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RESEARCH****Research Report****Detecting pop-out targets in contexts of varying homogeneity: Investigating homogeneity coding with event-related brain potentials (ERPs)***Anna Schubö\**, *Agnieszka Wykowska*, *Hermann J. Müller**Department of Psychology, Ludwig Maximilian University, Leopoldstr. 13, D-80802 Munich, Germany*

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## ABSTRACT

Searching for a target among many distracting context elements might be an easy or a demanding task. Duncan and Humphreys (Duncan, J., Humphreys, G.W., 1989. Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458) showed that not only the target itself plays a role in the difficulty of target detection. Similarity among context elements and dissimilarity of target and context are two main factors also affecting search efficiency. Moreover, many studies have shown that search becomes particularly efficient with large set sizes and perfectly homogeneous context elements, presumably due to grouping processes involved in target-context segmentation. Especially N2p amplitude has been found to be modulated by the number of context elements and their homogeneity. The aim of the present study was to investigate the influence of context elements of different heterogeneities on search performance using event-related brain potentials (ERPs). Results showed that contexts with perfectly homogeneous elements were indeed special: they were most efficient in visual search and elicited a large N2p differential amplitude effect. Increasing context heterogeneity led to a decrease in search performance and a reduction in N2p differential amplitude. Reducing the number of context elements led to a marked performance decrease for random heterogeneous contexts but not for grouped heterogeneous contexts. Behavioral and N2p results delivered evidence (a) in favor of specific processing modes operating on different spatial scales (b) for the existence of homogeneity coding postulated by Duncan and Humphreys.

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**1. Introduction**

There is a consensus that selective attention plays a central role for visual perception and visually guided action. However, exactly how visual attention works remains a matter of debate. Many theories of visual attention have been empirically tested using visual search paradigms (e.g., [Cave, 1999](#); [Found and Müller, 1996](#); [Treisman, 1988](#); [Treisman and Gelade, 1980](#); [Wolfe,](#)

[1994](#)). In visual search, observers are typically asked to look for a ‘target’ element that differs from the surrounding context, or ‘distractor’, elements in a particular visual feature (e.g., in a particular color or orientation), or in a combination of features. This resembles everyday situations where we search for a ‘relevant’ object among other, ‘irrelevant’ ones, for example, when looking for a friend in a crowd of people. Such a search task may be easy, for instance, when the target virtually ‘pops

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out' from the distractors based on its possessing a unique and 'salient' feature (e.g., the friend wearing a Mexican hat). In other cases, the search may be hard, requiring attentional processing, with the time taken to find the target increasing with the number of distractors. To describe the continuum of search difficulty, Wolfe (1998) suggested using the term 'efficiency'.

While classical search theories focused mainly on the target and its defining features, Duncan and Humphreys (1989) argued that the context elements must be taken into consideration as well. According to their *attentional engagement theory*, search efficiency is influenced by two factors: (i) the similarity between the target and context elements and (ii) the similarity among the context elements themselves (Duncan and Humphreys, 1989, 1992; Humphreys et al., 1989). They proposed that, at an early 'parallel' stage of visual coding, the input array is segmented into structural units at various spatial scales, based on the operation of elementary segmentation and grouping principles. These units form the input for the subsequent stage where selective-attention 'weights' are assigned based on a two-fold process. First, elements are weighted according to the degree to which they match the pre-specified target description (the target 'template'). Second, weights are spread across elements linked together at the preceding segmentation stage. Due to the first weighting process, search efficiency is influenced by the ease with which the target element can be classified as a target (and distinguished from the context elements): increasing the similarity between the target and context elements decreases search efficiency because distractors receive weights approaching that assigned to the target. As a result of the second weighting process, search efficiency is also dependent on the similarity among the context elements: similar elements allow for a 'stronger' linkage; hence, increasing the similarity of context elements increases search efficiency because grouped context elements can be rejected as a whole, that is, as a single unit. Note that both weighting processes – weighting with respect to target template matching and weight linkage among grouped elements – are assumed to operate at the same time and contribute both to search efficiency.

Duncan and Humphreys (1989) pointed out a special case in visual search, namely, conditions in which all context elements are perfectly homogeneous. In this case, all (similar) display elements are grouped together to form one unit and search can operate directly on the whole search array. That is, the whole array can be matched as a group with the target template (instead of matching single elements or groups of elements separately). Any dissimilarity detected at this whole-array level (on target-present trials) would automatically indicate target presence (homogeneity coding, Duncan and Humphreys, 1989).

Meinecke and Donk (2002), using a simple line orientation pop-out detection task, also found detection performance to be superior when targets were presented within a homogeneous context. They attributed this performance benefit to the operation of a special *irregularity detection* mechanism, which is sensitive to irregularities in otherwise homogeneous fields, as these indicate directly and unambiguously the presence of a target. This mechanism was assumed to be independent of other processes, such as spatial integration and visual grouping that may also operate on global aspects of

the stimulus display and could expedite target detection (e.g., Bacon and Egeth, 1991; Meinecke and Donk, 2002; Sagi and Julesz, 1987).

In a follow-up study, Schubö et al. (2004) found electrophysiological evidence for the notion of an irregularity detection process — in form of a posterior negative component in the time range 200–300 ms post stimulus, the so-called N2p (see also Berti and Schröger, 2006; Schlaghecken et al., 2001; Schubö et al., 2001). In more detail, Schubö et al. (2004) used a simple line orientation pop-out detection task (similar to Meinecke and Donk, 2002), varying the number of context elements presented simultaneously with the target. Event-related brain potentials (ERPs) were recorded and examined for target-present versus -absent trials and for contexts with varying number of elements. The N2p component was found to be increased for target-absent compared to target-present trials whenever the stimulus array contained  $\geq 45$  context elements. When the number of context elements was reduced to  $\leq 25$ , the differential N2p amplitude effect disappeared. Concomitantly, search performance (measured in terms of both accuracy and response times) deteriorated as the number of context elements decreased (for similar results, see Bacon and Egeth, 1991; Bravo and Nakayama, 1992; Meinecke and Donk, 2002; Nothdurft, 2000; Sagi and Julesz, 1987). In other words, search efficiency benefited from an increase in the number of context elements, likely due to a switch in processing modes towards one based on global aspects of the stimulus array, established by earlier processes such as grouping (e.g., Bacon and Egeth, 1991, see also Pomerantz, 1981). The differential N2p amplitude effect (i.e., the larger N2p amplitude for target-absent compared to -present trials) was taken to reflect this switch in processing mode—as the effect became manifest only when the stimulus array contained a large number ( $\geq 45$ ) of context elements, with an increase in effect size when the number was increased beyond 45 (Schlaghecken et al., 2001; Schubö et al., 2001, 2004). However, as the context elements were always homogeneous in the above studies, the nature of the differential N2p amplitude effect remained unclear. Does it relate to a global processing mode in general, for example, one based on spatial integration? Alternatively, is it indicative of a special mechanism of 'homogeneity coding' (Duncan and Humphreys, 1989) or 'irregularity detection' (Meinecke and Donk, 2002), both suggested for the detection of targets embedded in homogeneous contexts?

