Brief communication

Electrophysiological correlates of detecting a visual target and detecting its absence: The role of feature dimensions

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ABSTRACT

Electrophysiological measurements were taken from observers performing a visual search within a single feature dimension, and between multiple dimensions. The N2pc to selected singleton target stimuli (rightward tilted lines) was increased when targets varied between feature dimensions, compared to the N2pc to the same rightward tilted line targets, in a condition in which targets varied only between feature values within the same dimension. The anterior and posterior N2 were not reliably modulated, but P3(b) amplitude was higher for singleton present trials that varied between dimensions than for those that varied within. The ERP elicited by singleton absent trials showed reduced P3 amplitude in the between-dimension condition. The electrophysiological modulations were accompanied by increased reaction times in the between-dimension condition, on both singleton present and absent trials. The results suggested that visual target detection is affected by early dimension-specific weighting of the current attentional task set. Furthermore, exhaustively searching multiple feature dimensions to determine the absence of a target incurs dimensional switching costs, possibly at a later stage.

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Aspects of attention and perception in the visual domain have been productively investigated with visual search tasks, in which observers are asked to detect the presence of target stimuli amidst distractors (see Wolfe, 1998; Wolfe & Horowitz, 2004, for reviews). Behavioral performance on such tasks, that is, reaction time and report accuracy, has been shown to depend on a multitude of factors, but one particularly salient factor is the feature dimensionality of the stimulus displays. The dimensionality is determined by the number of feature dimensions (e.g., color or shape) that pertain to the stimuli. The principal finding is that singleton search is faster and more accurate when target stimuli are defined on the same feature dimension, compared to when they are defined on multiple dimensions. For example, if an observer is looking for a red singleton stimulus in a search task, this is easier if the possible search arrays only contain singletons defined in the color dimension (e.g., red and blue singletons), compared to when these contain singletons also defined on other dimensions (e.g., color and shape singletons). This has been explained by the need to weigh the priority of each of the feature dimensions in the latter case (Found & Müller, 1996; Müller, Heller, & Ziegler, 1995).

Some debate has arisen on the temporal locus of dimension weighting in the visual processing system, with some authors arguing it affects early (even "pre-attentive") stages (Müller, Reimann, & Krummenacher, 2003), and others arguing that it does not (Theeuwes, Reimann, & Mortier, 2006). To address this issue, electrophysiology is an ideal method, as it can precisely localize the dimensional weighting process in time, and thus several recent studies have employed it. Gramann, Töllner, Krummenacher, Eimer, & Müller (2007) showed that the anterior N2 (N2a) component of the event-related potential (ERP) was more negative for trials on which a dimensional change had to be made than for trials on which the relevant dimension was a continuation of the previous trial. The N2a component has been associated with executive control processes (see Folstein & van Petten, 2008, for an overview). The results of Gramann and colleagues suggested that such control is involved in switching attention from one feature dimension to another, a notion compatible with a degree of top-down control over this early process. In other studies, Töllner and colleagues showed that N2pc (N2 posterior contralateral; Luck & Hillyard, 1994) amplitude was slightly lower, and also peaked slightly later, for dimension changes, and that validly cued dimensions increased N2pc amplitude (Töllner, Gramann, Müller, Kiss, & Eimer, 2008; Töllner, Zehetleitner, Gramann, & Müller, 2010). The N2pc is thought to reflect the attentional processing of features at a lateralized position in the visual field (e.g., Kiss, van Velzen, & Eimer, 2008; Schubö & Müller, 2009). Modu-

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lations of this component thus seem to indicate a change in such relatively early feature-specific processing due to dimensional processing.

Priming and cueing effects, as described above, provide a straightforward index of dimensional switch costs, or the effort of adjusting dimension-specific weights. The implementation of a cognitive task set that specifies the parameters of the search that is to be performed by the observer is implicit in these designs. The current study was meant to address task set implementation explicitly. Thus, the study aimed to establish whether implementing single- and multi-dimensional task sets during visual target detection also affects early visual processing stages, as observed for dimensional cueing and switching. In the present experiment, observers were asked to look for singleton target stimuli in circular arrays of short vertical line elements, and to perform a simple target-present/absent judgment on each trial. In one task condition of the experiment, targets varied within the single feature dimension of line orientation: Targets consisted of tilted lines of various (non-vertical) inclinations. In the other task condition, targets varied between dimensions: Targets consisted of size, luminance, and orientation singletons. ERPs and reaction times were recorded to both target-present as well as target-absent trials.

