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Top-down weighting of visual dimensions: Behavioral and electrophysiological evidence

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ABSTRACT

Visual search for an odd-one-out target is speeded when observers are provided with a cue word indicating the most probable target-defining dimension (e.g., form) on a given trial (Müller, Reimann, & Krummenacher, 2003). According to the 'dimension-weighting' account (e.g., Müller, Heller, & Ziegler, 1995), this semantic cueing effect originates from a pre-attentive processing stage: the coding of stimulus saliency. However, alternative views (e.g., Theeuwes, Reimann, & Mortier, 2006) argue that pre-attentive saliency computations are top-down impenetrable, advocating a response-related origin of this effect. To establish the (pre-attentive and/or post-selective) locus of semantic dimension-cueing effects, the present study examined reaction time (RT) performance in combination with specific event-related brain potential components that are directly linkable to either pre-attentive or post-selective levels of processing. Targets preceded by valid (relative to invalid) cues were associated with faster RTs and both shorter peak latencies and larger amplitudes of the *Posterior-Contralateral Negativity* (PCN). In addition, dimension changes (relative to repetitions) across consecutive trials were accompanied by delayed PCN latencies, whereas response changes (relative to repetitions) gave rise to enhanced amplitudes of the (response-locked) *Lateralised Readiness Potential* (LRP). This pattern of effects clearly demonstrates that top-down dimensional sets modulate pre-attentive perceptual processing in the detection of pop-out signals. However, they cannot completely overcome automatic dimension-based weighting processes.

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1. Introduction

Searching visual scenes for objects of interest is one of the most frequent tasks we are performing every day. To efficiently guide the extraction of information relevant for achieving our current actions goals, a top-down perceptual set, or 'template', is established, representing the targets' feature descriptions (e.g., color, shape, etc.). For instance, when looking for our suitcase at the airport baggage claim, we may pay particular attention to the shape and/or color of our personal suitcase. Depending on how precisely this template matches the desired object, this top-down activation, in combination with bottom-up (saliency of the target) and inter-trial (previous search episode) factors, determines how efficiently we find the object we are looking for (see, e.g., Leonard and Egeth (2008), for review).

To approximate this kind of search situation in the laboratory, Müller, Reimann, and Krummenacher (2003) used a feature single-

ton ('pop-out') search task to investigate whether detection of pop-out targets is cognitively penetrable by top-down dimensional set. This question has been under debate for some time, with two alternative standpoints. One view is that pop-out detection is purely stimulus- (bottom-up-/saliency-) driven and not modulable by top-down dimension- and feature-based set (e.g., Maljkovic & Nakayama, 1994; Theeuwes, 1992; Theeuwes, Reimann, & Mortier, 2006). The alternative view is that top-down set modulates stimulus processing prior to focal-attentional selection (e.g., Folk & Remington, 1998; Müller et al., 2003; Wolfe, Butcher, Lee, & Hyle, 2003). To avoid confounding by passive (bottom-up) inter-trial priming, which might come into play when one stimulus dimension is more likely than another to be target-defining within a given block of trials, Müller et al. presented a semantic cue (the word 'Color' or 'Orientation') prior to each search display, which indicated the upcoming target dimension with a probability (validity) of 80%, and observers were instructed to actively set themselves for the indicated stimulus dimension on a trial-by-trial basis.

Using this procedure, Müller et al. (2003) found RT and accuracy benefits for valid-cue trials (on which the target was defined in the pre-cued dimension) and costs for invalid-cue trials (on which the target was defined in the noncued dimension) – relative to a

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neutral-cue condition (with the cue word 'Neutral'). Müller et al. took this pattern to demonstrate that, even in situations of high target saliency (i.e., with pop-out targets), stimulus-driven processes can be modulated by top-down dimensional set. However, even when the cue indicated the dimension of the upcoming target with perfect validity, there remained an RT cost if the new dimension was changed (rather than repeated) from the preceding trial. Müller et al. took this residual inter-trial effect to suggest that top-down activations cannot completely overcome automatic dimension-based weighting processes (which increase the processing weight for the current target-defining dimension and reduce the weights for the other dimensions).

Note that with semantic feature cues (e.g., the word 'Red', indicating that the upcoming target was 79% likely to be defined by the color red), Müller et al. (2003) observed RT benefits even for an unlikely (7%) target feature within the same dimension as the cued feature (e.g., a target singled out by the color blue), but RT costs for features defined in a different dimension (e.g., a target singled out by a left (7%) or right (7%) tilt relative to the upright non-targets). This pattern of results highlights the dimension-specific, rather than feature-specific, nature of (non-spatial) cueing effects in visual pop-out search.

1.1. Locus of the dimensional cueing effect?

According to the Dimension-Weighting Account (DWA; e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995) – which is essentially an extension of saliency-based processing architectures such as Guided Search (GS; e.g., Wolfe, 1994) – the performance advantage with valid, relative to invalid, dimension pre-cues reflects the intentional shift of processing 'weight' to the likely target-defining dimension in early, pre-attentive stimulus coding (prior to focal-attentional selection). Since the DWA assumes a limit to the total amount of attentional weight, weighting of one dimension (e.g., color) entails that less weight is available for other dimensions (e.g., orientation, motion, etc.). Thus, targets defined within the pre-cued dimension are detected faster based on enhanced saliency coding in this dimension (compared to others). The enhanced (local) saliency signal generated by the target in its defining dimension is then transmitted to – and integrated with any signals from other dimensions – by the corresponding overall-saliency ('master map') unit which, once activated above threshold, summons focal attention (which in turn mediates further processes of explicit stimulus analysis and stimulus–response mapping). By contrast, targets defined in an uncued dimension may require a time-consuming '(re-)weighting' process, in which processing weight is shifted from the old to the new target-defining dimension, prolonging the time required for the saliency signal to activate the master map unit above threshold (e.g., Found & Müller, 1996). Alternatively, weight shifting may not be a prerequisite for detecting a target in an uncued dimension; rather, the target might be also detected, albeit slower, in a non-weighted dimension and the re-weighting follows target detection as part of an implicit adjustment process optimizing target detection in the subsequent trial episode (Gramann, Töllner, Krummenacher, Müller, & Eimer, 2007). In either case, on the DWA, semantic dimensional cueing effects arise at a pre-attentive perceptual stage of processing, before the target is selected and analyzed by focal attention.

