The role of context homogeneity in deployment of visual attention

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CONTENTS

APPENDIX

SUMMARY

This dissertation presents a series of four studies in which the role of the visual context in the deployment of selective visual attention was investigated. Contexts describe large arrays of stimuli that structure the visual field and that are entirely (or mostly) irrelevant to the observer - but often modulate the way visual information is selected (Nothdurft, 1992; Sagi & Julesz, 1987). It has previously been found that one specific property of contexts is particularly important for visual processes: the homogeneity, i.e., how similar nearby context elements are or how regularly structured a context is. If sufficiently homogenous, contexts may enhance visual search due to spontaneous, pre-attentive grouping processes (Duncan & Humphreys, 1989). The present series of studies aimed to create a better understanding of how context homogeneity modulates selective visual attention and at what stages of visual processing benefits from context homogeneity occur.

Study I investigated how homogeneous contexts shape the focus of visual attention. It used a variation of the spatial cueing paradigm in which a particular location in a context of simple line elements was cued. Not only the cued location but also the entire cued context benefited from both exogenous and endogenous cues. Moreover, the less homogenous a context was, the less pronounced was the context advantage. Results from Study I suggest that grouping processes facilitate visual search within homogeneous contexts because the way attention was deployed in the visual field was determined by such grouping processes: Attention seemed to spread to entire contexts and only after a few hundred milliseconds focused on conspicuous locations. This spread of attention might be the reason why in Study II, III and IV, attention deployment towards targets within homogeneous contexts was more efficient.

Study II looked at more sustained effects of context homogeneity on visual attention and combined a visual search task with a subsequent probe task. It was found that probe identification was facilitated at the prior target location even when the context was not present anymore. Importantly, this sustained attentional facilitation was more pronounced after homogeneous than after heterogeneous contexts as evident in shorter response times and more pronounced P1 amplitudes. This suggests that stimuli embedded in homogeneous contexts yielded enhanced sensory gain for some time after contexts are shown. A more pronounced posterior N2 amplitude in target-absent trials compared to target-present trials was only observed in homogeneous but not in heterogeneous contexts, supporting the notion that the sustained attention effects were due to grouping processes.

Efficient visual processing does not only require prioritization of relevant information, but also suppression of irrelevant, potentially interfering information. Study III aimed to compare these two processes in contexts of varying homogeneity. To that end, a visual search task was used that contained not only a target but also a salient distractor. Target and distractor were embedded in either a homogeneous or in a heterogeneous context. Firstly, an earlier and more pronounced N_T component

in the ERP was found for homogeneous than for heterogeneous contexts, suggesting that prioritization of the target is more efficient and possible earlier in time for homogeneous contexts. Secondly, an earlier and more pronounced P_D component in the ERP was found for homogeneous than for heterogeneous contexts, suggesting that active suppression of the salient distractor is less efficient and delayed for heterogeneous contexts. A reason for such delayed suppression may be evident in the 'distractor negativity' prior to the P_D component that was only observed in heterogeneous contexts. This suggests that distractors captured attention before they could be actively suppressed in heterogeneous contexts. Results from Study III show that both target prioritization and distractor suppression contribute to more efficient attention deployment in homogeneous compared to heterogeneous contexts.

Study IV used a contextual cueing paradigm to investigate whether the benefit from homogeneous stimulus arrangements is limited to visual selection as such or might even affect later attention-related processes connected with long-term memory. Study IV found that faster attention deployment towards targets embedded in repeatedly presented contexts compared to novel contexts (i.e., the contextual cueing effect) was more pronounced when contexts were homogeneous. This suggests that memory representations of stimuli are more easily acquired when the stimuli can be processed as larger, grouped perceptual units – which is facilitated in more homogeneous stimulus arrangements.