1. Method

1.1. Participants

Sixteen right-handed students (11 female, 5 male) at the Ludwig Maximilian University Munich participated for course credit or monetary payment. Visual acuity was verified with a Rodenstock R12 vision tester (stimuli #112). Participants were unaware of the purpose of the experiment and had not taken part in other visual search experiments in the lab before. Mean age was 24.6 years (range 20–34 years).

1.2. Apparatus and stimuli

Participants were individually seated in a comfortable chair in an electrically shielded and sound attenuated testing chamber that was dimly lit. Stimuli were presented on an Iiyama 20 in. CRT screen, refreshing at a frequency of 60 Hz, which was placed at 100 cm distance directly in front of the participants. Search displays consisted of an array of dark blue vertical lines (luminance = . 6 cd/m², CIE xy coordinates: $x = .215$, $y = .165$) on a gray background (luminance = 10.9 cd/m², $x = .281$, $y = .366$). The lines were arranged on four invisible concentric circles with a diameter of 2.9°, 4.5°, 6.3°, and 8.0° that were centered on the screen. On these four circles 8, 10, 12, and 16 lines were evenly distributed, starting at 10°, 26°, 15° and 5° (respectively) clockwise from the 12-o'clock position. Each line was approximately 0.69° in length and 0.09° in width. Depending on the trial type, the arrays consisted of vertical lines only (singleton absent trials), or contained a target stimulus (singleton present trials). In the within-dimension condition, the singleton could be a horizontal, a leftward tilted (−45° from the vertical abscissa) or a rightward tilted (+45°) line. In the between-dimension condition the singleton could be a double-width line (size), a brighter blue line (luminance = 9.1 cd/m², $x = .41$, $y = .345$), or a rightward tilted line
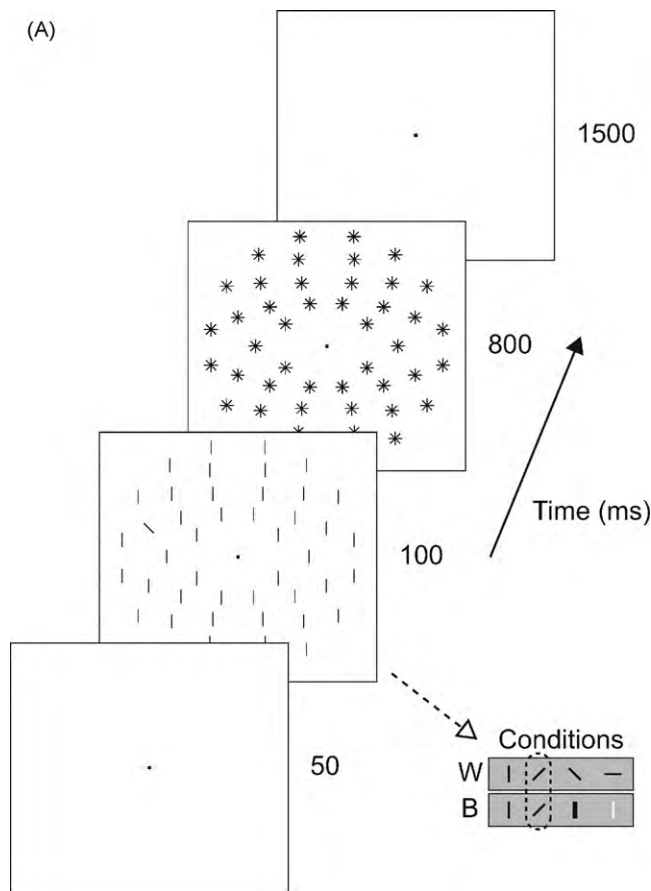