However, this view has been opposed by Theeuwes et al. (2006) who argued that the dimensional cueing effect reported by Müller et al. (2003) may represent effects that occur at post-selective, response-related stages of processing, after perceptual encoding mechanisms have been completed. This challenge has been based on the comparison of dimensional cueing effects between singleton detection tasks and compound-search tasks. In both tasks, observers received exactly the same stimulus material, with search

displays adapted from Theeuwes (1992). However, in the singleton detection task, participants were instructed to discern the presence (versus the absence) of any singleton in the search array (replication of Müller et al., 2003), whereas in the compound-search task, observers responded based on the orientation of a line segment located in the target singleton. The central assumption underlying the compound-task logic is the separability of perceptual and response-related factors (see also Bravo & Nakayama, 1992; Duncan, 1985). While the singleton detection task replicated the dimensional cueing effect as observed by Müller et al. (2003), the same cues failed to produce significant cueing in the compound-search task (though there was a numerical cueing effect). Since the main difference between both tasks was in the response requirements, Theeuwes et al. (2006) reasoned that the dimensional cueing effect in detection tasks must originate from processes that occur later within the processing hierarchy (e.g., response selection; see also Cohen & Magen, 1999).

However, another reason for the lack of an overall dimensional cueing effect in the compound-search task of Theeuwes et al. (2006) might lie in the more complex nature of this task (compared to singleton detection). To solve the compound-task, participants first have to find the singleton before they can extract the response-relevant feature necessary to initiate the motor response. Thus, observers may not have attempted to (consistently) set themselves for the indicated target dimension, since the dimensional cue contained no information relevant for the upcoming motor response. Also, due to the pop-out character of the (highly salient) singleton, use of the cue was not really necessary to perform the task. To test this possibility, Müller and Krummenacher (2006) used the same physical stimuli as Theeuwes et al. (2006) in association with an extra incentive to use the cue: observers had to rate, at the end of each block, how well they had 'attended' to the cued dimension. With this subtle change in procedure, Müller and Krummenacher (2006) observed a significant dimensional cueing effect of 11 ms in compound search, which was of about the same magnitude as the (non-significant) effect in Theeuwes et al. (2006, Experiment 3). However, it remains controversial whether or not there is a dimensional cueing effect in compound-search tasks and where, within the information-processing stream, such an effect would arise (e.g., Mortier, Theeuwes, & Starreveld, 2005).

Taken together, there is an ongoing debate concerning the origin(s) of the dimensional cueing effect, and thus, the controversial issue whether and/or to what degree pre-attentive perceptual processing in visual pop-out search is cognitively penetrable (see also Folk and Remington (2006), for a detailed review). Advocates of a pre-attentive perceptual locus (Leonard & Egeth, 2008; Müller et al., 2003; Treisman, 1988; Wolfe et al., 2003) would assume that the dimensional cueing effect is generated by – top-down adjustable – visual encoding processes at the early sensory input level. By contrast, opponents (Theeuwes et al., 2006; Cohen & Feintuch, 2002; Cohen & Magen, 1999) argue that expectancy-based, top-down knowledge cannot modulate stimulus-driven processes in the detection of pop-out signals.

1.2. Rationale of the present study

Although Theeuwes et al. (2006) failed to observe (statistical) dimension-cueing effects in compound searches (which they took as evidence for a response-based origin of the dimensional cueing effect), their study does not unequivocally exclude pre-attentive modulations. Rather, differential processing rates in early sensory stages might be masked by non-dimension-specific processing dynamics in later stages (e.g., response selection, response production, etc.), and thus remain 'invisible' to traditional behavioral measures such as reaction time (RT). In fact, a recent electroencephalogram (EEG) study by Töllner, Gramann, Müller, Kiss, and

Eimer (2008), which used a compound-search task with pop-out targets, revealed several experimental conditions, which led to equivalent RT performance, to exhibit remarkable differences with respect to the time course of the underlying, distinct sub-stages – pre-attentive perceptual versus post-selective response-related – of processing. Thus, behavioral RT measures alone appear to be insufficient to resolve this controversy in an appropriate manner.

Therefore, to provide a more detailed picture with respect to the mechanisms underlying the dimensional cueing effect, we combined mental chronometry with event-related brain potentials (ERPs), which permit a millisecond-by-millisecond measure of neural processing based on scalp-recorded voltage fluctuations. For the sake of comparability with the (behavioral) pattern observed by Theeuwes et al. (2006), we employed the same compound-search task as used by Töllner et al. (2008) – however, with search displays preceded by semantic dimension cues (e.g., the word ‘Color’, indicating that the upcoming target would be color-defined with a probability of 80%). Observers were required to search for a singleton target uniquely defined in either the color or shape dimension, before they could select the appropriate motor response, which was determined by the orientation of a grating (vertical vs. horizontal) within the target object (see Fig. 1).

The primary goal of the present study was to examine whether or not dimensional cueing modulates early, pre-selective stages of perceptual coding. To provide a clear-cut dissociation between perceptual and response-related processing at the electrophysiological level, we specifically focused on two well-established and extensively studied components of the ERP. The first component, typically referred to as N2pc (*N2-posterior-contralateral*; Luck & Hillyard, 1994; Eimer, 1996) or PCN¹ (*Posterior-Contralateral Negativity*; Ansgorge & Heumann, 2006; Jaskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002), is a negative-going deflection elicited at posterior electrodes contralateral to the location of an attended stimulus between 175 and 300 ms post-stimulus. A recent study (Hopf et al., 2006) combining event-related magnetic fields (ERMFs), functional magnetic resonance imaging (fMRI), and ERPs has shown the neural generators of this component to be located within the human homologues of monkey inferotemporal cortex and area V4. There is a general consensus that the PCN can be interpreted as reflecting the allocation of focal attention based on perceptual stimulus properties (Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999, 2003). Moreover, the latency of this component can be regarded as marking the transition from the pre-attentive sensory coding of the stimulus display to the focal-attentional stage of target selection. Such latency variations have been observed in a number of studies demonstrating that the timing of target selection can be modulated by, for instance, stimulus intensity (Brisson, Robitaille, & Jolicoeur, 2007), set size (Wolber & Wascher, 2005), or the definition of a singleton target in one versus multiple (redundant) dimensions (Töllner, Zehetleitner, Krummenacher, & Müller, in press). Thus, perceptual processes can be further differentiated by using the PCN latency as an index of pre-attentive processing speed and the amplitude of the PCN as an index of the amount of attentional-resource allocation. In the present study, we analyzed the PCN as a function of cue validity in order to explore pre-selective modulations.

