post display onset events. Trials with saccades (voltage exceeding ±30 μV in the HEOG channels) or eye blinks (voltage exceeding ±60 μV in the VEOG channels) were excluded from analysis. Muscular artifacts (voltage exceeding ±80 μV with permitted maximal voltage steps/sampling point of 50 μV in all channels) and dead channels with activity lower than 0.5 μV were removed from analysis on an individual channel basis. ERPs were averaged separately for each experimental condition (color, orientation, and redundant context displays) and pooled for the four possible target identities.

The N2pc was quantified by subtracting ipsilateral from contralateral ERPs at lateral posterior electrode sites PO7/PO8, relative to the display side of the target singleton. The sLRP waveforms were calculated by subtracting ipsilateral from contralateral ERPs at electrodes C3/C4 with respect to the unimanual hand responses. N2pc latencies were determined individually as the maximum negative deflection within the time

window of 150–350 ms poststimulus and, respectively, 0–600 ms poststimulus. For the computation of rLRP waveforms reflecting the motor execution stage, the whole EEG was re-epoched in 4000 ms (2000 ms before and after stimulus onset) segments. The baseline was corrected on the basis of a 100-ms prestimulus interval and the EEG, which was divided in 700-ms segments ranging from 600 ms before to 100 ms after response. Again, with respect to the unimanual hand responses, ipsilateral ERPs were subtracted from contralateral ERPs at electrodes C3/C4.

N2pc latency analyses were based on peak latencies. For the LRP latency analyses, onset latencies were determined according to Ulrich and Miller's (2001; Miller, Patterson & Ulrich, 1998) jackknife method. For the sLRPs, onset latencies were determined as the time at which the amplitude of the averaged waveform of all three context conditions reached 50% of its peak, which corresponds to a fixed criterion of 0.8 μV (this procedure was applied because visual inspection revealed the sLRP amplitudes to differ in magnitude among the three conditions). For the rLRPs (which showed no visible amplitude differences), the time at which the maximum amplitudes reached a relative criterion of 90% was taken as onset latency.[5] Latencies of all components were analyzed in repeated-measures ANOVAs with the single factor context condition (color, orientation, redundant). *F* values were corrected (indicated with the label F_c) according to the formula described by Ulrich and Miller (2001). Trials with RTs faster than 200 ms or slower than 1000 ms were excluded from analysis as anticipatory or exceedingly slow reactions (0.4% of all trials).

Behavioral results

Response Times

Mean target-present RTs (correct responses only) of the three experimental conditions were subjected to a one-way ANOVA with the factor context (color, orientation, redundant), in order to examine for the presence of mean RT redundancy gains (i.e., faster mean RTs on trials with redundant compared to nonredundant target-distractor differences). The main effect of context was highly significant, $F(2, 22) = 22.9$, $p < 0.001$. Follow-up *t* tests revealed the RTs to
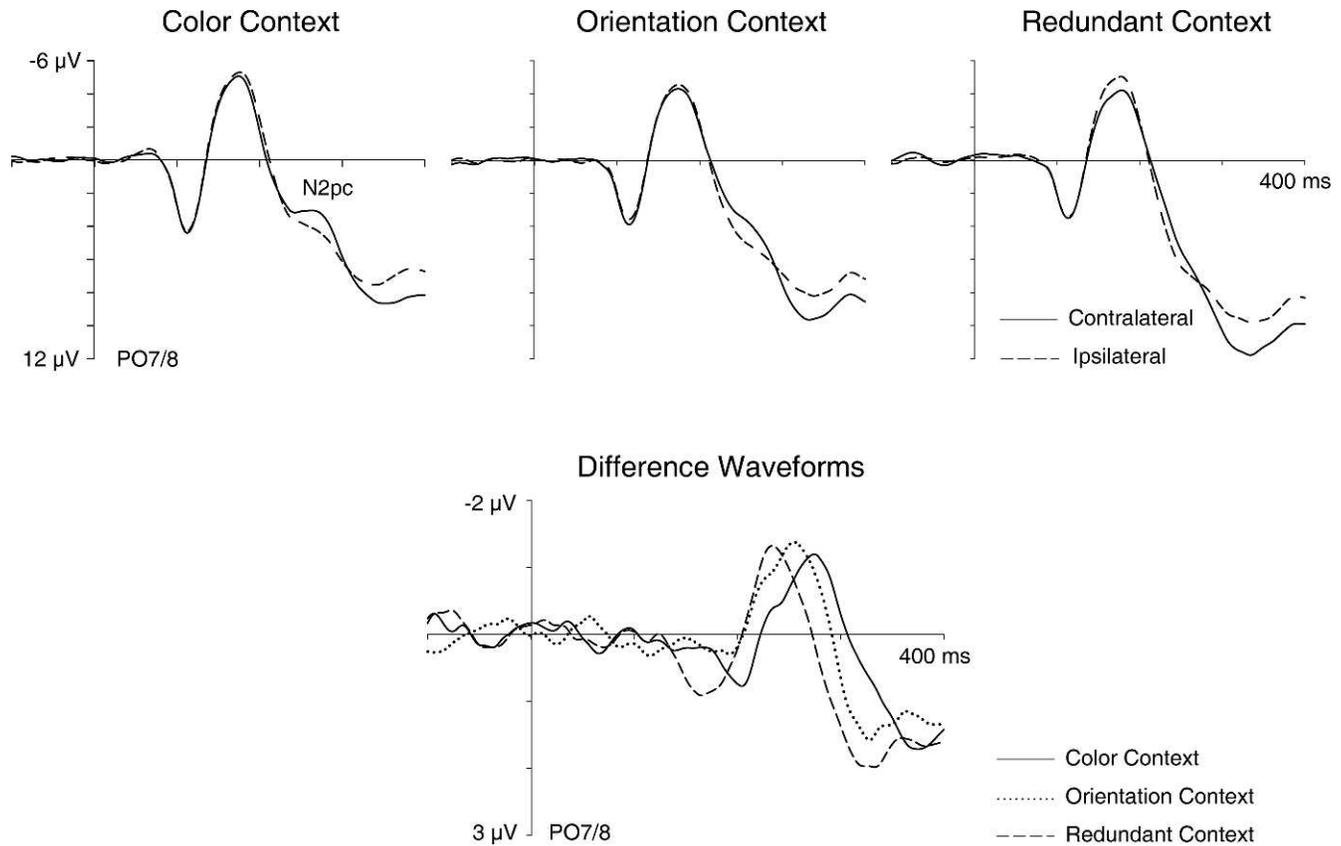
Figure 2. Grand average ERPs (top) elicited in the 400-ms interval after stimulus onset at electrode positions PO7/PO8 contralateral and ipsilateral to the side of the singleton target, separately for color (left), orientation (middle), and redundant (right) contexts. N2pc difference waveforms (bottom) for the three experimental conditions were obtained by subtracting ipsilateral from contralateral activity.