The global processing mode may be regarded as a more general mechanism that comes into play whenever the context allows for processing at the level of larger units (i.e., with contexts that permit grouping or spatial integration). By contrast, homogeneity coding and irregularity detection may be considered as special cases of global processing (Duncan and Humphreys, 1989) or, alternatively, as being independent of this mode of processing (Meinecke and Donk, 2002). The latter two mechanisms come into play provided both that the search array affords processing at a more global level and that it is perfectly homogeneous (enabling a processing 'strategy' exploiting homogeneity). However, the notions of irregularity detection and homogeneity coding are not identical: while the former emphasizes the coding of targets as irregularities within homogeneous contexts, the latter focuses on the processing of

perfectly homogeneous search arrays (without any irregularities). That is, the strategy to solve the task is based either on detecting the target (i.e., ‘biased’ towards target-present decisions) or on rejecting the context elements (i.e., ‘biased towards target-absent decisions).

The homogeneity coding account predicts that target-absent decisions are made faster than target-present decisions (see, e.g., Humphreys et al., 1989); and in the Search-via-Recursive-Rejection (SeRR) model of Humphreys and Müller (1993; a connectionist implementation of attentional-engagement theory), target-present decisions are made following the rejection of similarity-grouped distractors. However, under typical pop-out search conditions, target-present responses are usually faster than target-absent responses (e.g., Wolfe, 1998). This could argue that some additional processes – such as irregularity detection – might be operating on target-present trials, compensating for the target-absent advantage resulting from homogeneity coding.

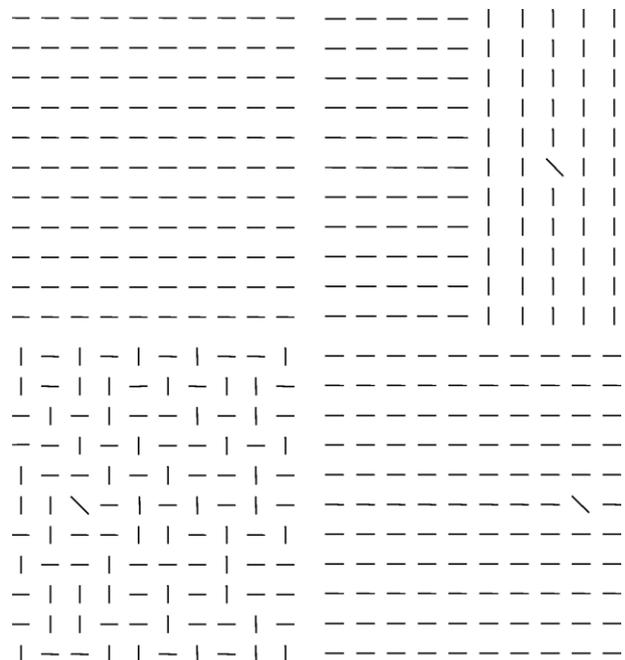
Event-related potentials may help to shed some light on this topic as ERP components also show modulations in the absence of RT effects (e.g., Schubö et al., 2001; Woodman and Luck, 1999). Besides the N2p described above, also the N2pc and the P3 component have been observed to be modulated in visual search tasks (e.g., Hopf et al., 2000; Luck and Hillyard, 1990; 1994a,b; Schubö et al., 2004; Wolber and Wascher, 2003). P3 amplitude was found to be enlarged for target-present compared to target-absent trials (Luck and Hillyard, 1990; Schlaghecken et al., 2001; Schubö et al., 2004; Wolber and Wascher, 2003). Although the precise role of the P3 in visual search is still under debate (e.g., Luck and Hillyard, 1990; Kok, 2001), it is generally considered to mirror task difficulty (see Kok, 2001 for a review). The N2pc (‘pc’=‘posterior contralateral’) is a negative voltage deflection in the N2 latency range observed at posterior-occipital electrode sites contralateral to targets or attended display elements (e.g., Luck et al., 1997; Luck and Hillyard, 1994a,b; Woodman and Luck, 2003). The N2pc has been found to be larger for targets surrounded by distracting context elements (Luck and Hillyard, 1994b) and larger in conjunction than in simple feature search (Luck et al., 1997)—and it has been considered to indicate focusing of attention (e.g., Hopf et al., 2000) or a shift of attention within the search display (Woodman and Luck, 1999, 2003). Assuming that the N2pc reflects attention being focused on a single (target) element in the search display, differential N2pc effects may indicate differences in the allocation of attention to targets embedded in contexts of varying homogeneity.

### 1.1. Rationale of the experiment

The aim of the present study was to empirically distinguish the three mechanisms considered above – global processing, irregularity detection and homogeneity coding – by examining the impact of different types of contexts on search efficiency while recording ERPs. Following Duncan and Humphreys’ arguments, contexts composed of different types of elements (heterogeneous contexts) were expected to influence target detection in a different manner to contexts consisting of the same elements only (homogeneous contexts). Specifically, it was investigated whether perfectly homogeneous contexts would trigger a different processing mode compared to more

heterogeneous contexts and whether these differences would be reflected in ERP components recorded in target-present and target-absent trials.

Observers were asked to search through arrays of different contexts and decide whether or not these contained a target. While the target was kept constant across different search displays, the surrounding context varied. The target was always an oblique line element presented in a context of vertical and/or horizontal line elements. Context elements could either consist of the same type of elements only (i.e., either vertical or horizontal lines, varied randomly across trials) forming a homogeneous context or they could consist of both types of element (i.e., both vertical and horizontal lines) that were either spatially grouped (forming a heterogeneous yet grouped context) or intermixed randomly in the display (forming a heterogeneous random context; see Fig. 1). Thus, since the classification of line elements remained the same for all three contexts (oblique line: target element; vertical and horizontal lines: context elements), template matching of targets and non-targets did not differ among the three conditions. However, the degree of homogeneity among neighboring context elements was varied, so that different grouping processes may have occurred. Assuming that the N2p component – more precisely, the larger N2p amplitude for target-absent compared to target-present trials – is indicative of differences in grouping processes operating on the global stimulus array, one would expect the N2p amplitude effects to differ between homogeneous and heterogeneous contexts. Moreover, if the N2p reflects homogeneity coding, one would expect its amplitude to increase for target-absent trials as the



**Fig. 1 – Examples of stimulus arrays with homogeneous contexts (upper left: target-absent trial, and lower right: target-present trial), grouped heterogeneous context (upper right) and random heterogeneous context (lower left). The target (an oblique leftward tilted line) could appear at the middle horizontal line 3.9° or 5° left or right from fixation.**

homogeneity of context elements increases. With an increase in the heterogeneity of the context elements, however, grouping processes may become more difficult as both global processing and homogeneity coding may be impeded. This should lead to a reduction in absolute N2p amplitude and the disappearance of the differential N2p amplitude effect. The latter could be explained either by the decrease in homogeneity as the similarity of the context elements is reduced (Duncan and Humphreys, 1989) or by an increase in heterogeneity rendering the detection of the relevant irregularity (the target) more difficult.