To control for possible response-related contributions to the dimensional cueing effect, we further focused on the *Lateralized Readiness Potential* (LRP) which, based on its extraction method from the ERP, has been linked to the activation and execution of motor responses (e.g., Coles, 1989; Hackley & Valle-Inclán, 2003). In more detail, the LRP is typically observed over the motor areas contralateral to the side of a uni-manual response, marking the

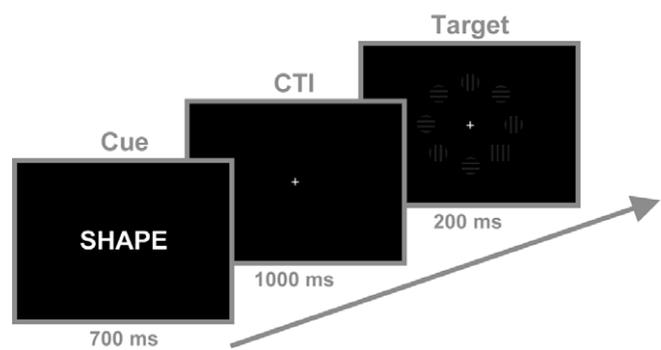


Fig. 1. Sequence of events on a trial in the present compound-search task. Each trial started with the presentation of either an informative or non-informative semantic pre-cue. Informative cues, the words “Color” or “Shape”, indicated the upcoming defining dimension of the singleton target with a validity of 80%; following a non-informative cue, the word “Neutral”, the target was equally likely to be color- or shape-defined. Whatever the dimension of the singleton, observers were required to discriminate the orientation of the grating inside it (horizontal vs. vertical) to select the appropriate motor response.

start of effector-specific (motor) activations, which occur after response selection processes have been completed. When computed relative to stimulus onset (stimulus-locked LRP), LRP onsets would reflect the time demands of those stages that occur prior to the start of selective motor activation (e.g., perceptual encoding processes, response selection). When computed relative to response onset (response-locked LRP), LRP onsets are determined by the time demands of those stages that occur after the start of selective motor activation (e.g., response execution processes; see also Leuthold, 2003, for methodological details).

According to the DWA, a top-down adjustment of dimensional weights in response to validly, as compared to invalidly, cued targets should be reflected in speeded PCN latencies, representing expedited pre-attentive encoding rates. Alternatively, if pre-selective processes are immune to top-down attentional sets and the dimensional cueing effect arises exclusively at post-selective, response-related stages, PCN latencies should not differ (between valid and invalid dimension-cue conditions) and LRP modulations would be expected instead.

A secondary aim of the present study was to explore the impact of the previous target identity (and motor action) on the detection of semantically pre-cued pop-out signals. Recall that Müller et al. (2003), as well as Theeuwes et al. (2006), had found persistent dimension-specific inter-trial facilitation effects suggesting that top-down modulations cannot completely overwrite stimulus-driven processes in visual pop-out search. That is, irrespective of the cue validity, participants reacted faster in response to targets defined within the same, compared to a different, dimension as on the previous trial. While the origin(s) of these dimension change costs *within* semantic dimension cueing tasks are also subject to an ongoing debate (pre-attentive perceptual vs. post-selective response-related locus; see Müller & Krummenacher, 2006, for a more detailed discussion), we additionally examined RT performance in association with ERPs in order to ascertain whether dimension-based inter-trial dynamics (as observed in feature singleton searches; Töllner et al., 2008) are still active on a pre-attentive level of processing when the dimensional identity of the upcoming target is highly (top-down) predictable.

2. Method

2.1. Participants

Fourteen observers (three female) took part in this study. Two observers had to be excluded from the analyses due to excessive

¹ Since both amplitude and latency of this component are clearly independent of the non-lateralized N2 component (Shedden & Nordgard, 2001), we prefer to use the term PCN (instead of N2pc) to preclude misleading interpretations.

eye blink artifacts. The ages of the remaining 12 observers ranged from 20 to 31 (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.

2.2. Stimuli and study design

Visual search displays were identical to the arrays used by Töllner et al. (2008). Eight colored shape stimuli arranged in a circular array were presented against a black background, each presented equidistantly (3.0° of visual angle) from a white central fixation point. On each trial, a singleton, equally often defined in either the color (red circle; CIE .544, .403, 25; 1.2° radius) or shape dimension (yellow square, CIE .463, .465, 25; 2.4° × 2.4°), was presented randomly at one of the six lateral positions among seven distracters (yellow circles; CIE .463, .465, 25; 1.2° radius). Each stimulus outline shape contained a grating consisting of three black bars (0.4° × 2.4°) separated by two gaps (0.3° × 2.4°). The gaps of the grating were either yellow (for squares and distracters) or red (for red circles). The orientation of the grating was randomly determined to be either vertical or horizontal. All stimuli were isoluminant (25 cd/m²).

Participants were seated in a dimly illuminated, sound-attenuated, and electrically shielded cabin (IAC). Stimuli were presented on a 17" computer screen, placed at a viewing distance of approximately 75 cm from the observer. One experimental session consisted of 24 blocks of 72 trials each, resulting in a total of 1728 trials. Each trial started with a centrally presented white fixation point for 500 ms, followed by a semantic cue (either the word 'FARBE' (German word for 'COLOR'), 'FORM' (German word for 'SHAPE'), or 'NEUTRAL' (identical meaning in both languages) for 700 ms. After a cue-target interval of 1000 ms, the search display appeared for 200 ms. A trial was terminated by the observer's response or after a maximum duration of 1000 ms. In case of an erroneous motor response or a response latency longer than 1000 ms, the word 'FEHLER' (German word for 'ERROR') appeared centrally for 1000 ms. The subsequent inter-trial interval (in which a central white fixation point was presented) varied uniformly between 950 and 1050 ms. In two thirds of the trials, the semantic precue indicated the upcoming target dimension with 80% validity; invalid and neutral cues were presented in each one sixth of the trials. Observers were instructed to maintain central fixation throughout a block and to make a forced-choice response indicating the (grating) orientation of the singleton target using their left and right thumb for a vertical and horizontal orientation, respectively. After the first experimental half (=12 blocks), assignments of thumbs to mouse buttons were reversed. To ensure correct stimulus-response mapping, participants performed at least one practice block prior to the start of each experimental half. In order to maintain the observer's motivation² throughout the experiment, he/she received summary performance statistics (mean error rate and reaction time) after each trial block.