Fig. 1. (A) The experimental procedure. After a 50 ms fixation dot, the search array is displayed for 100 ms. On singleton present trials, one distinctive stimulus is shown in an otherwise uniform array of vertical line elements. Singleton absent trials consisted of vertical lines only. A masking array ensued for 800 ms, in turn followed by the fixation dot for another 1500 ms. As shown, conditions were implemented as follows: (1) The within-dimension (W) condition featured either no singleton (depicted by a vertical line), a rightward tilted line, a leftward tilted line, or a horizontal line. (2) The between-dimension (B) condition featured either no singleton, a rightward tilted line, a thick vertical line, or a brighter vertical line.
(B) Waveforms recorded at the POz, FCz, and Pz electrodes (in μV), as well as N2pc contra-minus ipsilateral difference waveforms recorded from PO7/PO8 (ΔμV). For POz, FCz, and Pz, singleton absent trials are represented by thin lines, and singleton present trials by thick lines. For the Pz (singleton present trials only) and PO7/8 figures on the right, thin lines represent slow trials and thick lines represent fast trials. The between-dimension condition is represented by dashed lines, and the within-dimension condition by solid lines. Stimulus onset is set at 0 ms. Current source density plots are shown for the P3, N2pc and N1 time-windows. The maps represent a spherical spline interpolation of a 20 ms average. Conditions represented on each map from left to right are: Singleton absent between-dimension, Singleton absent within-dimension, Singleton present between-dimension, and Singleton present within-dimension.
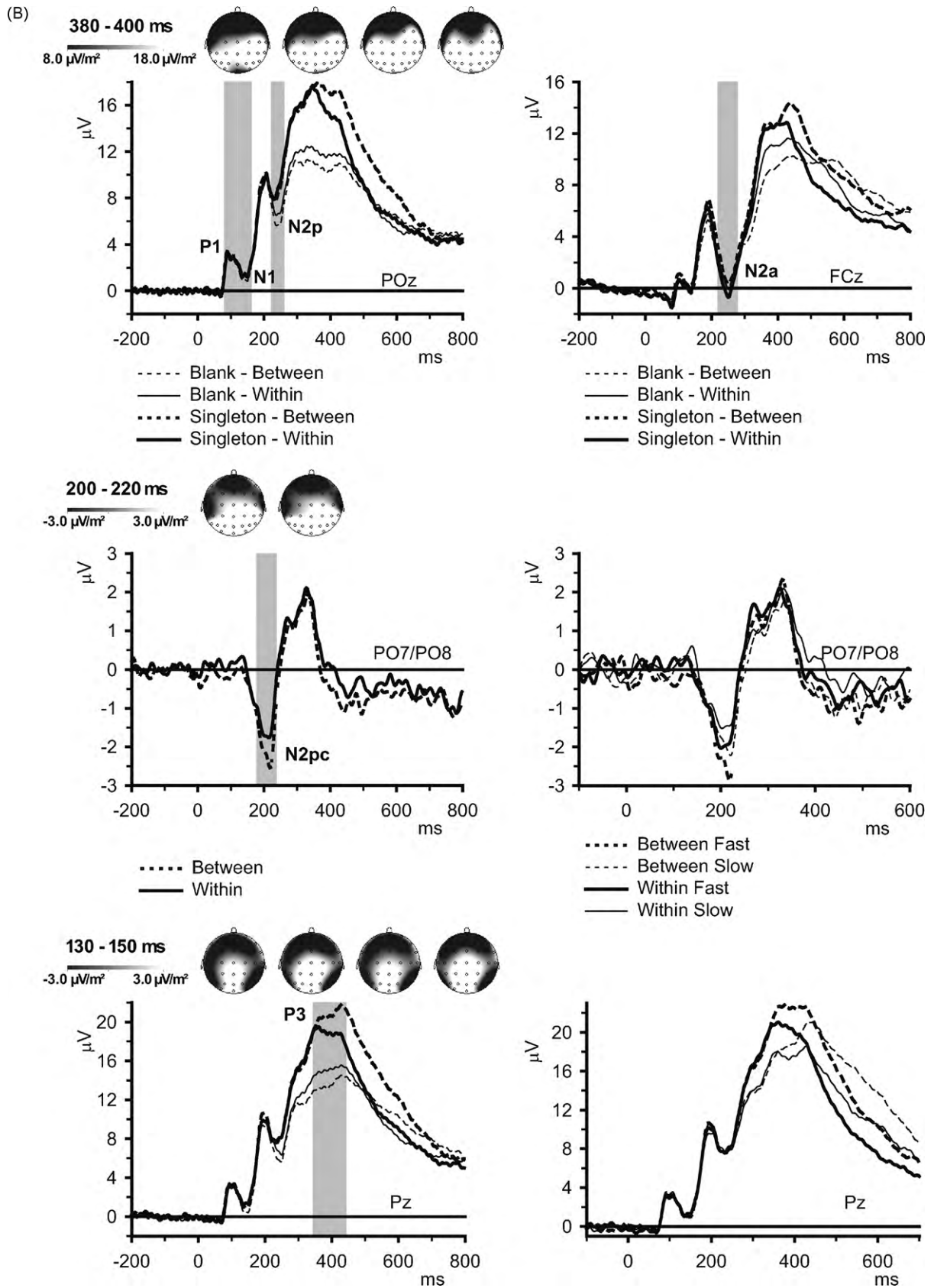
(B)