In sum, the present series of studies provided further evidence for the crucial role of context homogeneity in deployment of visual attention. Although in all experiments presented in this dissertation, contexts were entirely behaviorally irrelevant because observers did not need them at all to solve their task, contexts had a tremendous effect on how visual information was selected. Homogeneous contexts facilitated grouping processes and thus determined both early attentive processes and how attention spread in the visual field (Study I). As a result, in homogeneous contexts targets were processed more efficiently (Study II, III, IV) and salient distractors were suppressed more efficiently (Study III). This yielded sustained sensory gain subsequent to homogeneous contexts (Study II) and enhanced memory representations for homogeneous stimulus arrangements (Study IV).

1 INTRODUCTION

Our visual system is confronted with an overwhelming number of visual stimuli at any given moment. Nevertheless, we have an effortless understanding of our visual environment in which we perceive and act. Our neural system is incapable of processing all incoming information due to limited cognitive and brain resources (Broadbent, 1958; Reynolds & Chelazzi, 2004; Treisman, 1960). Thus, only a fractional part of the visual environment is further processed to prevent information overload (Koch & Tsuchiya, 2007; Posner, Snyder, & Davidson, 1980; Tsotsos, 1990) and to reduce costs of neural activity necessary for cortical computations (Attwell & Laughlin, 2001). To ensure efficient and accurate analysis of incoming information (and information stored in memory), the visual system needs to optimize the use of the system's limited resources and filter relevant from irrelevant information, or 'noise', within milliseconds (Eckstein, 2011; Wolfe, 2007). Preferential processing of relevant information and/or inhibition of irrelevant information is accomplished by a mechanism often described as *selective visual attention* (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, 1994). Selective visual attention can help us overcome the visual system's limited capacity, and optimize our perception and behavior, by enhancing neural representations of relevant locations or visual features and diminishing neural representations of less relevant locations or visual features (Carrasco, 2011; Luck, Chelazzi, Hillyard, & Desimone, 1997).

A vast number of studies published in the last decades have sought to uncover which principles the visual systems uses to select particular information and disregard the rest (for an overview, see Carrasco, 2011; Wolfe, 2007). There is a general agreement that one way the visual system limits the to-be-processed information is to not attend to all parts of the visual field to the same extent. Rather, certain locations receive prioritized processing compared to other locations. This notion of attention is supported by neurophysiological studies showing that the exact same physical input (constant retinal image) can produce different patterns of activity due to the attentional state of an individual which then also affects behavioral performance. For example, feature-specific cells in the visual cortex of monkeys have shown to increase firing rates when a stimulus with this feature is brought into their receptive field. This was more pronounced when the feature was currently task-relevant as compared to when it was currently not task-relevant (Moran & Desimone, 1985; see also Treue & Martinez-Trujillo, 1999). Neurophysiological studies also provided evidence for the notion that attention is a limited resource. When attention is deployed to a particular location in the visual field, fMRI activity representing this location has an increased baseline, while fMRI activity in brain regions representing the remaining visual field has a reduced baseline (for an overview see Carrasco, 2011). Moreover, when multiple stimuli are concurrently presented in a neuron's receptive field, the neuron's firing rate is often found suppressed compared to the presentation of a single stimulus (Luck et al., 1997). In fact, the firing rate was shown to be about the average of both stimuli presented individually, suggesting shared attentional resources (Reynolds, Chelazzi, & Desimone, 1999).

In accordance with these neurophysiological findings, visual spatial attention has been conceptualized as a focus that can be adjusted to the requirements of the visual field and that facilitates information processing at the focused locations (Belopolsky & Theeuwes, 2010; Eimer, 1999; Eriksen & James, 1986; LaBerge, 1983; Müller & Hübner, 2002; Posner et al., 1980). Although the information to be extracted from the visual environment is often defined by nonspatial features such as color, shape or size (e.g., "Is this a cherry or a deadly nightshade?"), it is usually assumed that visual selection is ultimately based on location, but nonspatial features may be used to determine where the attentional focus is guided to (Itti & Koch, 2000; Treisman & Gelade, 1980; Wolfe, 1994, 2007; for evidence that selection of features can occur without spatial attention, see Martinez-Trujillo & Treue, 2004; Zhang & Luck, 2009). For example in the widely recognized *Guided Search* model of selective visual attention (Wolfe, 1994, 2007), various nonspatial features (e.g., color, shape, orientation) are first used to determine most conspicuous locations. In a second step, attention is deployed to various locations in order of decreasing overall feature contrast (differences in color, shape, orientation etc.), which initiates a selection process.