2.3. EEG data acquisition and analysis

The electroencephalogram was recorded continuously from 64 scalp sites at a digitization rate of 1000 Hz. Electrodes were mounted on an elastic cap (Easy Cap, FMS), with positions corresponding to the 10–10 System (American Electroencephalographic Society, 1994). All electrodes were referenced to Cz and re-referenced offline to linked mastoids. The vertical electro-oculogram

(VEOG) was monitored by means of electrodes placed at the superior and inferior orbits. The horizontal EOG was recorded from electrodes placed 1 cm lateral to the outer canthi of the eyes. All impedances were kept below 5 kΩ. Electrophysiological signals were amplified by BrainAmp amplifiers (BrainProducts, Munich) using a 0.1–250-Hz bandpass, and filtered offline with a 1–40-Hz bandpass (Butterworth zero phase, 24 dB/Oct). Prior to epoching the EEGs, an Independent Component Analysis (ICA) – as implemented in the Brain Vision Analyzer software (BrainProducts, Munich) – was run to identify components of the EEGs that represent blinks and/or horizontal eye movements and to remove those before back-projection of the residual components. After epoching the EEG into stimulus-locked (see PCN analysis below) and response-locked segments (see LRP analysis below), only trials with correct motor responses and without artifacts – defined as any signals exceeding ±60 μV, bursts of electromyographic (permitted maximal voltage steps/sampling point of 50 μV), and activity lower than 0.5 μV within a 500-ms-interval (indicating dead channels) – were selected for further analyses.

For the PCN analysis, we epoched the EEG into 500-ms segments relative to a 200-ms baseline, which was used for baseline correction. This was followed by artifact rejection (see above) and averaging, before we computed the difference waveforms by subtracting ERPs, obtained at lateral posterior electrode positions PO7/PO8, ipsilateral to the side of the singleton in the search array from contralateral ERPs. PCN latencies were determined as the point in time when the PCN reached its maximum negative deflection (within the 150–350-ms time window post-stimulus). Amplitudes of the PCN were calculated by averaging five sample points before and after the maximum deflection.

To isolate the (response-locked) LRP from the EEGs, we first extracted stimulus-locked LRP waveforms – subtracting ERPs at electrodes C3/C4 ipsilateral to the side of uni-manual hand responses from contralateral ERPs according to the following formula: $(C4[left] - C3[left] + C3[right] - C4[right])/2$ (see Eimer & Coles, 2003, for methodological details) – into 4000-ms segments ranging from 2000 ms before to 2000 ms after stimulus onset. The next step involved a baseline correction based on the –200 to 0-ms pre-stimulus interval, before the data was then re-epoched into response-locked LRP waveforms ranging from 800 ms before to 200 ms after response onset. LRP amplitudes were calculated using the five sample points before and after the maximum negative deflection obtained in the time window 100–20 ms prior to response onset. Onset latencies of the response-locked LRP were determined based on the jackknife-based scoring method proposed by Ulrich and Miller (2001) (see also Miller, Patterson, & Ulrich, 1998). Following Miller et al. (1998), we used 90% maximum amplitude as an optimal criterion to define response-locked LRP onset latencies.

PCN (amplitudes/latencies) and LRP (amplitudes/onset latencies) components were examined using the same statistical analyses. For expectancy-driven effects, electrophysiological measures were analyzed by repeated-measures analyses of variance (ANOVAs) with the factor cue type (valid, neutral, invalid). To examine for inter-trial transition effects, ERP waveforms were subjected to two-way ANOVAs with the factors dimension change (same, different) and response change (same, different).

3. Results

3.1. Behavior

Overall error rates were low (5%) and error trials were excluded from the reaction time (RT) analysis. An ANOVA of the correct RTs with the factors cue type (valid, neutral, invalid), target type (color,

² Recall that Müller and Krummenacher (2006) had surmised that motivational factors might affect the occurrence of (pre-attentive) dimensional cueing effects in compound-search tasks.

form), dimension change (same dimension, different dimension), and response change (same response, different response) revealed the main effects of cue type ($F(2, 22) = 7.9, p < .002$, cf. Fig. 2) and dimension change ($F(1, 11) = 37.0, p < .001$) to be significant. Both cue type and dimension change interacted with target type (cue type \times target type: $F(2, 22) = 4.4, p < .03$, dimension change \times target type: $F(1, 11) = 9.5, p < .01$). Finally, there was a significant interaction between dimension change and response change ($F(1, 11) = 31, p < .001$), which is presented in Fig. 3.

Specifically, validly-cued targets were responded to 14 ms faster overall than invalidly-cued targets (605 vs. 591 ms; main effect of cue type). One-sided post hoc *t*-tests (Bonferroni corrected for multiple comparisons) revealed this RT difference between valid- and invalid-, as well as that between valid and neutral trials to be significant ($p < .03$ and $p < .05$, respectively). The RT difference between neutral and invalid trials was marginally significant ($p < .06$). While a cueing effect in terms of 'costs-plus-benefits' (i.e., a difference between valid- and invalid-cue trials) was manifest with both color- and form-defined targets (effects of 12 and 16 ms, respectively, both $p < .03$), reaction speed on neutral-cue trials depended on the target dimension: for form-defined targets, neutral-cue RTs were almost as fast as valid-cue RTs; conversely,

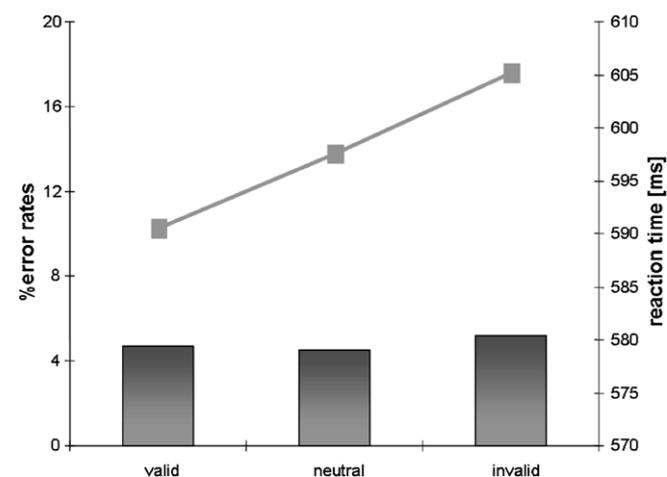


Fig. 2. Reaction times (line) and error rates (bars) as a function of cue type (valid, neutral, invalid).

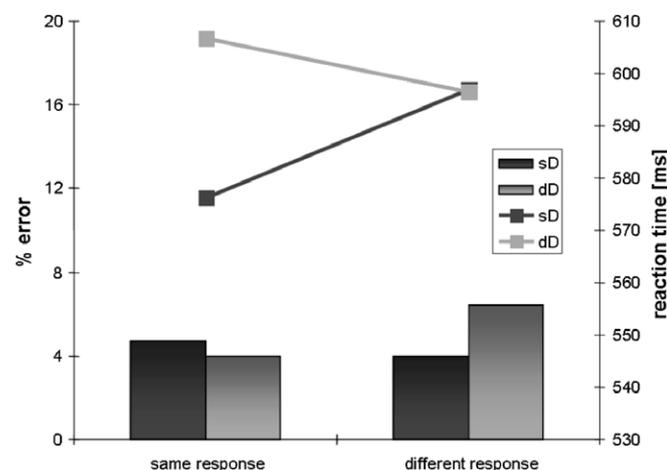


Fig. 3. Reaction times (lines) and error rates (bars) as a function of the target-defining dimension and the motor response on the previous trial (sD = same dimension; dD = different dimension).

for color-defined targets, neutral-trial RTs were about as slow as invalid-trial RTs. This pattern suggests that observers prepared to neutral cues in a fashion similar to form cues. Furthermore, RTs were faster overall on same-dimension than on different-dimension trials (587 vs. 604 ms; main effect of dimension change), with the dimension change effect being larger for color than for form targets (22 vs. 12 ms; dimension change \times target type interaction).