Fig. 1. (*Continued*)

(again + 45° from the vertical). The singleton stimulus appeared with equal probability on one of four possible target positions on the third circle (with a diameter of 6.3°); one in each quadrant with an eccentricity of 3.1°. Masking displays were constructed by superimposing the vertical line and the three other orientations for each line on the display, resulting in an array of star-like elements which appeared at the same positions as the lines in the search array. Each of these masks covered an area of about 0.69° by 0.74°. A jitter was imposed on both the search stimuli and their masks so that each element was randomly displaced between zero and three pixels in all four directions. The fixation point subtended a visual angle of approximately 0.46° by 0.46°.

1.3. Procedure and design

Trials were randomly distributed over two sets of 12 blocks, one set for each of the within- and between-dimension conditions. The order of these conditions was counterbalanced across participants. Each block consisted of 72 trials. Half of the trials were target-present trials and each kind of target singleton had an equal probability to occur. At the beginning of each set of experimental blocks, a training block of 144 trials was run to familiarize participants with the task. Each trial started with a 50 ms fixation point in the center of the screen, which remained visible throughout the trial. The search array was then displayed for 100 ms and covered by the mask array which remained on the screen for 800 ms before disappearing so that only the fixation point remained for another 1500 ms, after which the next trial began. Fig. 1A shows a schematic representation of the trial structure. Response time and accuracy were registered on a custom response pad connected to the parallel port of the PC. The pad could be operated with the fingers of one hand. The assignment of target present and absent responses to the buttons of the pad was counterbalanced between participants (i.e., left key = present, right key = absent, and vice versa). Responses below 100 ms and above 1200 ms were discarded (4.6%).

1.4. Electrophysiological recording and data analysis

Ag–AgCl electrodes recorded the EEG from 64 positions that were laid out in an elastic cap according to the extended international 10–20 system. The electrodes were referenced to Cz and re-referenced offline to the average of both mastoids. Horizontal and vertical EOG were recorded from electrodes near the outer canthi of the eyes, and above and below the left eye. Impedances were kept below 5 kΩ. The amplifier used a 0.1–125 Hz band-pass filter. EEG was digitized at a frequency of 500 Hz.

The data were filtered off-line with a 40 Hz lowpass filter. Trials that showed amplitudes exceeding ±80 μV, voltage steps exceeding ±50 μV between two sampling points, or voltages lower than 0.10 μV for a 100 ms interval were excluded from further analysis. Ocular artifacts (blinks and eye-movements) were corrected by applying the Gratton–Coles procedure (Gratton, Coles, & Donchin, 1983). Baseline correction was done using a 200 ms pre-stimulus interval. EEG was averaged off-line in 1000 ms epochs, starting 200 ms prior to the onset of the search array and ending 800 ms afterwards. Only trials with correct responses were considered.

For the electrophysiological analyses, two participants (1 female and 1 male) were excluded because of excessive artifacts in the data. Repeated measures analyses of variance (ANOVAs) were performed separately on the target-absent trials and the rightward singleton stimuli that were physically identical and equally frequent in the two experimental conditions. The other singleton stimuli were thus excluded from the analysis. This comparison was purposefully chosen to isolate the effect of just the experimental manipulation on the ERP, and to avoid confounds due to stimulus features. The analyses thus had one within-subject variable: Dimension (within and between). The ANOVAs were performed for mean amplitude values in the following time windows: P1 (80–120 ms after stimulus onset), N1 (120–160 ms), N2pc (180–240 ms), N2p (220–260 ms), N2a (220–280 ms), and P3 (340–440). The following electrodes were selected, in line with standard practice: POz (P1, N1, and N2p), PO7/PO8 (N2pc), FCz, (N2a), and Pz (P3). To compute the N2pc, ipsilateral waveforms (i.e., recorded from the left hemisphere electrode site when the singleton was in the left visual field, and the same for the right hemisphere site and right visual field) were subtracted from contralateral waveforms (i.e., left site and right visual field, and right site and left visual field). The singleton absent trials were not used in the analysis of the N2pc, since these do not feature lateralized stimuli of interest.