A large body of literature was designated to investigate what determines priority in attention deployment in situations with various potential selection alternatives, i.e. to model the factors that determine which information is selected and which is disregarded (or processed to a lesser extent). These factors have often been separated in bottom-up factors that are defined by physical properties inherent of the visual stimuli and top-down factors that are set "in the observer". Bottom-up factors, often described in terms of *salience* (e.g., Wolfe, 2007), that determine efficiency of attention deployment are for example set size (e.g., Palmer, 1995), similarity of relevant and irrelevant information (e.g., Wolfe & Horowitz, 2004), or Gestalt principles like closure or homogeneity (e.g., Nothdurft, 1992; Sagi & Julesz, 1987). Top-down factors are for example current goals and intentions of the observer (e.g., Folk, Remington, & Johnston, 1992; Wykowska & Schubö, 2011), rewards associated with certain stimuli (e.g., Anderson, Laurent, & Yantis, 2012) or prior knowledge (e.g., Chun & Jiang, 1998). Top-down factors can affect visual search by weighting some dimensions more than others (e.g., color more than shape; Müller, Heller, & Ziegler, 1995) or by weighting some features more than others (e.g., red more than green; Wolfe, 2007) which allows for a more flexible usage of bottom-up signals by the visual system (Fecteau & Munoz, 2006). However, attention deployment is possible even under complete absence of intentions of the observer, then guiding attention purely on the basis of bottom-up signals (Wolfe, 1994). One bottom-up factor that has proven to be particularly powerful in determining attention deployment, and which is subject of the present dissertation, is stimulus homogeneity (Duncan & Humphreys, 1989; Nothdurft, 1991, 1992;

Schubö, Akyürek, Lin, & Vallines, 2011; Schubö, Wykowska, & Müller, 2007). More specifically, the present series of studies investigated how the homogeneity of *task-irrelevant* stimuli (the *context homogeneity*; Schubö, Schröger, & Meinecke, 2004) affects the way visual attention is deployed across the visual field and how *task-relevant* stimuli are processed. The interplay of context homogeneity and top-down factors such as prior knowledge and current goals of the observer were also taken into account.

1.1 Homogeneous stimulus configurations allow faster visual search

One of the first studies to provide evidence that homogeneity affects the way attention is deployed in the visual field comes from letter cancellations tasks, a precursor of visual search tasks. Gordon (1968) showed that participants were faster at manually crossing out pre-defined target letters (e.g., “a”) from a large list of letters when nontarget letters were more similar to each other (e.g. “b” and “d”) than when they were less similar (e.g. “b” and “e”), see Figure 2A. Related to this, Kahneman & Henik (1977) found that subjects made fewer errors in reporting target letters defined by a specific color, while ignoring distractor letters of a different color, when target and distractor letters were spatially separated into homogeneous groups of one color, instead of a more heterogeneous, alternating arrangement. This finding suggests that the visual search for target letters was aided by stimulus similarity and related grouping mechanisms.