Furthermore, search performance was expected to reflect context differences: homogeneous contexts were expected to enhance performance, compared to grouped heterogeneous and random heterogeneous contexts.

## 2. Results

### 2.1. Behavioral data

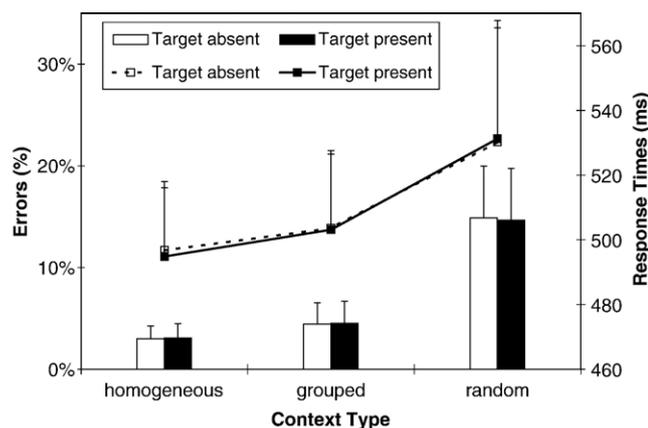
Error rates and response times are illustrated in Fig. 2. As participants were instructed to stress accuracy more than speed, errors were given priority.

#### 2.1.1. Errors

Error rates showed a significant main effect of the factor CONTEXT,  $F(2,22)=6.94$ ,  $p<0.01$ . Subsequent paired *t*-tests revealed that significantly more errors were made with random heterogeneous contexts ( $M=14.6\%$ ,  $SEM=5.1\%$ ) compared with both homogeneous contexts ( $M=3.1\%$ ,  $SEM=1.4\%$ ),  $t(11)=2.65$ ,  $p<0.05$  and grouped heterogeneous contexts ( $M=4.5\%$ ,  $SEM=2.2\%$ ),  $t(11)=2.49$ ,  $p<0.05$ . No other effects reached significance (all  $p>0.07$ ).

#### 2.1.2. Response times

Although response times also increased with context heterogeneity (cf. Fig. 2), the factor CONTEXT failed to reach significance,  $p>0.13$ . Responses were fastest for homogeneous



**Fig. 2 – Error rates (bars) and response times (lines) for target-present (black bars and solid lines) and target-absent trials (white bars and dashed lines) for stimulus arrays with homogeneous (left column), grouped heterogeneous (middle column) and random heterogeneous (right column) contexts.**

contexts ( $M=493$  ms,  $SEM=21$  ms), intermediate for grouped heterogeneous contexts ( $M=503$  ms,  $SEM=23$  ms) and slowest for random heterogeneous contexts ( $M=532$  ms,  $SEM=40$  ms). The RT difference of 39 ms between homogeneous and random contexts also failed to reach significance,  $p>0.07$  (one-tailed *t*-test).

### 2.2. ERP data

ERPs elicited at posterior electrode sites in target-absent and target-present trials in homogeneous, grouped heterogeneous and random heterogeneous context conditions are shown in Fig. 3. Fig. 4 provides a direct comparison of ERPs recorded in target-absent and target-present trials in all three context conditions.

#### 2.2.1. N2p

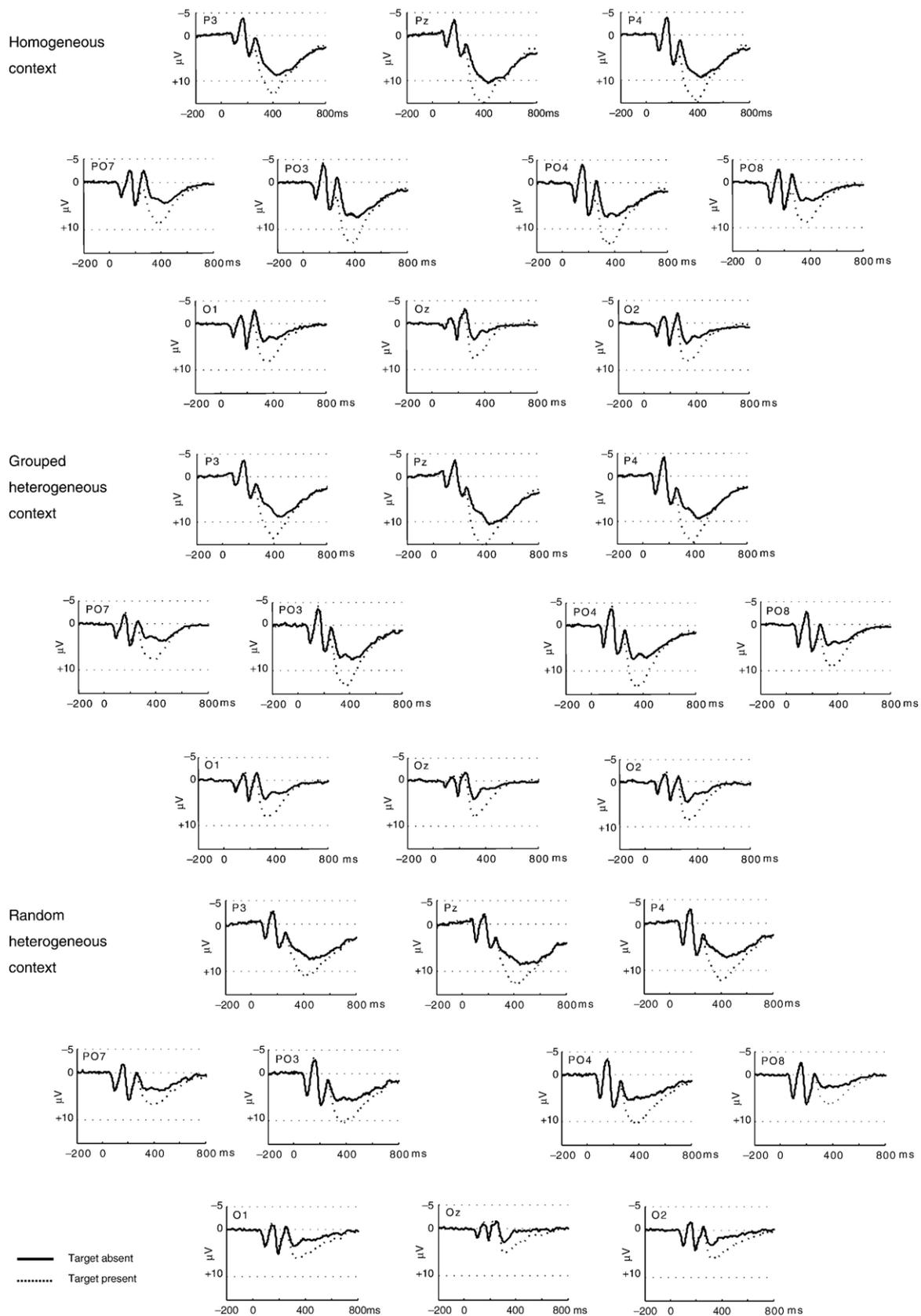
N2p amplitude was significantly increased for target-absent compared to target-present trials — the differential N2p amplitude effect  $F(1,11)=22.55$ ,  $p<0.001$ . A significant TARGET  $\times$  CONTEXT interaction,  $F(2,22)=11.16$ ,  $p<0.0005$ , indicated that there were differences in N2p amplitude elicited by target-absent and -present trials in the three context conditions. Subsequent ANOVAs conducted separately for the three context conditions revealed significant differences in N2p amplitude between target-absent and -present trials for homogeneous contexts,  $F(1,11)=23.74$ ,  $p<0.0005$ , and for grouped heterogeneous contexts,  $F(1,11)=19.0$ ,  $p<0.005$ , but not for random heterogeneous contexts,  $p>0.27$ . To examine whether the (significant) differential N2p amplitude effect differed between homogeneous and grouped heterogeneous contexts, an ANOVA with the factors TARGET (absent vs. present), ELECTRODE (PO3, PO4, PO7, PO8) and CONTEXT was carried out on these two context conditions only (homogeneous vs. grouped). This ANOVA revealed both a significant main effect for the factor TARGET,  $F(1,11)=24.66$ ,  $p<0.0005$ , and a significant TARGET  $\times$  CONTEXT interaction,  $F(1,11)=6.32$ ,  $p<0.05$ , with the differential N2p amplitude effect (i.e., the difference in N2p amplitude between target-absent and -present trials) being more pronounced for homogeneous than for grouped heterogeneous contexts.