redundant targets (426.3 ms) to differ reliably from those for each of the two single-target conditions (color: 454.9 ms, ± 28.6 ms; orientation: 455.5 ms, ± 29.1 ms); both $t[11] > 6.0$, $p < 0.001$); RTs to the two single targets did not differ (color vs. orientation: ± 0.5 ms, $t[11] < 1$, n.s.).

Tests of the entire RT distributions for violations of Miller's (1982) RMI, $P(RT < t \mid CO) \leq P(RT < t \mid C) + P(RT < t \mid O)$, showed that the summed probabilities for C and O trials were below the criterion probability (C&O) indicative of a parallel race between competing signals. As can be seen from Table 1, the RMI was significantly violated at the 5% and 10% quantiles of the cumulative RT distributions. The finding of RMI violations argues against a parallel race model underlying the processing of redundant signals, and in favor of the RT redundancy gains being the results of parallel coactive processing.

Errors

Error rates were analyzed in an ANOVA with the single factor context (color, orientation, redundant), which revealed the context main effect to be significant,

$F(2, 22) = 10.7$, $p = 0.001$. Importantly, t-tests conducted to follow-up on the main effect revealed that error rates were significantly reduced on redundant (color and orientation) target trials (2.7%) as compared to trials with single color, 5.0%; $t(11) = 4.9$, $p = 0.001$, and single orientation targets, 5.4%; $t(11) = 4.0$, $p = 0.006$; error rates did not differ between the two types of single targets, $t(11) < 1$, n.s. As the error rates were reduced on redundant trials, the RT redundancy gains cannot be attributed to a speed–accuracy trade-off.