A more systematic analysis of the role of stimulus homogeneity was possible with the *visual search task*, which allows to examine how attention is deployed across the visual field (Duncan & Humphreys, 1989; Found & Müller, 1996; Nobre, Coull, Walsh, & Frith, 2003; Theeuwes, 2010; Treisman & Gelade, 1980; Wolfe, 1998; Wykowska & Schubö, 2011; Yeshurun & Carrasco, 1998). In a typical visual search task, participants are asked to identify a pre-defined target presented within a set of distracting nontargets (‘distractors’) that differ from the target by a particular feature (e.g. color or shape) or a combination of such features (see Figure 1). Abstract geometric stimuli and very limited exposure durations are often used in such visual search paradigms to allow a well-controlled manipulation of visual search conditions. As such, visual search task have the potential to simulate the common everyday situation that we are looking for a particular piece of information while we ignore potentially distracting information. For example, when we are looking for our favorite large blue ‘Homer Simpson’ coffee cup in the cabinet of our institute’s kitchen, we are specifically searching for a certain color (‘blue’), shape (‘cylinder’) and size (‘large’) or maybe other distinct features that this cup possesses (‘imprinted yellow head’). At the same time, we try to ignore other objects of different colors, shapes and sizes that potentially distract from our ‘target cup’.

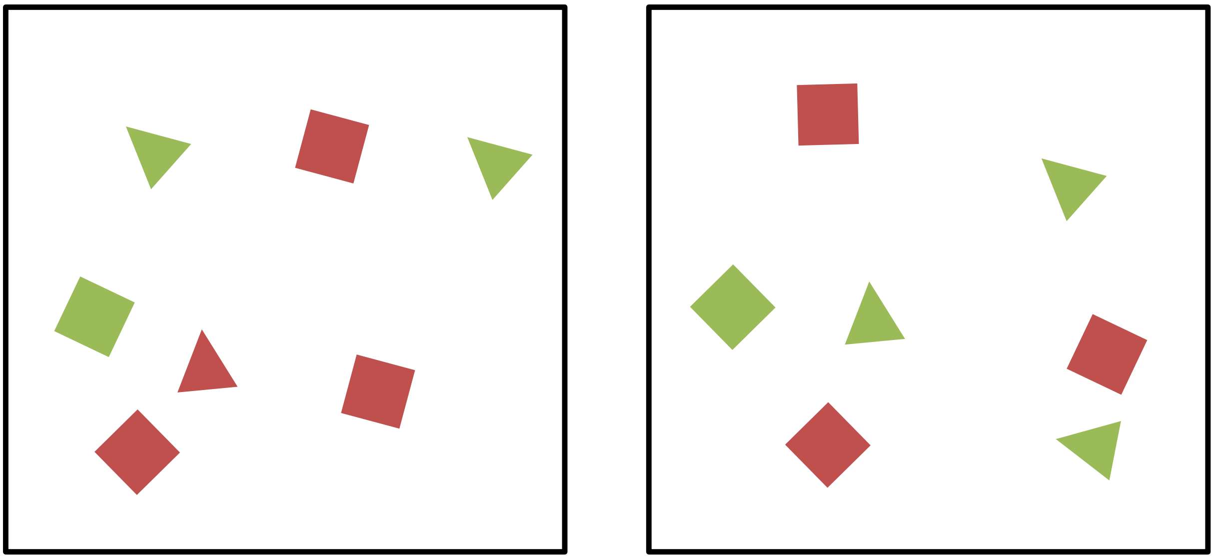

Figure 1. *In a typical visual search task, participants have to find a pre-defined target (here: red triangle) among distracting nontargets (here: green triangles, red rectangles, green rectangles). The left panel shows a target-present search display, the right panel shows a target-absent search display.*

In a seminal work, Duncan and Humphreys (1989) used a visual search task to examine the impact of distractor homogeneity on attention deployment. Participants were presented with a display of L-shaped items and asked to indicate the presence or absence of an upright “L” item serving as the target while ignoring “L”s rotated 90° to the right or left serving as distractors. Distractors could either be all of the same type (homogeneous condition; e.g., all Ls were rotated 90° to the left) or of two types (heterogeneous condition; e.g., half the Ls were rotated to the left, half the Ls were rotated to the right), see Figure 2B. The number of distractors varied from two to six. Results showed that response times for targets in the homogeneous condition were consistently shorter than in the heterogeneous condition. This response time advantage suggests faster deployment of attention to the target when only one distractor type had to be ignored (Duncan & Humphreys, 1989). Moreover, the response time advantage increased with increasing number of distractors, i.e., the more numerous the distractors were, the more search was benefiting from increased homogeneity. This supports the idea that more homogeneous distractors make attention deployment more efficient (Duncan & Humphreys, 1989; see also Wolfe, 1994).