#### 2.2.2. N2pc

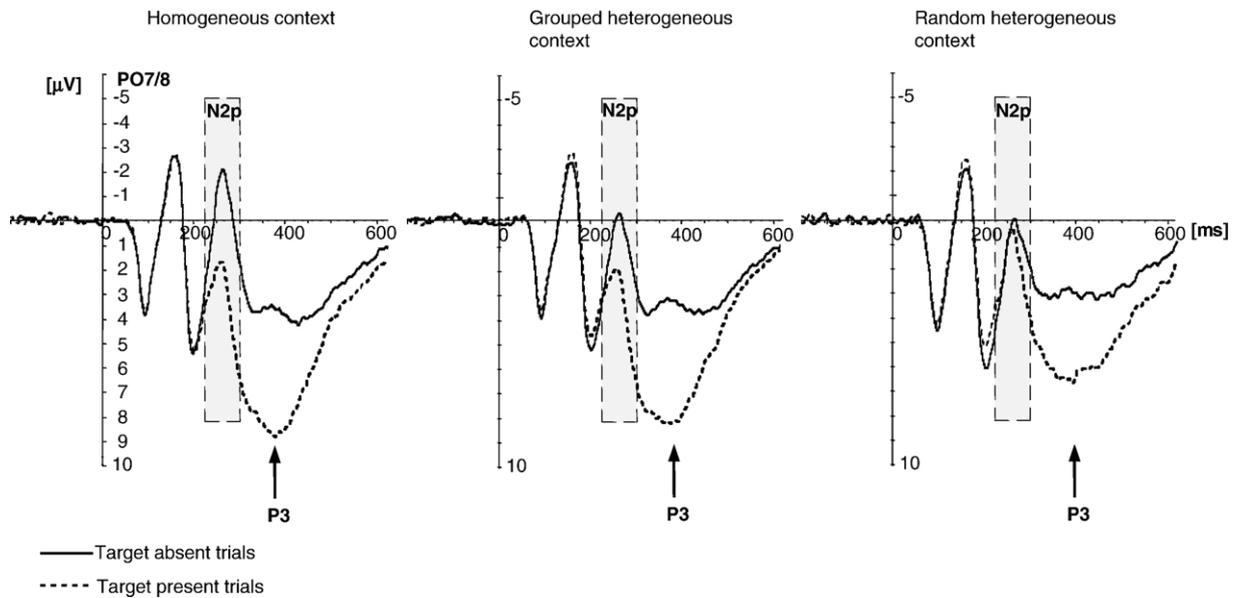
The ANOVA revealed a significant main effect of laterality,  $F(1,11)=23.03$ ,  $p<0.001$ , indicating that across all three context conditions, an N2pc component was observed. Although there was a tendency for a CONTEXT  $\times$  LATERALITY interaction, it failed to reach significance ( $p=0.059$ ). Subsequent ANOVAs which were conducted separately on all three context conditions revealed significant N2pc components for homogeneous contexts,  $F(1,11)=18.29$ ,  $p=0.001$ , grouped heterogeneous contexts,  $F(1,11)=24.65$ ,  $p<0.005$ , and random heterogeneous contexts,  $F(1,11)=18.49$ ,  $p=0.001$  (cf. Fig. 5).

#### 2.2.3. P3

For all three context conditions, P3 amplitudes were increased for target-present compared to target-absent trials, as indicated by a significant main effect of TARGET,  $F(1,11)=30.21$ ,  $p<0.0005$ . Additionally, P3 amplitudes were differentially affected by CONTEXT condition,  $F(2,22)=3.91$ ,  $p<0.05$ . A



**Fig. 3 – Grand average ERPs elicited at parietal, parieto-occipital and occipital electrode sites in target-absent (solid lines) and target-present trials (dotted lines) in homogeneous (upper panel), grouped heterogeneous (middle panel) and random heterogeneous context conditions (lower panel).**



**Fig. 4** – Grand average ERPs elicited at posterior-occipital electrode sites (averaged across PO7 and PO8), in target-absent (solid lines) and target-present trials (dashed lines) in homogeneous (left panel), grouped heterogeneous (middle panel) and random heterogeneous context conditions (right panel). N2p time windows are indicated by the gray rectangles, P3 amplitudes are indicated by the arrows.

planned comparison revealed the P3 amplitude to be reduced for random heterogeneous contexts compared to homogeneous and grouped heterogeneous contexts combined,  $F(1,11)=5.12$ ,  $p<0.05$ .