Event-Related Potential

N2pc

Figure 2 (top panels) presents ERPs obtained at electrode sites PO7/PO8 contralateral and ipsilateral to the side of the singleton target, separately for the color (left), orientation (middle), and redundant (right) context conditions, together with the difference waveforms (ipsilateral activity subtracted from contralateral activity) for each of the three experimental conditions (bottom panel).[6] A solid N2pc was elicited in all three conditions. N2pc peak latencies were subjected to a
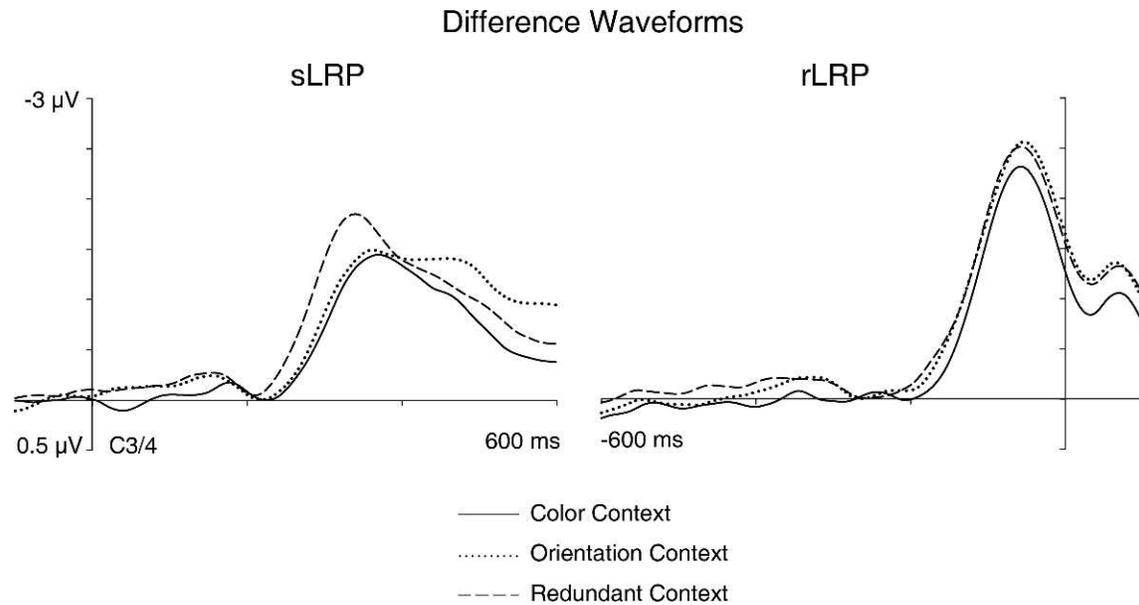
Difference Waveforms

Figure 3. sLRP (left) and rLRP (right) difference in waveforms elicited in the 600-ms interval after stimulus onset and prior to response, respectively, at electrode positions C3/C4 for each of the three experimental conditions.

repeated-measures ANOVA with the single factor context (color, orientation, redundant), which revealed the main effect of context to be significant, $F(2, 22) = 16.3$, $p < 0.001$. Peak latencies were fastest on redundant-target trials (235.9 ms), followed by latencies on trials with single orientation (261.8 ms) and single color targets (279.4 ms). Follow-up t-tests confirmed the gains, in terms of the N2pc latencies, for redundant targets to be reliable relative to both single-color, ± 43.5 ms, $t(11) = 4.4$, $p = 0.003$, and single orientation targets, ± 25.9 ms, $t(11) = 4.1$, $p = 0.005$; N2pc latencies were also significantly shorter for single-orientation relative to single color targets, ± 17.6 ms, $t(11) = 2.9$, $p = 0.047$.

Lateralized Readiness Potential

The LRP difference waveforms (contralateral activity minus ipsilateral activity) obtained at C3/C4 electrode sites for the three experimental conditions (color, orientation, redundant signals) are shown in Figure 3 (left-hand panel: sLRP; right-hand panel: rLRP). In analogy to the N2pc, stimulus- and response-locked LRP onset latencies were analyzed in two separate repeated-measures ANOVAs. The ANOVA of the sLRP latencies revealed the context effect to be significant, $F_c(2, 22) = 5.3$, $p = 0.013$. The sLRP onset latencies were 304.8 ms (color), 297.1 ms (orientation), and 273.3 ms (redundant), respectively. Follow-up tests revealed the redundancy gains to be significant, color versus redundant: $t(11) = 3.5$, $p = 0.015$, or borderline significant, orientation versus redundant: $t(11) = 2.8$, $p = 0.052$. For the rLRPs latencies, by contrast, the

context effect was nonsignificant, $F_c(2, 22) = 1.4$, $p = 0.272$, with latencies of -81.5 ms (color), -79.0 ms (orientation), and -84.4 ms (redundant), respectively.

The redundancy gains in the sLRP latencies are expected given that the sLRP latencies include all processes, including those reflected in the N2pc, prior to response production). However, behavioral redundancy gains were definitely not reflected in the timing off the rLRPs.