More efficient search for targets within similar distractors led Duncan and colleagues emphasize the role of distractor homogeneity in the deployment of visual attention in the *Attentional Engagement Theory* (Duncan & Humphreys, 1989, 1992; for neural evidence see Chelazzi, 1999; Desimone & Duncan, 1995). They proposed that at an early parallel stage of visual coding, incoming visual information is effortlessly segmented into structural units according to shared physical features. At this early stage, elements that are physically similar are linked together to form a larger perceptual group that is subsequently processed as one single structural unit. The more similar distractors are at each of these hierarchical levels, the stronger they are linked and grouped. This unit grouping leads to

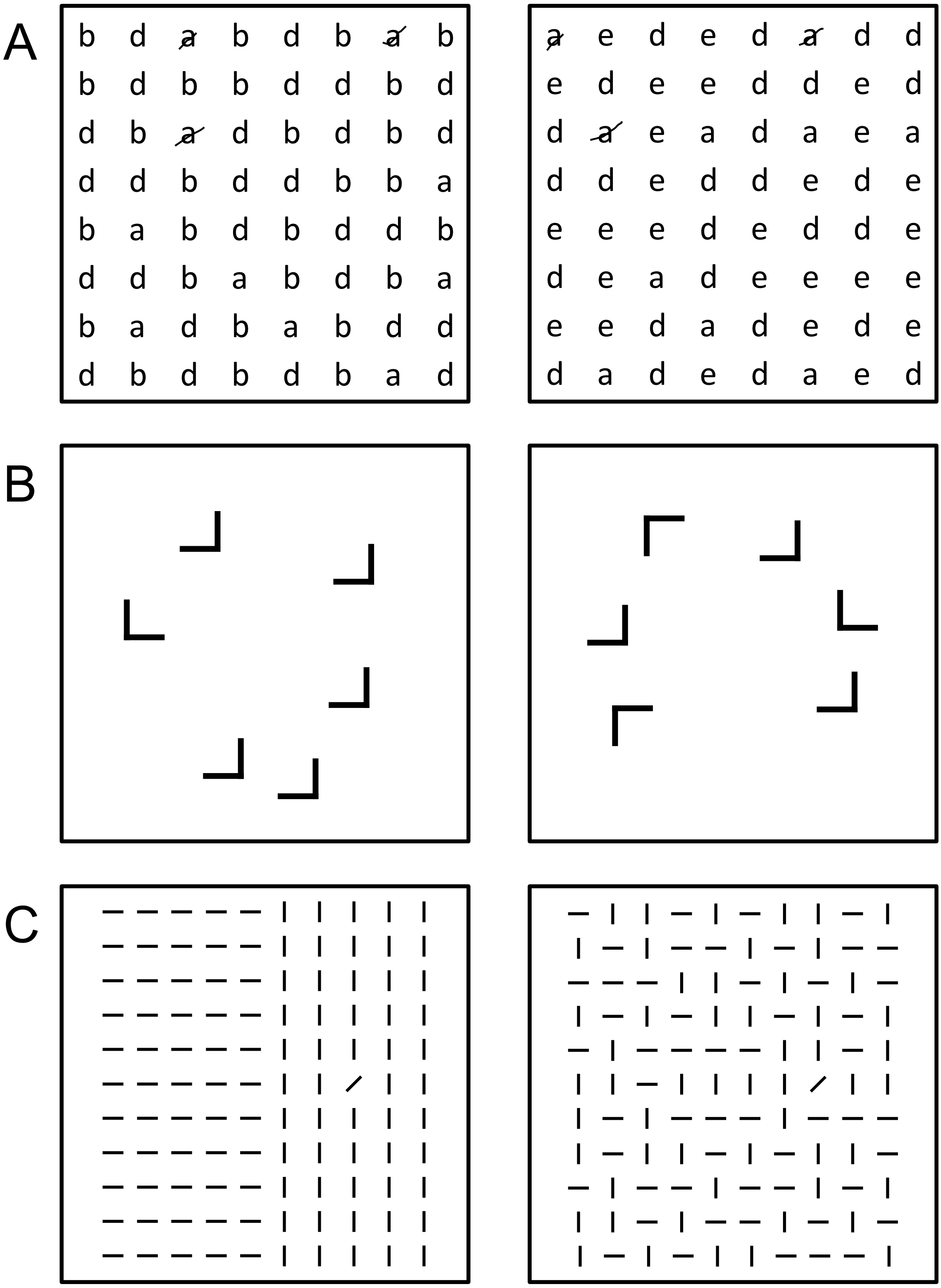

Figure 2. *The role of stimulus homogeneity in selecting visual information was investigated in various paradigms.* ***(A)*** *shows a letter cancellation task as used by Gordon (1968). Participants had to cross out 'a' letters with a pen while ignoring distractor letters. When distractor letters were more similar (left panel; 'd' and 'b'), participants were faster in crossing out target letters then when distractor letters were dissimilar (right panel; 'd' and 'e').* ***(B)*** *shows search displays as used by Duncan & Humphreys (1989). Participants had to indicate as fast as possible whether an upright L was present while ignoring rotated Ls (distractors). Participants were faster in detecting the target when distractors were all identical, building a homogeneous context (left panel) than when distractors were of varying orientation building a heterogeneous context (right panel).* ***(C)*** *shows search displays as used by Schubö et al. (2007). Participants had to detect an oblique line serving as the target while ignoring horizontal and vertical lines (distractors). Search was more accurate when distractors were arranged in grouped (more homogeneous) contexts than when they were arranged in random (more heterogeneous) contexts.*