### 3. Discussion

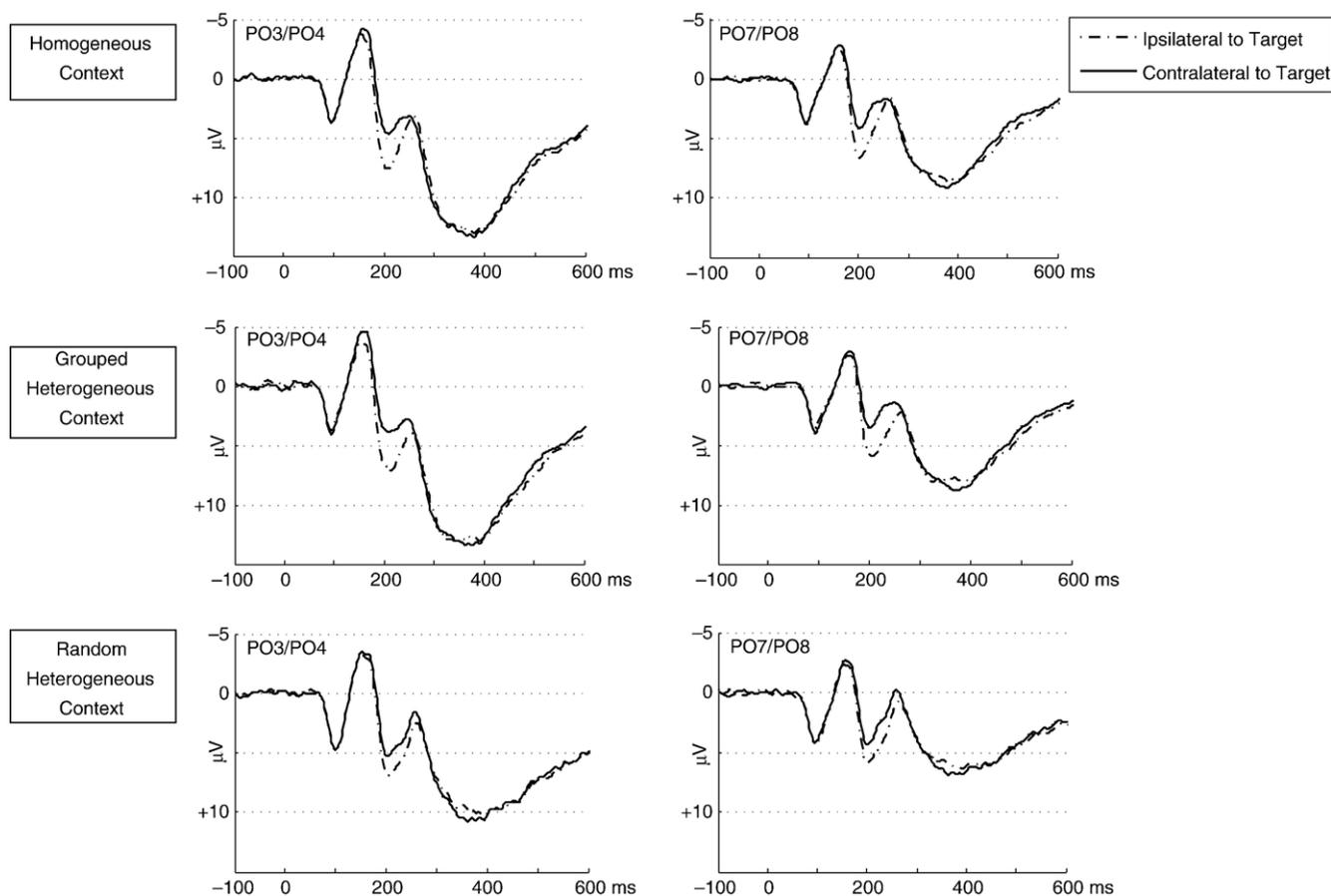
Behavioral data showed a decrease in search performance with an increase in context heterogeneity. Interestingly, the increase in RT and error rate was observed between grouped heterogeneous and random heterogeneous contexts. Purely homogeneous contexts showed only a small benefit compared to the heterogeneous, but locally homogeneous, grouped context.

As expected, the differential (target-absent vs. target-present) N2p amplitude effect was observed for homogeneous contexts. A smaller differential N2p amplitude effect was found for grouped heterogeneous contexts, while no such effect was observed for random heterogeneous contexts. Fig. 6 shows voltage maps of the scalp topographies of the N2p differential amplitude effect for homogeneous, grouped heterogeneous and random heterogeneous contexts. Blue regions, indicating negative voltage differences, were observed for homogeneous and grouped heterogeneous contexts only. For random contexts, no marked differences in scalp voltage between target-absent and target-present trials were observed. Again, the difference between grouped heterogeneous and random heterogeneous contexts was more pronounced than that between homogeneous and grouped heterogeneous contexts.

An N2pc was observed in target-present trials for all three context conditions. Interestingly, N2pc was slightly smaller for targets in random heterogeneous contexts compared to targets

in grouped heterogeneous and homogeneous contexts (however, with  $p>0.05$ , this effect failed to reach significance).<sup>1</sup> Although there is some debate concerning the precise interpretation of the N2pc (e.g., Eimer, 1996), there is some agreement that the N2pc is indicative of enhanced attention being allocated to an element in the stimulus array, for example, as a result of an attention shift to the element's location (Woodman and Luck, 2003). Accordingly, one could assume that there was approximately the same amount of attention allocated to the target element among the various context conditions. This would be in line with the intention to keep the target feature constant across all context conditions while only varying the homogeneity of context elements: as the target was the same oblique line element in all three context conditions, also the matching of array elements with the target template may have remained (nearly) the same. The finding of equivalent N2pc's in all three contexts conditions may suggest that the

<sup>1</sup> One may wonder why N2pc was smallest for targets in random heterogeneous contexts as response times and error rates indicated that target detection was least efficient in this condition. Traditional N2pc interpretations assume that the largest N2pc should be observed in conditions that impose the highest attentional demands on target detection. In the present experiment, however, N2pc was slightly larger for more efficient search conditions (that is, for target detection in homogeneous and grouped heterogeneous contexts). Following an N2pc interpretation in terms of target template matching, one could assume that the slight decrease in N2pc for targets in random heterogeneous contexts may have resulted from surrounding context elements: while for homogeneous and grouped heterogeneous contexts surrounding context elements (being either all horizontal or all vertical) had a similar effect, they may have - due to their heterogeneity - slightly hindered target template matching in the random context condition.



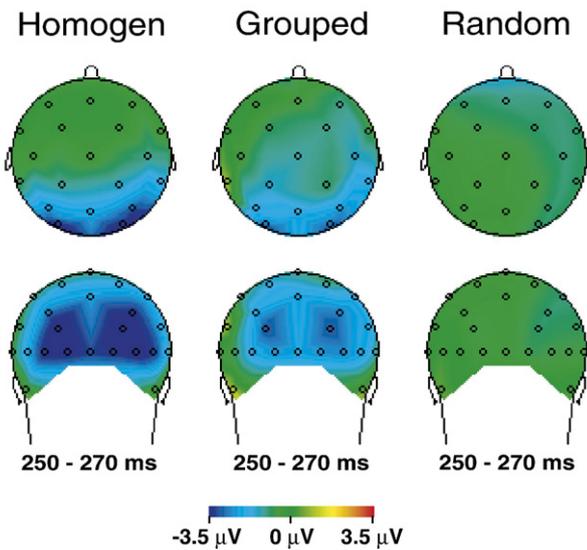
**Fig. 5** – Grand average ERPs recorded in target-present trials at electrode sites contralateral (solid lines) and ipsilateral (dashed lines) to target-presentation at posterior-occipital electrode sites PO3 and PO4 (left panels) and PO7 and PO8 (right panels), separately for targets presented in homogeneous contexts (upper panels), grouped heterogeneous contexts (middle panels) and random heterogeneous contexts (lower panels). Waveforms have been collapsed across hemispheres: ipsilateral waveforms contain left hemisphere recordings for targets presented in the left visual field and right hemisphere recordings for targets presented in the right visual field, while contralateral waveforms contain right hemisphere recordings for targets presented in the left visual field and left hemisphere recordings for targets presented in the right visual field. The N2pc is calculated as the difference in mean amplitude between contralateral and ipsilateral electrode sites observed 170–270 ms post stimulus.

target was detected via its match to a ‘left-tilted line’ template by similar processes of target matching in target-present trials in all three context conditions.