An analogous ANOVA of the error rates revealed a significant main effect of dimension change ($F(1, 11) = 7.0, p < .02$), with more errors after dimension changes compared to repetitions (5.4% vs. 4.2%), suggesting that the RT effects reported above are not due to speed-accuracy trade-offs. This main effect was qualified by a significant interaction between dimension change and response change ($F(1, 11) = 18.54, p < .001$): changing the target-defining dimension across consecutive trials led to an increased error rate when the motor response had to be changed (6.7%), rather than repeated (3.6%), concurrently.

3.2. Electrophysiology

3.2.1. Expectancy-driven effects

Fig. 4 displays grand average ERP waveforms elicited by target displays that followed valid, neutral, and invalid cues, respectively. Separate waveforms for contra- and ipsilateral targets with respect to the hemisphere of the recording electrode (PO7/PO8) are shown in the top panel, while the bottom panel represents the corresponding contralateral-minus-ipsilateral difference waveforms. For all three cue conditions, a solid PCN was triggered, which can be seen as a more negative (i.e., less positive) voltage starting at approximately 180 ms post-stimulus.

As can be seen from Fig. 4, the rise of the PCN occurred earlier and was more pronounced when the search target was defined in the cued (valid cue), rather than the uncued (invalid cue), dimension, yielding a significant main effect of cue type for both PCN latencies [$F(2, 22) = 6.23, p < .007$] and PCN amplitudes [$F(2, 22) = 6.95, p < .005$]. Specifically, the PCN peaked 11 ms earlier and was 0.38 μ V larger for valid (233 ms; -2.78μ V) as compared to invalid-cue trials (244 ms; -2.40). For neutral-cue trials, the PCN latencies and amplitudes (237 ms; -2.65μ V) were in-between those for valid- and invalid-cue trials, though neither the benefits and nor the costs were separately significant. Nevertheless, the pattern of a significant difference between valid- and invalid-cue trials ('costs-plus-benefits') in terms of both PCN latencies and amplitudes is indicative of speeded and facilitated coding of target (saliency) information at the pre-attentive processing stage when the target was defined within the cued, rather than the uncued, dimension.

Two further repeated-measures ANOVAs, each with the factors cue type (valid, neutral, invalid) and Electrode site (O1/O2, PO7/PO8, PO3/PO4, P7/P8), examined whether this expectancy-based PCN (latency and amplitude) pattern generalizes across surrounding electrode positions. For PCN latencies, this ANOVA revealed both main effects [cue type: $F(2, 22) = 4.006, p < .033$; Electrode site: $F(3, 33) = 4.246, p < .012$] as well as their interaction [$F(6, 66) = 2.512, p < .030$] to be significant. As confirmed by further (Tukey HSD) post hoc comparisons, the cue validity effect was evident at all ($p < .04$) but one (O1/O2, $p > .342$) electrode sites. For PCN amplitudes, the main effect of cue type reached significance [$F(2, 22) = 5.611, p < .011$], replicating more negative-going deflections elicited by validly-cued (-2.15μ V) compared to invalidly-cued targets (-1.9μ V). In addition, the main effect of Electrode site approached statistical significance [$F(3, 33) = 8.728, p < .001$] due to stronger activations at electrode site PO7/PO8 as compared to neighboring electrodes, which did not differ between each other (Tukey HSD test).