Discussion

The results of the present experiment are straightforward. Search (detection) RTs to a feature target that remained constant throughout the entire experiment were significantly expedited when targets differed from distractors redundantly in two dimensions (color plus orientation) rather than in just a single dimension (either color or orientation). Furthermore, RTs to redundant targets significantly violated the RMI, indicative of target detection decisions being coactivated by feature differences in the two dimensions in which the target was a feature singleton. Note that numerical behavioral (mean RT) redundancy gains in the present experiment (with a constant target and variable distractors) are near-equivalent to those reported by Töllner, Zehetleitner, Krummenacher et al. (2011; variable target and constant distractors): ± 29.0 ms versus ± 28.9 ms. This pattern is inconsistent with accounts on which search would be predominantly feature-based in this situation, and suggests instead

that search is largely salience-based, even though the precise target features are invariable. That is, in terms of the functional architecture outlined in the Introduction, the signals that drive search and focal-attentional selection are indeed featureless saliency signals, rather than signals that carry feature-specific information.

This conclusion is also supported by the ERP data. Crucially, behavioral redundancy gains were solely reflected in faster latencies of the N2pc (and, nonsignificantly, the latencies of the sLRP), but not the rLRPs. In fact, numerically, the mean N2pc latency gain for redundant relative to nonredundant signals was near-equivalent to the (behavioral) RT gain: ±34.7 ms versus ±28.9 ms. Although the latencies of the sLRP were not significantly influenced by the distractor variation, there was a tendency for redundant target signals to be processed faster than single signals (by ±18.1 ms on average). This is not surprising, as the sLPR latencies would include all processes prior to response production, including pre-attentive perceptual coding. However, given that the sLRP effect was not larger than the N2pc effect (and given that there was no rLRP effect), one may conclude that in the present (detection) task, there are no redundancy gains arising from processes subsequent to those reflected in the timing of the N2pc (i.e., processes of focal-attentional stimulus analysis, S-R mapping, and response production; see Töllner, Gramann, Müller, Kiss, & Eimer, 2008). Interestingly, the sLRP latencies were, on average, only some 30 ms longer than the N2pc latencies, suggesting that postselective processes subsequent to target selection are minimal in the present (detection) paradigm. Note that, like the behavioral effects (see above), the present ERP effects are in line with the pattern reported by Töllner, Zehetleitner, Krummenacher et al. (2011). This argues in favor of an architecture in which redundant signals are integrated at a processing stage prior to focal-attentional target selection, rather than coactivating postselective processes (such as target checking, S-R mapping, or the response itself), independently of whether the target is constant (and the distractors variable) or the target is variable (and the distractors constant).

What follows is a discussion of the implications of the present findings for theories of visual search: GS, Dual-Route Account (DRA), DAM, and DWA.

Implications for theories of visual search

Guided search

Assuming that search is always guided by a combination of bottom-up (feature contrast computation) and top-down (target feature template-based) processes, GS (Wolfe, 1994, 2007) would have predicted the manifestation of coactivation effects in the present study. Critically, though, these effects should have been reduced compared to the standard experimental setup with a variable target and constant distractors (as implemented in, e.g., Krummenacher et al., 2001, 2002, and Töllner, Zehetleitner, Krummenacher et al., 2011), which was not the case.

In more detail, when the target is featurally fixed (and the distractor context variable), as in the present experiment, the GS model would predict only limited redundancy gains because observers could adopt an essentially feature-based (cf. Bacon & Egeth, 1994) search mode. This mode involves top-down enhancement of detectors coding known target features, which would expedite the emergence of a target signal on the overall-saliency map. With the (fixed) red vertical target in the present experiment, for example, feature detectors coding red and detectors coding vertical would be top-down pre-activated, so that, when a target is presented, the accumulation of activation starts from a higher base level compared to when there is no top-down enhancement, shortening the time for evidence accumulation to threshold. However, because the two target-defining features are the same whatever the distractor background (so that both feature expectations are confirmed in 100% of the [target-present] trials), target signal computation should generally be enhanced in all conditions, whether the target is defined singly or redundantly relative to the distractor context. Consequently, there should be only small redundancy gains under the conditions of the present experiment. This prediction takes into account that in all conditions (of the present experiment) with singly defined—i.e., color and orientation—targets, all items in the nontarget-defining dimension shared one potential target-defining feature, thus diminishing the target-to-distractor signal ratio on the search-guiding activation map. To elaborate, the target (in one particular condition) was invariably *yellow* and *vertical*. So with color-only (yellow) targets, distractors were red and *vertical*—so all *vertical* items would have received top-down guidance, and with orientation-only (vertical) targets, distractors were *yellow* and horizontal—so all *yellow* items would have received top-down guidance. (In the redundant-target condition, the distractors were all red and horizontal, so that distractor locations would not have received any top-down activation.) This would mean that, on a combined top-down guidance map (i.e., a map combining top-down signals across dimensions), in the color and orientation target conditions, the target location would have received activation from two sources and all other (distractor) locations from one source. As a result, while the target signals in the color only and orientation target conditions would have received exactly the same degree of coactivation as in the redundant-target condition (in which the target location was the only location to receive top-down activation),

the distractor locations would have received a degree of activation as well—thus lowering the signal-to-noise ratio on the "top-down" guidance map.[7] (A similar argument could be developed with regard to the bottom-up guidance map). Logically, however, target detection should have benefitted from top-down signals in two dimensions in both the color and the orientation target condition, even though not to the same degree as in the redundant-target condition—permitting GS to predict a measure of redundancy gains, and RMI violations, even under the conditions of constant target definition realized in the present experiment.