Concerning the P3 component, its amplitude was increased for target-present compared to -absent trials in all context conditions. This is consistent with previous studies of search tasks, which have reported P3 amplitudes to be larger for target compared to non-target trials (e.g., Luck and Hillyard, 1990; Schlaghecken et al., 2001; Schubö et al., 2004). Interestingly, the difference in P3 amplitude between target-present and -absent trials was less pronounced with random heterogeneous contexts compared to the other two context conditions. This pattern is in line with earlier P3 findings of P3 amplitude differences varying in classification tasks (e.g., Mecklinger and Ullsperger, 1993). For example, when elements had to be classified into categories such as targets versus non-targets, the P3 was modulated dependent on the difficulty of the required categorization (e.g., Kok, 2001). Previous studies also showed a decrease in P3 amplitude with a general increase in task difficulty (e.g., Brookhuis et al., 1981; Kramer

et al., 1986). For example, an increase in the demands of a perceptual task (e.g., by degrading the visual stimulus) led to a decrease in P3 amplitude (Christensen et al., 1996). The present P3 results may also relate to these findings as increasing context heterogeneity could be regarded as an increase in perceptual task demands. The decrease in P3 amplitude observed for random contexts could therefore be interpreted in terms of an increase in perceptual difficulty and a concomitant decrease in confidence (i.e., an increase in uncertainty) about having detected a target among the heterogeneous context elements (Johnson and Donchin, 1985; Ruchkin and Sutton, 1978).

In the following, we discuss differences found in the processing of homogeneous versus grouped heterogeneous contexts separately from differences found in the processing of grouped versus random heterogeneous contexts. We will argue that the former mainly affected processing on target-absent trials, while the latter can be considered as reflecting different processing modes on both target-present and -absent trials.



**Fig. 6 – Topographic voltage maps showing the distribution of the N2p differential amplitude effect for homogeneous (left panels), grouped heterogeneous (middle panels) and random heterogeneous (right panels) contexts. Minimum and maximum values are  $-3.5$  and  $+3.5$   $\mu\text{V}$ , blue regions indicate negative values. Maps show voltage difference (target-absent minus -present trials) recorded in all three context conditions for an average N2p peak latency range of  $260 \text{ ms} \pm 10 \text{ ms}$ .**

### 3.1. Homogeneous versus grouped heterogeneous contexts: comparing irregularity detection and homogeneity coding

Comparing homogeneous and grouped heterogeneous contexts revealed only slight differences. At the behavioral level, there were virtually no differences. Only the differential (target-absent versus -present) N2p amplitude was found to be reduced with grouped heterogeneous relative to homogeneous contexts. Importantly, this difference was mainly due to a decrease in N2p amplitude for target-absent trials; on target-present trials, N2p amplitude was near-equivalent in the two context conditions (see Fig. 4). This may indicate that target processing, on ‘target-present’ trials, differed little between the two types of context, while processing was different on target-absent trials. This suggestion receives further support from the fact that the N2pc showed no differences in target processing between the two types of context.

How could the differences between homogeneous and grouped heterogeneous contexts be described in terms of the concepts of ‘irregularity detection’ (Meincke and Donk, 2002) and, respectively, ‘homogeneity coding’ (Duncan and Humphreys, 1989)? According to the irregularity detection account, one would expect visual search to be particularly efficient for targets embedded in perfectly homogeneous contexts because the irregularity signal could be directly translated into a positive response. In contrast, with grouped heterogeneous contexts, a second, interfering ‘irregularity’ signal would be generated at the vertical midline of the stimulus array, due to the transition from vertical to horizontal context elements

(see Fig. 1, upper right). As a result, detection of an irregularity signal cannot be directly translated into a target-present response. On target-absent trials, observers have to classify the transition-irregularity as task-irrelevant and to-be-ignored. On target-present trials, they have to select the task-relevant irregularity (produced by the target) from the irrelevant one (produced by the transition). According to these considerations, both target-absent and -present decisions should be more difficult with grouped heterogeneous than with homogeneous contexts. However, the data revealed differences in the N2p component mainly for target-absent trials (with a decrease in N2p amplitude for grouped heterogeneous contexts), while target-present trials were virtually unaffected. Therefore, an alternative interpretation focusing on target-absent trials may be more appropriate.

The homogeneity coding account explicitly refers to the ‘special’ situation of arrays with perfectly homogeneous context elements (Duncan and Humphreys, 1989). In such displays, all homogeneous elements are thought to be linked to form a single unit that can subsequently be rejected as a whole, on both target-absent and target-present trials. On the latter trials, the target would then be selected (it may be considered to form a one-element unit that matches the target template).<sup>2</sup> In the present experiment, the conditions for applying homogeneity coding (i.e., perfect similarity of context elements, plus, on target-present trials, a dissimilar target) were met with homogeneous, but not grouped heterogeneous contexts. In grouped contexts, horizontal and vertical elements may have been linked separately, forming two smaller (yet homogeneous) units, rather than one large unit. The differences in N2p amplitudes between the two context conditions may mirror these differences in grouping: a large differential N2p amplitude effect was observed with homogeneous contexts and a markedly reduced effect with grouped heterogeneous contexts. This is consistent with the SeRR model of visual search (Humphreys and Müller, 1993): SeRR would involve two recursive rejection steps in the latter, compared to just one in the former, condition.

The N2p results may also shed some light on an issue already raised by Duncan and Humphreys (1989), namely, whether homogeneous contexts constitute a special case due to homogeneity being directly perceived or, alternatively, due to the strong linkage of context elements causing a perfect spread of suppression and thereby allowing for efficient target selection. While the present results may not completely resolve this issue, the fact that differences between homogeneous and grouped heterogeneous contexts were observed only on target-absent trials (while both the N2p amplitude and the N2pc elicited on target-present trials were virtually equivalent) has implications for this question. In particular, adding a second group of homogeneous context elements to a

<sup>2</sup> The ‘advantage’ of homogeneity coding derives from the fact that perfect homogeneity permits the complete stimulus array to be directly matched with the target template. That is, template matching, which takes place after homogeneity grouping, does not need to be repeated for different ‘candidate’ subgroups. While this holds for both target-present and -absent trials, the special benefit of homogeneity coding results from the single-step rejection of the group of homogeneous context elements (rather than the detection of the target as an irregularity).