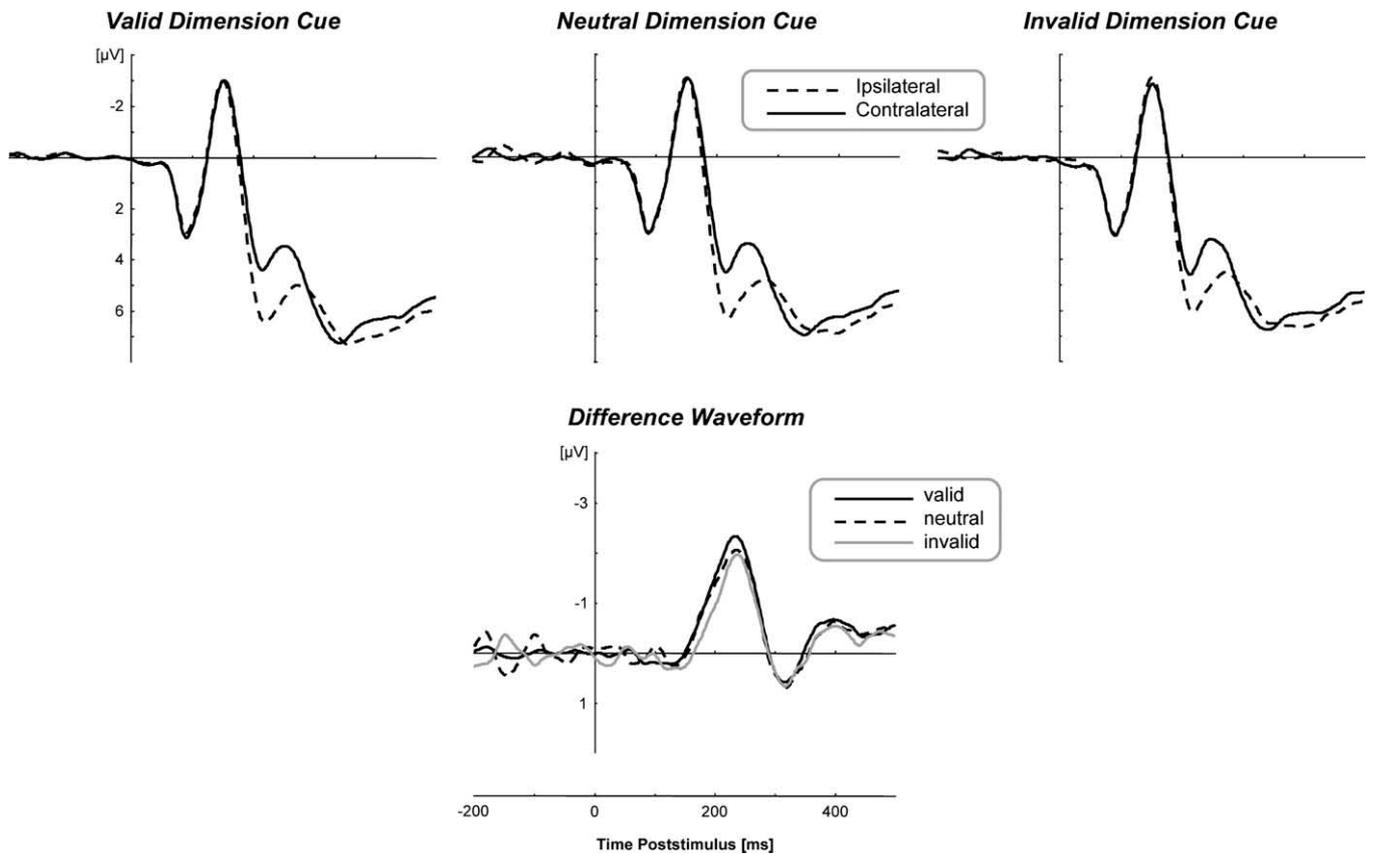


Fig. 4. Upper panel: grand averaged event-related brain potentials elicited in the 500 ms interval following stimulus onset at electrode positions PO7/PO8 contralateral (solid line) and ipsilateral (dashed line) to the singleton position. Bottom panel: PCN difference waveforms obtained by subtracting ipsilateral from contralateral activity for each of the three cue type conditions (valid, neutral, invalid).

Fig. 5 presents the stimulus-locked (left side) as well as response-locked (right side) LRP waveforms separately for each of the three dimension-cue conditions at C3/C4. For stimulus-locked LRPs, this figure suggests an earlier rise and enhanced amplitudes of the LRP in response to validly-cued compared to invalidly-cued targets. Numerically, the onsets latencies were 11 ms shorter and the amplitudes $0.18 \mu\text{V}$ larger when the upcoming target dimension was correctly (370 ms ; $-1.56 \mu\text{V}$), rather than incorrectly (381 ms ; $-1.38 \mu\text{V}$), pre-cued. Note that this latency difference of 11 ms was exactly the same as that obtained for the PCN latencies (see above). However, cue validity failed to influence both the on-

set latencies [$F_c(2, 22) = 0.72$, $p_c > .497$] and amplitudes [$F(2, 22) = 1.70$, $p > .207$] of the stimulus-locked LRP, and the onset latencies [$F_c(2, 22) = 0.62$, $p_c > .549$] and amplitudes [$F(2, 22) = 2.03$, $p > .155$] of the response-locked LRP.

3.2.2. Previous trial effects

Fig. 6 (left side) displays PCN activations as a function of the previous visual dimension and motor response. When analyzed with respect to the preceding trial episode, latencies of the PCN were about 6 ms slower when the target-defining dimension changed (236 ms), as compared to being repeated (230 ms), across con-

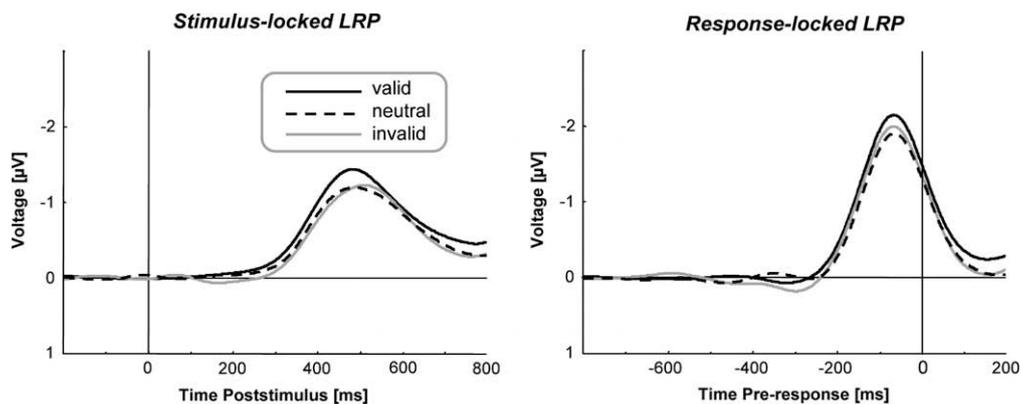


Fig. 5. Lateralized readiness potentials (LRPs) for each of the three cue type conditions (valid, neutral, invalid) at electrode positions C3/C4. Left side: LRP waves time-locked to the onset of the search display. Right side: LRP waves time-locked to the onset of the motor action (i.e. button press).

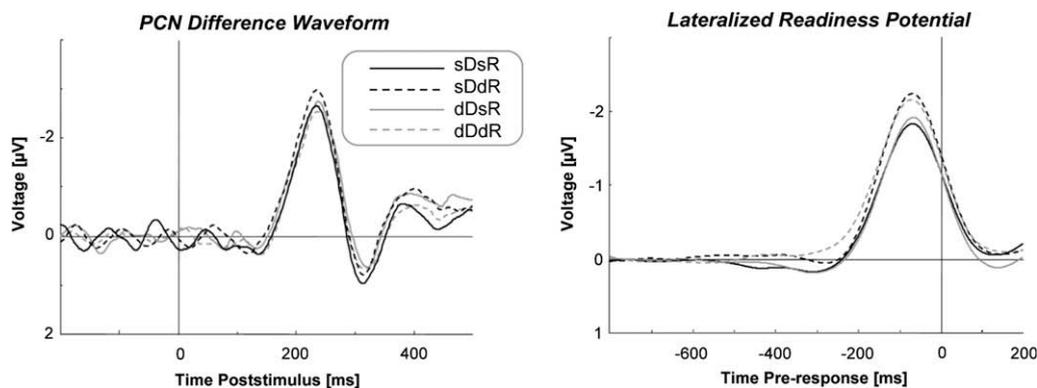


Fig. 6. Lateralized ERP potentials as a function of the target-defining dimension and the motor response on the previous trial (sDsR = same dimension/same response; sDdR = same dimension/different response; dDsR = different dimension/same response; dDdR = different dimension/different response). Left side: PCN difference waveforms elicited in the 500-ms interval following stimulus onset at electrode positions PO7/PO8. Right side: Lateralized readiness potentials elicited in the 800-ms interval prior to response onset at electrode positions C3/C4.

secutive trials [main effect of dimension change, $F(1, 11) = 8.01$, $p < .016$]. This PCN latency effect was purely perceptual in nature, as indicated by the absence of a significant effect for [$p > .41$] and/or interactions with [$p > .89$] the factor response change. For PCN amplitudes, the repeated-measures ANOVA revealed an interaction between dimension change and response change [$F(1, 11) = 9.64$, $p < .010$], suggesting enhanced amplitudes for repeated target-dimensions on response change, but not response repetition trials. However, this interaction could not be substantiated by subsequent post hoc contrasts ($p > .15$).