2. Results and discussion

2.1. Behavior

Accuracy on singleton present trials was affected by Dimension, $F(1, 15) = 35.40$, $MSE = .002$, $p < .001$. Average accuracy in the within-dimension condition was 96.2%, compared to 90.5% in the between-dimension condition. On the singleton absent trials, a numerical difference in the same direction was not quite reliable (within 97.2%; between 96.3%, $F < 2.8$). Reaction time analyses of

the singleton present trials showed a main effect of Dimension, $F(1, 15) = 9.12$, $MSE = 1426.42$, $p < .01$. Reaction times within-dimension were faster (420 ms) than reaction times between-dimension (444 ms). As an extra step, the data selected for the electrophysiological analyses (i.e., rightward tilted singletons) were examined separately, and these also showed a reliable effect of Dimension, $F(1, 13) = 5.01$, $MSE = 618.62$, $p < .05$, with mean reaction time averaging 414 ms within-, and 435 ms between-dimension. Dimension also affected the singleton absent trials, $F(1, 15) = 4.82$, $MSE = 742.95$, $p < .05$. The singleton absent trials averaged 450 ms within-, and 471 ms between-dimension. As would be expected, this pattern replicated the findings of Müller et al. (1995).

2.2. Electrophysiology

For both singleton absent and singleton present trials, the analyses of the P1 and N1 components did not show any reliable effects ($Fs < 1.1$). The N2pc was the earliest component to show an effect of Dimension, $F(1, 13) = 10.27$, $MSE = .206$, $p < .01$. The N2pc to the target singleton was larger in the between-dimension condition than in the within-dimension one (-1.93 μV and -1.38 μV, respectively). To check whether the underlying waveforms indeed reflected a proper N2pc, an analysis was carried out across electrode position and visual field side. Neither of these had a reliable effect on its own, but their interaction was highly significant, $F(1, 13) = 42.28$, $MSE = .904$, $p < .001$, as would be expected for an N2pc component.

For the N2p, the analysis of the singleton present trials did not reveal a significant effect ($F < 1$), but there was a marginally significant effect for the singleton absent trials, $F(1, 13) = 3.35$, $MSE = 1.515$, $p < .09$. N2p component amplitude was more negative for the between-dimension condition (6.27 μV, compared to 7.12 μV). The N2a was not affected by Dimension ($Fs < 1.9$).

Dimension clearly affected the P3, for both singleton absent trials, $F(1, 13) = 6.48$, $MSE = 2.370$, $p < .05$, and singleton present trials, $F(1, 13) = 5.81$, $MSE = 3.432$, $p < .05$. These effects were different, however, and an overall analysis of Dimension across both singleton present and absent trials showed a clear interaction effect, $F(1, 13) = 27.70$, $MSE = 1.268$, $p < .001$. While P3 amplitude was higher in the within-dimension condition (15.04 μV), compared to the between-dimension condition (13.56 μV) on singleton absent trials, the pattern was reversed for the singleton present trials (18.90 μV within, and 20.58 μV between). Given that the effect on the singleton present trials was most prominent in the later part of the component, and that the singletons were all task-relevant, this modulation seemed related to the P3b, rather than the P3a (or novelty P3; see Polich, 2007). Fig. 1B shows the waveforms recorded at the POz, FCz, and Pz electrodes, and the N2pc difference waves computed from the PO7/PO8 electrode pair.

2.3. Analysis of behavioral effects on electrophysiology

In order to investigate the potential effects of generic task difficulty on the ERP components, the data were divided by a median split of reaction times. For each participant, and for each experimental condition, the median RT served as the cut-off mark between high and low RT trials, which were then entered into an ANOVA with the additional variable of Speed (high or low). Analyses were run for those components that showed (nearly) significant effects of Dimension only.