a fully hierarchical representation by repeating segmentation at different levels of scale (Duncan & Humphreys, 1989, 1992). For example, when looking at a forest scene, the leaves of a tree may be described as units at the same hierarchical level, several leaf units would then be combined at the next level to describe the crown of the tree, and several trees would be combined at the next level to describe the forest, which is perceptually separated from a partly cloudy blue and white sky on the same hierarchical level. These structural units form the input for subsequent processing stages at which the selection of visual information occurs: Visual information is selected based on the comparison of perceptual input and a target template, while other input is suppressed. According to the *Attentional Engagement Theory,* this is done by assigning weights to units according to their physical congruency with the target template. Moreover, when the weight of an individual structural unit is changed, there is a change in the weight of other structural units proportionally to the strength of grouping between these units, a process called 'weight linkage'. For example, if you are looking for a friend in a forest, a distracting item (e.g., a particular maple tree) would receive a low weight because it is very dissimilar to the target (e.g., your friend). This will cause other distractors very similar to this distractor (e.g., other maple trees) to also receive low weights since they are strongly linked due to their similar physical appearance (e.g., same color, texture etc.). Additionally, weights for only slightly similar distractors (e.g., an oak tree) would receive slightly reduced weights (e.g., due to a slightly different shade of green). When nearby distractors are very similar and build a homogeneous structure (e.g., a group of trees forming a grove) this leads to efficient "spreading suppression", i.e. suppression of all visual information except for the target which then stands out against the background. You would then easily find your friend if she is distinct enough from the surrounding, e.g. because she wears a yellow jacket. However, if your friend wears a green jacket, she may be less distinct from the distracting trees and also receive lower weights, thus, making it harder for the visual system to find her. For less homogeneous contexts, suppression is not spreading as efficiently because distractors are linked more weakly and the target stands out less or later (Desimone & Duncan, 1995; Duncan & Humphreys, 1989, 1992). Even when your friend is wearing a yellow jacket, you may have a hard time finding her in in colorful theme park due to the more heterogeneous background.