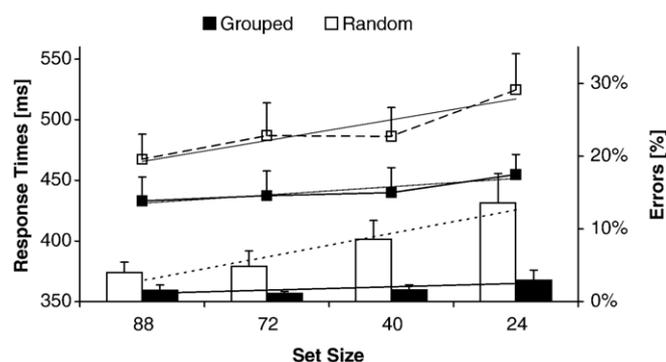
first group (as in the grouped heterogeneous context condition) caused mainly differences in rejecting displays as not containing a target, while target detection itself was unaffected. Consequently, the benefit for homogeneous contexts may derive from the direct perception of (perfect) homogeneity on target-absent trials, rather than from processes taking place on target-present trials. On the latter, the target may be processed independently of the homogeneous context elements, that is, target detection may also be based on target-specific processes that enter into a race with the grouping-and-rejection processes operating on the homogeneous context elements. Of course, determining the exact processes reflected in the differential (target-absent) N2p amplitude modulation – differences in grouping, advantage of matching a whole-unit array or direct perception of homogeneity – is left to further research. It is clear, however, that this modulation is directly related to ‘homogeneity coding’.

### 3.2. Grouped heterogeneous versus random heterogeneous contexts: evidence for differential processing modes

Comparing grouped heterogeneous and random heterogeneous contexts revealed manifold differences. The differential search efficiency manifest in the behavioral data (see Fig. 2) already indicated that processing was slower and more error-prone with random contexts than with grouped contexts. Moreover, the disappearance of the differential (target-absent vs. -present) N2p amplitude effect with random contexts suggests that the mode of processing differed between the two conditions. Interestingly, the absence of a differential N2p amplitude effect with random contexts was due to an increase, relative to grouped heterogeneous and homogeneous contexts, in N2p amplitude on target-present trials (see Fig. 4; though the increase failed to reach significance,  $p > 0.12$ ), rather than a further reduction of N2p amplitude on target-absent trials. This increase in N2p amplitude in target-present trials indicates that the difference in processing in random heterogeneous and grouped heterogeneous contexts extends (contrary to the difference between homogeneous and grouped heterogeneous contexts that was observed mainly

for target-absent trials) to both target-present and target-absent trials. Behavioral and ERP results suggest that while in grouped heterogeneous contexts target-present and -absent trials are distinguished already at an early processing level, this distinction seems less clear in random heterogeneous contexts. Rather, processes similar to the ones observed in less efficient search tasks seem to be needed to distinguish between target-present and -absent trials in random heterogeneous contexts.

To investigate the processing modes in grouped versus random heterogeneous contexts in more detail, a second experiment was conducted in which the number of context elements presented together with the target was reduced systematically from 88 to 24 elements. If the processing modes differed between grouped and random contexts, then also search performance – more exactly, the slope of the function relating search RT to set size – should differ between the two conditions when the number of context elements is reduced. As in the first experiment, differences in the absolute level of performance were expected to be evident as well. However, while such differences may reflect more general differences in task difficulty (in terms of perceptual and response selection demands), differences in search slopes with a decrease in set size would be indicative of differential processing modes used under random and grouped context conditions (e.g., Bacon and Egeth, 1991; Meinecke and Donk, 2002; Sagi and Julesz, 1987; Schubö et al., 2004; also Wolfe, 1998). Results are shown in Fig. 7. Search performance (measured in terms of error rates and RTs) decreased in both context conditions; however, the decrease was more pronounced with random than with grouped contexts (significant  $\text{CONTEXT} \times \text{SET SIZE}$  interaction for the error rates,  $F(1,8) = 10.40$ ,  $p < 0.05$ ; for RTs,  $p > 0.06$ ). Thus, target-present and -absent responses in random contexts were (i) generally slower and more error-prone compared to grouped contexts (evidenced in terms of a performance difference for each individual set size) and (ii) were more impeded when the number of context elements was reduced (evidenced in terms of a steeper slope of the linear trend across set sizes). At the same time, performance for grouped contexts was found to remain efficient even when the number



**Fig. 7** – Error rates (bars) and response times (lines and squares) for set sizes 88, 72, 40 and 24, for stimulus arrays with grouped heterogeneous (black bars and solid line with black squares) and random heterogeneous (white bars and dashed line with white squares) contexts. As there were no differential effects for contexts and set sizes for target-present and -absent trials, results were averaged across both conditions. Solid and dotted lines indicate the linear trends for the grouped and random heterogeneous context conditions.

of context elements was markedly reduced. Probably, context elements could already be linked when 24 elements were presented in the display, and this process was largely unaffected by the set size manipulation. The slope difference observed between grouped and random contexts provides another hint – in addition to the difference in the N2p amplitude effect – for different processing modes being used with grouped and random heterogeneous contexts.

Assuming different processing modes for grouped and, respectively, random heterogeneous contexts, how can one characterize these different processing modes? We assume that random heterogeneous contexts cause a different pattern of search performance when compared to grouped heterogeneous contexts as processing is likely to be performed on different spatial scales in both conditions (cf. Duncan and Humphreys, 1989). Displays with grouped contexts can still be processed at a global level where grouping processes operate, providing a rapid segmentation of the display into separate units. Similar context elements are grouped and subsequently rejected as whole units and target search can be performed quite rapidly on both target-present and -absent trials. In contrast, processing is not as efficient for displays with random contexts. Grouping is – for randomly distributed vertical and horizontal context elements – not as strong as in grouped heterogeneous contexts and segmenting the random display into target and non-target elements yields more (and smaller) sub-units that are not as clearly separated as the sub-units in grouped contexts (where there are two separate, but homogeneous ‘groups’). Additionally, the sub-units in random contexts are less clearly separable from the target element as the target is surrounded by both vertical and horizontal context elements and similar sub-units may be formed in target-present and target-absent trials. Rather than having a distinction into target-present and -absent trials on an early segmentation stage that can be matched to the target template, the display has to be segmented into many sub-units that need repeated template matching until a target-present or -absent decision can be made.

Rather diffuse grouping and weak linkages of elements around the target location may also explain the marked deterioration in search performance with decreasing numbers of context elements observed in the random-context condition (see Fig. 7). With group contexts, the same processes (i.e., grouping and subsequent segmentation) could be applied to displays of small and large set sizes. In contrast, with random contexts, processing may have changed from a still partially global mode (operating on sub-units) to a more fine-grained analysis of context elements as set size was decreased. For smaller set sizes, only regions with diffuse groupings – around the target locations – would have been left, requiring a fine-grained analysis (operating on few elements) for differentiating between target and context elements—yielding longer response times and an increase in error rate. This is in line with Meinecke and Donk (2002) who assumed that, with a decrease in the number of context elements, processing switches from a global processing mode to one based on single elements. Thus, in random contexts, processing may have suffered from a decrease in context elements as processing could no longer be based on larger units of the search array.