In marked contrast to the PCN activations, changes of the motor response across consecutive trials had a remarkable impact on the response-locked LRP (rLRP) component. As can be seen from Fig. 6 (right side), targets that required a change of the motor response gave rise to more negative-going deflections prior to response onset than targets demanding the same motor response as on the previous trial ($-2.30 \mu\text{V}$ vs. $-1.98 \mu\text{V}$) [main effect of response change on rLRP amplitudes, $F(1, 11) = 4.49$, $p < .05$]. Importantly, this was the case irrespective of the dimensional identity of the previous singleton [dimension change: $p > .92$; interaction: $p > .70$]. By contrast, rLRP onset latencies (as determined by the jackknife-based scoring method of Miller et al., 1998) did not differ systematically between previous-trial conditions (dimension change: $p_c > .99$; response change: $p_c > .16$; interaction: $p_c > .12$), suggesting that (motor) weighting dynamics are predominantly operating at the level of response activation, rather than response execution (see also Töllner et al., 2008).

4. Discussion

By examining event-related brain potentials, the present study was designed to shed new light on the controversial issue whether or not early pre-attentive perceptual stages of information coding are modulable by top-down, dimension-based intentions in singleton (pop-out) search. Combined with mental chronometry, ERP techniques provide the possibility to capture processes that might be invisible when analyzing behavioral measures only and, thus, can help decide between alternative hypotheses with respect to the nature of pre-attentive vision (top-down penetrable: e.g., Eimer & Kiss, 2008; Müller et al., 2003; Wolfe et al., 2003; impenetrable: e.g., Cohen & Feintuch, 2002; Theeuwes et al., 2006).

Behaviorally, the present study replicated the dimensional cueing effect described by Müller and colleagues (Müller & Krummenacher, 2006; Müller et al., 2003; see also Zehetleitner, Müller, Krummenacher, & Geyer, submitted for publication), with faster reactions to validly, compared to invalidly, cued targets. This indi-

cates that observers were able to make use of the cue even in a compound-search task, in which the cue (and the actual target-defining dimension) contained no information with respect to the required motor response. Additionally, behavioral reactions also benefited when the visual dimension as well as the motor response remained unchanged across consecutive trials. This pattern resembles that observed in previous studies conducted to investigate the origin of dimension-specific inter-trial facilitation effects in feature singleton searches (Müller & Krummenacher, 2006; Töllner et al., 2008, see also Pollmann, Weidner, Müller, Maertens, & von Cramon, 2006). That is, with respect to the previous trial, the dimension of the singleton (color vs. shape) in interaction with the motor action (e.g., left vs. right thumb) determined the speed of behavioral RTs (but see discussion of electrophysiological results below). As in the studies of Müller and Krummenacher (2006) and Theeuwes et al. (2006), the present (compound-task) data revealed no interaction between expectancy-based (cue type) and stimulus-dependent (previous target dimension) effects. This may be taken to suggest that both attentional mechanisms (expectancy- and stimulus-dependent) modulate pop-out target detection in an autonomous fashion³ – though, following the DWA (Müller & Krummenacher, 2006), any such modulations have their loci at pre-attentive perceptual stages, influencing dimension-specific signal strength prior to the stage of focal-attentional target selection.⁴

³ Although there was no cue type \times dimension change interaction evident at the behavioral level, this does not unequivocally exclude possible interactions acting at underlying distinct 'sub-stages' of the processing cycle. However, due to trial limitations (especially for neutral and invalid conditions) in the present study, this possibility could not be tested exhaustively and needs to be examined in future, systematic studies.

⁴ Note, however, that Müller et al. (2003) did find an interaction in simple-detection tasks when the neutral-cue condition was blocked: the dimension change effect was significantly reduced for valid- and invalid-cue trials relative to neutral-cue trials (see also Weidner a Müller submitted for publication, who found a similar, but numerically much larger difference in a singleton conjunction search task). Arguably, blocking of the neutral cues permits stimulus-dependent inter-trial effects to be observed in a pure fashion, as observers are unlikely to take note of the cue word ("Neutral") beyond using it as a temporal warning signal. By contrast, when (rare) neutral cues are presented randomly interspersed with (frequent) informative-cue trials, observers might carry over a strategy to top-down set themselves for one of the two dimensions, for instance, that which they might find easier to prepare for (e.g., shape in the present study). Consequently, the inter-trial effects observed for neutral-cue trials would not provide a proper baseline (of purely stimulus-dependent influences) against which to compare the effects of informative cues. Thus, it remains an open issue whether top-down dimensional set influences inter-trial effects in compound searches in a similar fashion as in simple-detection tasks.

4.1. Electro-cortical evidence for expectancy-driven modulations of pre-attentive processing

At the electrophysiological level, targets defined in semantically pre-cued dimensions induced significantly shorter PCN latencies compared to targets defined in uncued dimensions. Recall that the latency of the PCN component provides a marker of the transition between pre-attentive processing and the attentional stage of target selection (Töllner et al., 2008; see also Luck et al., 2006), thus reflecting the efficiency of pre-attentive coding processes. Importantly, there was no indication of a dimensional cueing effect acting at later post-selective stages, as there were no modulations in the timing and activation of the (stimulus- and response-locked) LRP. If anything, there was a numerical difference between validly and invalidly cued dimensions in the stimulus-locked LRP onset latencies, which was of exactly the same magnitude (11 ms)⁵ as the PCN latency difference between the two cue conditions. Note, however, that these latencies inherently include any pre-selective processing differences between conditions because they encompass both the time required for attentional target selection and that for post-selective stimulus–response mapping. Thus, when subtracting the PCN latencies from the stimulus-locked LRP latencies, there were no additional contributions left over at the levels of post-selective stimulus analysis and response selection.

Accordingly, our results provide unequivocal evidence in favor of top-down influences operating on pre-attentive stages of processing. In terms of the DWA, faster PCN latencies originate from enhanced coding of feature contrast within the pre-cued dimension, which in turn speeds up the accrual of above-threshold activation at the master map level. Importantly, this implies that observers are able to intentionally shift processing resources to the dimension indicated by the cue, modifying the initial weight distribution across dimensions at the sensory-coding level. In any case, the systematic, dimension-related variations in PCN latencies revealed in the present study are at variance with the alternative, response-related views (e.g., Cohen & Feintuch, 2002; Theeuwes et al., 2006), which strictly deny the possibility of expectancy-based influences at the level of pre-attentive processing.