In contrast, though, substantial redundancy gains, and violations of the RMI, would be expected under conditions of variable target definition (and a constant distractor context; as in the Töllner, Zehetleitner, Krummenacher et al. 2011 study)—which makes a feature-based search mode less applicable (e.g., because, in the conditions of Töllner, Zehetleitner, Krummenacher et al., 2011, one feature would be disconfirmed in two thirds of the trials); instead, observers would have to rely more on a singleton-based search mode (cf. Bacon & Egeth, 1994), which—via the GS saliency summation architecture—would give rise to the coactivation redundancy gains seen in Töllner, Zehetleitner, Krummenacher et al. (2011).

Thus, while coactivation effects would not be unexpected under the condition of the present study, they should have been reduced compared to the standard setup (as implemented with essentially the same stimuli in Töllner, Zehetleitner, Krummenacher et al., 2011). Actually, however, the RMI violations observed in the present experiment were comparable to those reported by Töllner et al. (i.e., the difference in the probabilities of having responded fast to a redundant target compared to the summed probabilities of nonredundant targets was significant). Although this does not falsify GS, it would mean that selection was at least as much based on feature contrast/saliency computations—as opposed to target feature-based biasing—in the present experiment (with fixed target features) as it was in Töllner, Zehetleitner, Krummenacher et al.'s (2011) experiment (with variable target features). This finding does not seriously challenge GS, because GS is simply not specific enough about the relative strength of target feature-based guidance in the conditions of the present search variant—although GS does assume "a substantial top-down component even to the simplest of feature searches" (Wolfe et al., 2003, p. 500).

Note that GS would also allow for a postselective component of coactivation at the level of (focal-attentional) target feature checking: matching the attentionally extracted target features against the target template, which is considered an obligatory stage in GS. Assuming that multiple features can be matched in parallel, this could give rise to coactivation effects. However, given that the target's two defining features are invariable, this stage would not have contributed to the coactivation effects seen in the present study (the logic here is similar to that elaborated with regard to the DAM; see below). Arguably also, given that the N2pc and sLRP timing showed little difference in the present study, there is presumably very little (if any) postselective target checking in simple detection tasks. This would be consistent with Müller, Krummenacher, and Heller (2004), who found that observers in a simple search task exhibited no explicit (above-chance) knowledge of a pop-out target—that is, of the dimension and the specific feature by which it was defined—to which they had just given a correct detection response, even if they could tell with near-100% reliability where in the field it was located (target localization was required for performing a secondary task). This lack of explicit knowledge of target-defining attributes suggests that encoding of these attributes (e.g., for purposes of template-matching) is not obligatory in detection tasks.

Dual-route accounts

While GS is not critically challenged by the present results, DRAs along the lines elaborated by Chan and Hayward (2009) encounter a more critical challenge—because, essentially, they do not envisage a spatial route contributing to performance in simple target detection tasks. Assuming that in the standard paradigm (variable target, constant distractors), detection responses are expedited by redundant targets because *nonspatial* detection units (e.g., units that pool analyzer activity across all locations in a given feature map—henceforth referred to as pooling feature units [PFUs]; see, e.g., Zehetleitner, Goschy, & Müller, 2012, for an explication of a dual-route architecture) tuned to the two target-defining features would coactivate a common output unit mediating overt responses (henceforth referred to as response unit), as compared to the output unit being activated by just one nonspatial detection unit. The essential assumptions here are that with fixed (i.e., known) target features (e.g., as in Krummenacher et al., 2001, 2002; Töllner, Zehetleitner, Krummenacher et al., 2011), the relevant nonspatial detection units (PFUs) can be selected in advance, and given that these units signal feature-specific activity in a nonspatial fashion, focal-attentional orienting (which requires the computation of spatial signals) is not necessary for target detection. Arguably, however, this account would not work when the target is constant and the distractors variable, because in this case, the detection units that are tuned to the two target features would be activated to the same extent whether the target is singly or redundantly defined. Note, though, that this account