The N2pc was only marginally affected by Speed, $F(1, 13) = 4.12$, $MSE = .476$, $p < .06$. N2pc amplitude was higher when RT was low (-1.81 μV), than when it was high (-1.44 μV). There was no sign of an interaction with Dimension ($F < 1$). The middle and lower right panel of Fig. 1B shows P3 (singleton present trials only) and N2pc amplitude split between high and low RT trials. The effect of Speed

on the N2p (singleton absent trials) was also unreliable ($F < 1.7$), as was its interaction with Dimension ($F < 1$). Finally, on the P3, the effect of Speed became more pronounced. On the singleton present trials, P3 amplitude was 21.20 μV on fast trials, compared to 18.33 μV on slow trials, $F(1, 13) = 26.69$, $MSE = 4.306$, $p < .001$. The interaction with Dimension was again unreliable ($F < 1.6$). On the singleton absent trials, Speed had a significant effect, $F(1, 13) = 33.97$, $MSE = 3.066$, $p < .001$. P3 amplitude was 15.69 μV on fast trials, compared to 12.96 μV on slow trials. The interaction effect was once again insignificant ($F < 1$).

Taken together, the observed effects of Speed seemed to be additive to the effects of Dimension. The effect of Speed was only truly reliable on the P3, and in all cases there was no hint of any interaction with Dimension. Thus, although task difficulty as indexed by RT did influence the ERP to a degree, it did not confound the interpretation of the Dimension effect.

3. General discussion

The present study demonstrated how the dimensionality of a visual search task affects the detection of a target stimulus and the detection of its absence in different ways. Singleton detection on target-present trials was shown to be faster in the within-dimension condition than in the between-dimension condition, and the underlying ERP showed distinct modulations. Between-dimension singletons elicited increased N2pc and P3(b) components. The involvement of the N2pc suggests that the dimensionality of the search task affects early feature-specific processing stages of the attentional system (Akyürek, Dinkelbach, & Schubö, 2010; Kiss et al., 2008; Schubö & Müller, 2009). Although the N2pc is a relatively early component (peaking at just over 200 ms in the present study), and although it preceded the N2a and N2p components in time, there was no evidence for an even earlier locus of modulation on the P1 and N1 components, suggesting that the earliest deployment of attention might not be strongly sensitive to feature dimensionality.

Higher N2pc amplitude has been taken to reflect increased processing (Eimer, 1996), or filtering (Luck & Hillyard, 1994). In this framework, the present results could also fit: The singletons required more intensive processing at a relatively early stage when multiple feature dimensions were relevant for the search task. In other words, if N2pc amplitude is taken to indicate how much focal attention is necessary to discern a target, then more attention is necessary in the between-dimension condition than in the within-dimension condition. This may be the case because in the latter condition the selection criterion is set at a finer resolution, that is, at the level of specific feature values (e.g., blue vs. red) rather than whole dimensions (color vs. shape). Thus, the identification of a specific feature value in the within-dimension condition required the attentional monitoring of just a single dimension, whereas multiple dimensions had to be attended to in the between-dimension condition. Note that this does not necessarily imply that feature-based attention starts at the N2pc. There is indeed evidence that feature-based attention can modulate even the P1 (Zhang & Luck, 2009).

The dimensional modulation of the P3 on target-present trials could mean that memory was involved in the application of the task set, a view supported also by previous behavioral data that have shown effects of implicit and explicit memory on dimensional switching (Müller, Krummenacher, & Heller, 2004), and previous work that has related the P3 to memory processes or context updating (Donchin & Coles, 1988; Polich, 2007). P3 amplitude can also be taken to reflect attentional resources, when task conditions in general (i.e., a simple detection task) are relatively undemanding (Polich, 2007). In this case, the increased P3 in the present study could be taken to reflect that search between multiple dimensions

required more effort because a somewhat more complex task set had to be established. Further alternative interpretations of the P3 are of course conceivable, one of which is that the component reflects a monitoring process that mediates between perception and action (Verleger, Jaśkowski, & Wascher, 2005). Although it seems more difficult to interpret the current modulation in those terms, the data do not speak strongly in favor of one particular functional role of the P3.