This electrophysiological evidence for pre-attentive modulations by dimensional cues (and changes of the target dimension) is consistent with data from a recent signal detection study of the dimensional cueing effect (Zehetleitner et al., submitted for publication). In principle, the effect of dimensional cues on RTs (as in Müller et al., 2003; Müller & Krummenacher, 2006) can originate from pre-attentive as well as post-selective processing stages (Santee & Egeth, 1982). However, in a signal detection task with short presentation times (and without emphasis on response speed), only pre-attentive differences in processing would lead to modulations of accuracy. In accordance with the DWA, Zehetleitner et al. (submitted for publication) found valid (as compared to invalid) dimensional cues to increase 'sensitivity' in a pop-out binary localization (left vs. right hemi-field) task. This lends further support to the view that intentional preparation for a specific dimension increases pre-attentive processing efficiency.

Furthermore, our line of arguments is consistent with an fMRI study by Weidner, Pollmann, Müller, and von Cramon (2002), which showed that top-down factors play a role in modulating the dimension-specific allocation of attentional resources. Weidner et al. (2002) compared singleton feature search tasks with singleton conjunction search tasks, in which the target was defined by a specific cross-dimensional feature combination (size with color or size with motion direction). While the primary target-defining dimen-

sion (size) was set to remain constant, the secondary dimension (color or motion direction) could vary unpredictably across trials (cross-dimension search condition). Weidner et al. reasoned that, if observers intentionally weighted the (100% predictive) size dimension, less weight would be available to be assigned to the secondary target-defining dimensions. Consequently, the cost of changing the secondary dimension should be more pronounced in conjunction search than in feature search tasks (for color- and motion-direction defined targets). Exactly this behavioral pattern was observed by Weidner et al. (with dimension change effects being some four times larger in the conjunction search task). Furthermore, the fMRI data revealed a double dissociation in anterior prefrontal cortex accompanying dimension changes: for more stimulus-driven searches (feature task), selective activations associated with dimension changes were observed in the left frontopolar cortex, but not in left frontomedian cortex (pregenual anterior cingulate cortex, BA32/24); this pattern was reversed for more top-down controlled searches (conjunction task). Thus, these areas seem to be involved in the control of dimensional weight setting (see also Pollmann, Weidner, Müller, & von Cramon, 2000, 2006; Gramann et al., 2007), that is: the detection of a change and the initiation of a re-weighting process adjusting the dimensional weights to the new stimulus conditions. While this may be performed relatively automatically in singleton feature search tasks (in which observers are not normally able to report the target-defining properties explicitly; see Müller, Krummenacher, & Heller, 2004), it requires more active control in singleton conjunction search tasks (where observers invariably encode the target-defining properties into short-term memory; Weidner & Müller, 2009).

Finally, the results presented above are consistent with a recent ERP study by Eimer and Kiss (2008) (see also Kiss, Jolicoeur, Dell'Acqua, & Eimer, 2008), which likewise used the PCN as a marker of selective attentional processing in order to investigate whether attentional capture by salient visual events is triggered purely in a bottom-up fashion, or whether it depends on current (top-down) task sets. In this study, participants had to respond to the orientation of a target bar, which was preceded by a spatial-cue display in which an odd-one-out (color, form, or size) item indicated the position where the upcoming target would appear. When the target was presented amongst distracters, Eimer and Kiss found a marked behavioral spatial-cueing effect accompanied by a cue-induced PCN component. However, when the target appeared without distracters, the physically identical cues failed to facilitate target detection and no cue-induced PCN was elicited. Thus, this pattern demonstrates that attentional capture is strongly dependent on the current task set, indicating that top-down intentions modulate bottom-up encoding processes.

4.2. Electro-cortical dissociation of visual dimension changes and motor response changes

The inter-trial transition ERP effects observed in the present cueing task are in close resemblance to those reported for feature singleton searches (Töllner et al., 2008): changes (vs. repetitions) of the target-defining dimension across consecutive trials were reflected in delayed latencies of the PCN component, irrespective of whether or not the motor response was changed; by contrast, motor response changes (vs. repetitions) were associated with enhanced response-locked LRP amplitudes, whatever the dimensional inter-trial history. This electro-cortical dissociation clearly contradicts the notion (of, e.g., Theeuwes et al., 2006, and Cohen & Magen, 1999) that *dimension-specific* inter-trial effects originate exclusively from post-selective, response-related processes. As evidenced by the systematic dimension-based PCN latency variations, pre-attentive processing speed for semantically pre-cued targets differs with respect to the dimensional identity of the preceding

⁵ Note that, due to temporal 'smearing', ERP latency differences should not be regarded as representing the 'true' extent of underlying processing differences.

target, consistent with the view that dimension-specific saliency computations are modulated by the (competitive) assignment of weights based on the inter-trial target history.

Also of theoretical importance is the finding of the second inter-trial effect, namely, systematic response-based enhancements of LRP amplitudes owing to motor response changes. This demonstrates a role of the response production stage in the times required to respond to dimensionally pre-cued pop-out signals, and emphasizes that it is not sufficient to solely consider perceptual and/or response selection processes when decomposing RT differences between experimental conditions. As for visual dimensions (and perceptual modalities; see Töllner, Gramann, Müller, & Eimer, 2009), this LRP amplitude effect might represent an implicit update mechanism that keeps track of the prevailing motor action in order to optimize processing at the (later) motor-response production stage. Specifically, repetitions of the motor response on consecutive trials might benefit from residual activations from the previous trial biasing the correct response. By contrast, changing the motor response across trials might involve a shift of motor activity between the hemispheres in order to drive the required motor signal above threshold. While the present study shows unequivocally that pre-attentive (visual) dimension-specific coding processes are cognitively penetrable (independently of dimension-based inter-trial dynamics; but see footnote 3), the question arises whether an analogous pattern of *expectancy-based* motor activations (which do not interact with effector-specific inter-trial dynamics) might be observed for motor-response production. However, this remains an open issue to be addressed in future research. In any case, traditional models of visual search performance (such as GS and the related DWA) need to be augmented in order to accommodate the motor-action-specific inter-trial dynamics contributing to the behavioral detection of (dimensionally pre-cued) pop-out signals.

5. Conclusion

In summary, the present study provides electrophysiological evidence for expectancy-driven modulations of pre-attentive processing. PCN latencies systematically varied as a function of cue validity, revealing a pre-attentive perceptual locus of the dimensional cueing effect. This demonstrates that participants are able to (top-down) set themselves to a specific target dimension, thereby modulating pre-attentive processing speed. However, as indicated by the dimension-specific inter-trial PCN activations, these top-down adjustments cannot completely overwrite automatic dimension-based weighting processes.

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