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would need to be adapted to the conditions of the present experiment, in order to deal with the fact that on target-absent trials in the color and orientation target conditions, one of the two (target feature) detection units would also be activated. This poses a problem for deciding on a correct target-absent response in an architecture in which the integrating response unit is configured as an INCLUSIVE OR detector—which would produce an output (i.e., a target-present response) whether one or the other or both pooling feature units are activated. To illustrate the problem, suppose the target is defined singly by, say, orientation, that is: The target would be *vertical* and *yellow*, and the distractors horizontal and *yellow* (i.e., all distractors share a target-defining feature: color). The corresponding target-absent display would consist of distractors that are all horizontal and all *yellow*. Thus, because all distractors are yellow (sharing a target-defining feature), the PFU for yellow would be activated and this would in turn activate the integrating response unit, triggering an incorrect, target-present response. Thus, because the target-absent displays corresponding to singly defined (orientation and, respectively, color) targets would always favor a target-present response (because all distractors share one target-defining feature), a target-present/-absent decision could not be based on the output of a single PFU. Instead, one would need to compute a conjunction or disjunction of PFUs (for target and nontarget features) in order to produce the correct response (e.g., if the PFU for yellow is activated AND that for vertical, respond target-present! but if the PFU for yellow is activated AND that for horizontal, respond target-absent!), but the detection-route cannot handle such conjunctions, as a result of which the system would have to revert to operation via the spatial route.[8]

However, there is a simple solution to make the detection route work in principle, namely, to configure the response output unit as a logical AND detector (rather than as an INCLUSIVE-OR detector): An integrating response unit set up as an AND detector would produce an output only if both PFUs are activate, but not if only one is activated. Thus, in case of target-absent displays where the distractors share one target-defining feature (i.e., target-absent displays for the conditions of singly defined orientation and color targets), only one PFU would be activated and pass on its output to the response stage, but this activation would not be sufficient to trigger the response unit, which requires two units of activation to fire, a condition met only on (all) target-present trials (whether the target is a color singleton, an orientation singleton, or color-plus-orientation singleton). However, the present results are at variance with performance operating via this type of adapted detection route scheme: First, there were mean RT redundancy gains

and violations of the RMI, which cannot be explained in terms of feature-selective processing via the non-spatial detection route, and these effects were reflected in the timing of the N2pc, which by definition is an inherently spatial (i.e., lateralized), rather than non-spatial, signal.

Theoretically, one could now argue that (for some reasons) response units cannot be set up as AND detectors—though this would not be convincing, as one would then be unable to explain how a feature conjunction search task is solved. Arguably, conjunction search requires some response-triggering template that acts like an AND detector (i.e., both features must be given for the triggering condition to be met). Also, if one argues that, under the conditions of the present experiment, the system solves the task by operating via the spatial route, then one would also have to assume that the same route is used to solve the task under the standard conditions of Krummenacher et al. (2001, 2002) and Töllner, Zehetleitner, Krummenacher et al. (2011), which produced equivalent effects patterns: namely violations of the RMI coupled with inherently spatial N2pc effects. That is, one would have to assume that the standard task too is solved via the spatial route, even though no conjunction of the PFUs is necessary to resolve the standard task (a simple INCLUSIVE-OR response unit could coherently produce correct target-present and -absent response). This would raise a question as to the explanatory value of the dual-route account with respect to redundant-signals effects.

Dimension-action model

A similar challenge is faced by DAM of Cohen and colleagues (Cohen & Feintuch, 2002; Cohen & Magen, 1999, Cohen & Shoup, 1997; Feintuch & Cohen, 2002). Essentially, the DAM is a two-stage account, which assumes a parallel-race architecture mediating focal-attentional target selection at a pre-attentive stage and coactive processing of dimensionally organized response selection operations at the postselective stage. That is, coactive processing of (response-based) information in separate dimensions is enabled only when the relevant stimuli are represented postselectively, within the focus of attention (Cohen & Feintuch, 2002; Feintuch & Cohen, 2002). In more detail, Cohen and colleagues' dimensional action system envisages dimensional modules, each consisting of a set of spatiotopically organized feature maps, which have separate response selection devices. Furthermore, "attention is simultaneously connected to all dimensional modules. ... When people focus their attention on a particular location, the activation at that location is enhanced simultaneously in all dimensional modules" (Cohen & Magen, 1999, p. 306). The dimensional

response devices are mutually inhibitory, so that one response must win the competition to be transferred to the central response execution stage. With multiple stimuli in the display, such as in the flanker paradigm used by Cohen and Shoup (1997, 2000), multiple (incompatible) response units may be activated in parallel by the central target and the flanking stimuli, respectively. To resolve the ensuing competition, spatial attention must be focused on the task-critical, central stimulus for its associated response to win the competition. That is, the mechanism by which a dimensional response decision unit is assigned to a specific stimulus is location-based attention. Accordingly, coactivation of the central response execution stage by separate dimensional response decision units is possible only within the focus of attention. Restated, deploying the focus of attention to the target is a prerequisite for coactivation effects to occur, so that, logically, processing leading up to target selection must be a parallel race.