Search during singleton absent trials resulted in a markedly different modulation of the ERP. Similar to the singleton present trials, singleton absence in the within-dimension condition was detected as such faster than in the between-dimension condition. As has been observed before, it seemed to be easier to consider a single dimension for the absence of salient stimuli, than to do the same for several dimensions (e.g., Müller et al., 1995). In the ERP analyses, there was some evidence for an increased negativity starting at the N2p, although this was only a marginal trend. However, the negativity also reliably affected P3 amplitude later on, resulting in higher amplitude to singleton absent trials in the within-dimension condition. The comparatively early decrease of P3 amplitude was not observed on target-present trials, on which P3 amplitude was enhanced. This leads to an important qualification of these modulations: The interaction between dimensional complexity of the task and the processing of a *target* results in increased P3 amplitude, while target-absent search that does not require this stimulus-related processing does not similarly modulate P3 amplitude. Consequently, the negativity that had started at the N2p was able to carry over into the P3 time range in target-absent trials. Although P3 amplitude was thus modulated differently for singleton present and absent trials, RT was faster for both in the within-dimension condition. This might be explained by thinking of the P3 modulations as reflecting two different routes of processing, which still result in a comparable time of arrival when the response is due. These two routes reflect differences in search between singleton present and singleton absent trials. Specifically, in the latter type of trials, the search array is special in that it is perfectly homogeneous. This has been found to allow processing of the array as a single unit, leading to differences in RT and N2 amplitude (Duncan & Humphreys, 1989; Schubö, Wykowska, & Müller, 2007). Of course, this account is speculative at this point.

The present results highlight some differences with previous studies on inter-trial dimensional switching (Gramann et al., 2007; Töllner et al., 2008). First, the N2a component was not reliably modulated in the present study. If the N2a can be taken to reflect executive control processes, it may be expected that this component should be modulated particularly when an active switch has to be carried out (as in Gramann et al., 2007). The general implementation of a particular task set, as investigated in the present study, does not necessarily require the active involvement of such executive control. To get an index of the N2a dependent on active dimension switching, an analysis of dimension switch and continuation trials was made even though the experiment was not designed for such a comparison (i.e., it had block-wise conditions and a fully random trial sequence). This analysis nonetheless replicated the reduced N2a for between-dimension trials reported by Gramann et al. (2007), averaging .63 μV in the within-dimension condition, and 1.34 μV in the between-dimension condition. It has to be noted that this trend was not reliable statistically ($F = 1.19$, $p > .29$), which was likely due to the limited number of trials available for this analysis. In any case, these preliminary findings do confirm that dimensional switching and task set processing can have separable effects.

Second, the N2pc modulation observed previously by Töllner et al. (2008) pointed towards slightly decreased N2pc amplitude for switch trials, and slightly later peak amplitude, as compared to

no-switch trials. In the present study, N2pc amplitude was relatively strongly increased in the between-dimension condition, but a latency change was not apparent. These findings can be reconciled when one considers the underlying logic of these studies. Töllner and colleagues measured inter-trial priming, and as such the reduction in N2pc can be understood as an expression of the costs associated with making a dimensional switch. In the present paradigm, such switch costs were not measured directly, but rather the implementation of a multi-dimensional task set. The modulation of the N2pc in this case may be understood as a shift in the 'baseline' activity needed to perform the task. On the trial-level, deviations from this baseline may occur when actual dimensional switches are required. For the research question of the present study, these potential deviations were not targeted and indeed cannot be reliably investigated, as this would have required a trial sequence balanced for inter-trial contingencies. Even though a preliminary analysis of the N2a was still possible (see above), the number of trials available was not sufficient to perform an N2pc analysis, as this component requires a higher signal to noise ratio to investigate reliably.

In summary, when a visual search task involves multiple feature dimensions, increased attentional processing of stimulus features, as expressed by N2pc amplitude, is elicited. When a target singleton is present, the subsequent processing (or hypothetically, consolidation) effort, expressed by P3(b) amplitude, is affected in the same way. However, when no target is present, this later modulation is not observed, and P3 amplitude is reduced as a consequence of the onset of a negativity in the N2p time range. These modulations can be taken to reflect the implementation of single- and multi-dimensional task sets, which are separately observable, similar to (and presumably alongside) trial-level dimensional switch costs.

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