In summary, the present data provide evidence in favor of the existence of homogeneity coding, as postulated by Duncan and Humphreys (1989), mirrored by the differential N2p amplitude effect. Contexts with perfectly homogeneous elements were indeed found to be special compared to contexts that were made up of more than one type of context element, even when the elements provided a locally homogeneous background surrounding the target. Splitting up the context elements into two subgroups reduced the homogeneity coding benefit (evidenced by a marked decrease in the differential N2p amplitude effect), even when the subgroups formed homogeneous hemifields of elements. A further increase in context heterogeneity, by distributing the two types of context elements randomly across the display, led to a more pronounced and probably qualitative change in processing. Finally, ERPs, especially the N2p component, were found to be sensitive to contexts of varying homogeneity.

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## 4. Experimental procedure

### 4.1. Participants

Twelve paid volunteers (5 male) aged 21–32 (mean age: 25.3) years participated in the experiment. Two of the participants were left-handed, all had normal or corrected-to-normal vision. Visual acuity was tested with a Rodenstock R12 vision tester (stimuli 112). The experiment was conducted with the understanding and consent of each participant. None of the observers had taken part in a visual search experiment before.

### 4.2. Stimuli and apparatus

Participants were seated in a dimly lit, electrically shielded and sound attenuated chamber, with a response pad placed under their left and right index fingers. Stimuli were presented on a 17-inch computer screen with a 75 Hz refresh rate placed at a distance of 100 cm. Stimulus arrays contained 110 black lines ( $1^\circ$  of visual angle in length and approximately  $0.05^\circ$  in width), arranged on an imaginary matrix consisting of 10 columns  $\times$  11 rows of evenly spaced cells (total size  $13.5^\circ \times 15^\circ$ ). Stimuli were black on a light-gray background.

The context elements consisted of vertical and horizontal lines that were distributed differently in the three context conditions (cf. Fig. 1). Homogeneous contexts consisted of either horizontal lines or vertical lines only, presented with equal probabilities. Grouped contexts consisted of both horizontal and vertical lines arranged separately in the two visual hemifields. Random contexts also contained both horizontal and vertical lines, which were, however, arranged randomly (without any constraints) across the visual field. The target (if present in an array) was a single oblique line element tilted  $45^\circ$  to the left. The target could appear at the middle horizontal line of the matrix,  $3.9^\circ$  or  $5^\circ$  to the left or right from the center of the screen. Target-absent and target-present trials were equiprobable. The mask, presented immediately after the search array, was constructed by superimposing horizontal, vertical and left- and rightward-tilted line elements at each matrix cell, resulting in a  $10 \times 11$  array of asterisk-like elements.

#### 4.3. Procedure

A trial started with the presentation of a central fixation point that remained on the screen for 100 ms. The fixation point was followed by the search array which was presented for 100 ms and subsequently masked. After 800 ms, the mask was followed by the fixation point which remained on the screen for 1400 ms. Participants were asked to press the one (e.g., the right) response key if they had detected a target in the search array (target-present trial) and the other (left) key if they had not detected a target (target-absent trial); the response assignment was balanced across participants. Participants were asked to respond as accurately as possible and to respond as fast as possible—however, with greater stress placed on response accuracy compared to speed.

While target-absent and -present trials and target positions were mixed randomly within trial blocks, context conditions were blocked. The experiment was divided into three parts, one for each context condition (after each part, participants were allowed to rest and/or leave the experimental chamber). Each condition started with a practice block followed by 8 experimental blocks of 80 trials each. After every block, participants received feedback on the number of errors they had made and their response speed.

#### 4.4. ERP recording

EEG was recorded with Ag-AgCl electrodes from the electrodes F7, F3, Fz, F4, F8, FC1, FC5, FC6, FC2, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, PO7, PO3, PO4, PO8, O1, Oz, O2, and both mastoids (according to the extended international 10–20 system). Horizontal and vertical EOG were recorded bipolar from the outer canthi of the eyes and from above and below the observer's left eye, respectively. All electrodes were referenced to Cz and re-referenced offline to the average of the left and right mastoid. Electrode impedances were kept below 5 k $\Omega$ . Sampling rate was 500 Hz, amplifier bandpass was 0.016–30 Hz.

#### 4.5. Data analysis

Prior to analysis, for each participant, mean response time (RT) and standard deviations were computed for each experimental block. Trials with no responses and trials on which RT was more than two standard deviations above or below the mean were excluded from the analysis (<5%). From the remaining data, mean RTs and errors were determined for target-absent and -present trials for each context condition. ANOVAs with the factors TARGET (absent vs. present) and CONTEXT (homogeneous vs. grouped vs. random) were calculated separately for errors and response times (RT analysis was run on 'correct' trials only). When appropriate, specific sub-group differences were tested with paired-samples *t*-tests.

EEG was averaged offline over a 1200-ms epoch including a 200-ms pre-stimulus baseline interval. Ocular artefacts (blinks and eye movements) were corrected according to the Gratton–Coles procedure (Gratton et al., 1983). Trials with muscular and other artefacts (indicated by any voltage exceeding  $\pm 80$   $\mu$ V, voltage steps between two sampling points exceeding 50  $\mu$ V and voltages lower than 0.10  $\mu$ V for a 100 ms interval) were

excluded from analysis. Only trials with correct responses were analyzed.

EEG was averaged separately for target-absent and -present trials and for each context condition, resulting in a total of six ERP waveforms for each participant. To examine N2pc effects, ERPs elicited on target trials were further analyzed according to target and electrode location (target in left or right visual field; left or right electrode site), resulting, with two electrode pairs analyzed (PO3 and PO4; PO7 and PO8), in eight additional ERP waveforms for each participant.

Repeated-measures analyses of variance (ANOVAs) were performed for the peak amplitude values obtained in the N2p time window (220–300 ms) and the P3 latency range (280–480 ms). Appropriate time windows were determined in accordance with earlier studies (Schubö et al., 2001, 2004). For the N2p amplitude, analyses were performed for the posterior sites PO7, PO3, PO4 and PO8, with the factors TARGET (absent vs. present), CONTEXT (homogeneous vs. grouped vs. random conditions) and ELECTRODE (PO3, PO4, PO7, PO8). For the P3 amplitude, the analysis was run on the electrode Pz with the factors TARGET (absent vs. present) and CONTEXT (homogeneous vs. grouped vs. random conditions). For the N2pc, mean ERP amplitudes were determined for the 170–270 ms interval post stimulus onset for target-present trials, and an ANOVA was run on the electrodes PO7, PO3, PO4 and PO8 with the factors CONTEXT (homogeneous vs. grouped vs. random), LATERALITY (electrode ipsi- versus contralateral to target location), ELECTRODE LOCATION (left vs. right electrode sites) and ELECTRODE PAIR (PO3 and PO4 vs. PO7 and PO8).

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