Given this, the violations of the RMI demonstrated in the standard paradigm with variable targets and fixed distractors (e.g., Krummenacher et al., 2001, 2002; Töllner, Zehetleitner, Krummenacher et al., 2011) would be attributable to a postselective (response) decision stage, rather than a preselective (saliency computation) stage. However, according to the DAM, there should have been no violations of the RMI in the present experiment—because, with the fixed target, the response is always (maximally) coactivated by post-selective decision units coding the (fixed) target features in the two dimensions. (Note, though, that the model allows for mean RT redundancy gains, due to the [parallel] race for selection being concluded earlier when the target is redundant, as compared to singly, defined.)

Thus, while the DAM could explain the coactivation effects observed in experiments using the standard search paradigm (variable targets, constant context), it could not account for violations of the RMI in the present variant of the search task (constant target, variable context), unless it admits that coactivation effects arise in preselective processing, which would require giving up one of the central tenets of the DAM. Arguably also, DAM would encounter a difficulty explaining the inherently spatial (i.e., lateralized) N2pc effects if one assumes that that the final response decision is computed by a nonspatial, central mechanism.

Dimension-weighting account

Thus, given the difficulties encountered by the approaches discussed above, the present results would be most consistent with the DWA of Müller and colleagues (e.g., Found & Müller, 1996; Müller et al., 1995; Müller et al., 2010). In essence, the DWA assumes that visual search for *singleton* targets is largely feature contrast-/saliency-based (and thus essentially spatial in nature), with minimal, if any, contributions by mechanisms biasing processing towards specific target-defining features.[9] Feature contrast (i.e., featureless) signals indicating the presence and location of singleton targets are computed in multiple dimensions in parallel and can thus coactivate the overall-saliency signal that guides the allocation of focal attention. In this sense, coactivation effects arise at a pre-attentive stage of spatial processing: the overall-saliency map. Feature-specific information is then extracted postselectively only for the attended item, to mediate S-R mapping processes. The extent to which such processes are engaged depends on the demands of the task: They are minimal in simple detection and localization tasks, but prominent in tasks requiring explicit target identification of responding to target features that are separate from search-critical features (as in what is referred to as a compound search tasks). This is consistent with the pattern of N2pc effects: The timing of the N2pc exhibits redundancy gains (present study and Töllner, Zehetleitner, Krummenacher et al., 2011) and scales with feature contrast strength (Töllner, Zehetleitner, Gramann et al., 2011), but is not influenced by the demands placed on stimulus analysis (Töllner et al., 2013) and/or S-R mapping processes (Töllner, Range-lov, & Müller, 2012).

Note that the DWA does not deny the existence of coactive processing of multidimensional stimulus features at late stages of processing at which task-critical features are extracted and translated into the instructed response or, respectively, at which the motor response itself is generated. In fact, such cases have been well documented in the literature (Cohen & Feintuch, 2002; Feintuch & Cohen, 2002; see also Miller, Beutinger, & Ulrich, 2009; Mordkoff & Yantis, 1993; for a review, see Miller & Reynolds, 2003), though typically using paradigms in which displays consisted only of one or two stimuli presented at an invariant location, thus minimizing the demands on the attentional selection of the task-relevant stimuli. In fact, the existence of postselective coactivation effects is not necessarily ruled out by evidence of coactive processing at pre-attentive stages; rather, there may well be multiple stages at which coactivation can occur.[10] Nevertheless, using a paradigm in which only one stimulus was presented at a fixed location, but which otherwise closely resembled visual search for a variable singleton target within a field of homogeneous, fixed distractors, Krummenacher et al. (2010) failed to find evidence for coactivation. In more detail, in a nonsearch task adapted from Mortier, Theeuwes, and Starreveld (2005), Krummenacher et al. (2010) presented observers with either a standard green vertical bar, which required a target-absent response (just as a search display consisting of green vertical bars

only), or a *red* or *blue* vertical or a green *left-tilted* or *right-tilted* bar, or a bar that differed from the standard by both color and tilt (a *red left-* or *right-tilted* bar or a *blue left-* or *right-tilted* bar), which required a target-present response (just as any such stimulus would have required a target-present response if embedded within a field of homogeneous green vertical bars). While the search task produced significant violations of the RMI, there were no such violations in the nonsearch task, at variance with a postselective locus of the coactivation effects in the search task.[11] However, absence of evidence is not evidence of absence, and given that postselective effects have been reliably demonstrated in a range of other paradigms (see above), future research might be directed towards clarifying precisely under which conditions coactivation does or does not occur at postselective stages of processing.

Conclusion

In summary, the present—behavioral and electro-physiological—results argue in favor of singleton search being mediated by a dimensions-specific feature contrast computation and cross-dimensional saliency summation architecture along the lines envisaged in DWA. Search is guided largely by featureless target signals, with processes that extract precise feature information coming into play only late, following focal-attentional selection. While this does not rule out postselective stages of signal integration (e.g., parallel coactive matching of multiple features onto templates of possible targets), further work is necessary to understand under which task conditions one or the other or both sources of redundancy gains come into play.

Keywords: saliency-based mechanisms, pop-out search, event-related potentials

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Footnotes

[1]While this is similar to the architecture envisaged in GS, the DWA assumes that the integration of separate dimensional feature contrast signals is weighted by the priority assigned to the various dimensions in terms of both intertrial history (implicit, bottom-up component: The weight is increased for target-defining dimensions/features and decreased for nondefining dimensions/features) and in instructed relevance (explicit, top-down component). Another difference concerns the operation of top-down feature biases (see below for details).

[2]In addition, RMI violations were dependent on the intertrial history: Repeated redundant targets produced more robust RMI violations compared to repeated color and repeated orientation targets, relative to nonrepeated targets, consistent with dimension-based modulations of the integration weights, as predicted by the DWA.

[3]In Töllner, Zehetleitner, Krummenacher et al. (2011), distractors were always *yellow horizontal* bars, and targets differed from distractors either only by color (*red* horizontal bar) or only by orientation (yellow *vertical* bar), or redundantly by both color and orientation (*red vertical* bar)—see Figure 1 for an illustration.

[4]The difference between featureless and feature-specific processing in pop-out search may be seen as mapping onto Egeth and Bacon's (1994) distinction between a singleton detection and a feature search mode (see also Zehetleitner, Goschy, & Müller, 2012).

[5]Mordkoff, Miller, and Roch (1996) propose an alternative procedure for the computation of the LRP: LRP = (C3L − C4L) − (C3R − C4R), equation 2 (p. 36). Calculating both the sLRP and rLRP components according to Mordkoff et al.'s (1996) procedure yielded results that are highly comparable to the ones obtained using the procedure described in the Methods section. Jack-knifed onset latencies (50% and 90% onset criteria on the sLRP and rLRP data, respectively) on color, orientation, and redundant trials: sLRP (color: 308.9 ms; orientation: 299.3 ms; redundant: 287.5 ms; $F_c(2, 22) = 2.0$, $p = 0.159$); rLRP (color: −71.7 ms; orientation: −71.4 ms; redundant: −83.4 ms; $F_c(2, 22) < 1$).

[6]In the 140–200-ms poststimulus time window, there is a short-lived positivity preceding the N2pc (see Figure 2). This positivity was driven purely by target color—that is, it was significant only for trials on which a color difference was present in the display (i.e., on color and redundant-target trials, both $t[11] = 3.7$, $p = 0.003$, but not on orientation target trials, $t[11] < 1$). The onset latencies of the positivity preceding the N2pc, determined using a 50% criterion, were shorter on redundant (144 ms) than on color target trials (182 ms; $t[11] = 4.9$, $p < 0.001$). This ERP pattern is wholly in line with the positivity posterior contralateral (Ppc)

component recently established by Corriveau et al. (2012), who took this component to reflect spatially selective processing of any color difference prior to the selection of a particular color value. Accordingly, the Ppc can be interpreted as a marker of the generation of a (global) signal on the salience map, with the subsequent N2pc reflecting the allocation of focal attention to this particular color difference. To date, however, the Ppc has only been found with color differences (confirmed in the present experiment), thus arguably limiting its explanatory power with regard to the redundant-signals effect (on the N2pc) revealed in the present study.

[7]Note that distractor locations receiving a degree of top-down activation also applies to the target-absent trials in the orientation and color target conditions—a point which is developed in more detail in the discussion of dual-route accounts below.

[8]We are grateful to Louis K. Chan for pointing this problem out to us (personal communication, January 6, 2014).

[9]This is not to deny the possibility of top-down biasing, for example, in search for fixed/known or precued targets (in fact, see, e.g., Müller, Reimann, & Krummenacher, 2003, who reported RT benefits when a singleton target was defined by a feature in the dimension indicated by a symbolic precue).

[10]Curiously though, while this is expressly acknowledged by DWA (e.g., Krummenacher et al., 2010), other accounts, such as the DAM of Cohen and colleagues, are exclusivist in terms of admitting coactive processing only at one—in their case: a postselective—stage of processing.

[11]In fact, in the nonsearch task, there was some evidence that response-critical features were matched serially against the set of target templates.

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