Although initially the *Attentional Engagement Theory* was used to explain findings in visual search tasks with relatively low numbers of stimuli and a single target item to be searched for (see also *Guided Search* in which similarity effects are implemented; Wolfe, 1994), the high distractor similarity is closely related to homogeneous structures that were investigated in *texture segmentation* tasks (but see Wolfe, 1992). Texture segmentation tasks require identifying regions in the visual field which are comprised of a high number of stimuli based on basic physical features such as line orientation. For example, Nothdurft (1992; see also 1991) presented participants with a rectangular patch of simple oriented lines on a background of lines with different orientation, and varied the homogeneity of the background, i.e., the background was comprised of lines that varied slightly in orientation (high homogeneity) or that varied largely in orientation (low homogeneity). Independently, the border contrast (the orientation difference of neighboring lines at the border) was varied, i.e. the foreground and background lines could be orthogonal (high contrast) or close to parallel (low contrast). Nothdurft found that accuracy in identifying the orientation of the foreground (i.e. the rectangular patch) increased with increasing border contrast between fore- and background, and with increasing background homogeneity. When the visual field is structured by such textures, the elements of each texture can be grouped pre-attentively and processed as a unit (Ben-Shahar, Scholl, & Zucker, 2007; Julesz, 1986; Nothdurft, 1991, 1993; Wolfe, 1994). Grouping supports the effortless and spontaneous segmentation of the visual field into distinct areas without the requirement of focal attention (Humphreys, 1998). Related processes may be at work in visual search tasks whenever targets need to be found in homogeneous contexts[1].

1.2 The role of grouping in processing homogeneous contexts

For efficient grouping, stimuli need to be numerous enough to produce sufficient proximity and they need to have similar visual properties (Ben-Av & Sagi, 1995; Nothdurft, 1993; Sagi & Julesz, 1987). Following this logic, in a series of visual search studies the role of grouping processes in the deployment of visual attention was explored by varying the efficiency of grouping in two ways: using contexts of varying homogeneity and of varying set size (Schubö et al., 2011, 2004, 2007; see also Meinecke & Donk, 2002). In one study, Schubö et al. (2004) found that for perfectly identical distractors, increasing the number of distractors does not always hamper search performance, but instead can lead to a U-shaped function of performance. Participants were shown oblique line elements, with all but one tilted into the same direction, and were asked to detect whether a target line orthogonal to the distractors was present. When the number of context elements increased from 1 to 5, performance dropped, but when the number of context elements further increased to 49, performance was rising again and comparable to the condition with a low number of distractors. These results

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[1] *It should be noted that the terms used to describe stimulus configurations varies across the original articles that are part of this dissertation. This is mainly due to reviewers' requests for the use of specific expressions, or due to the aim of highlighting a specific aspect that was addressed by a paper. For reasons of better comprehensibility, in this cumulative dissertation a consistent terminology was chosen that is briefly explained here. In the literature, visual structures that comprise of many simple line elements are sometimes referred to as 'texture' and sometimes as 'context'. Although these terms may not always refer to the exact same thing, in the remainder of this dissertation the more general term 'context' will be used for reasons of simplicity for various sorts of distractor arrangements. That is, the term 'context' will be used for displays of 100 line elements (Study I and Study II) as well as for displays with 458 line elements (Study III) and for displays with 14 elements (Study IV). Another clarification is needed for the terms 'similarity' and 'homogeneity'. While the term similarity describes the physical match of two or more stimuli (Duncan & Humphreys, 1989), the term homogeneity is related but refers to larger entities of stimuli. When stimuli within a context are physically similar, the context is homogeneous. In contrast, when stimuli within a context are physically dissimilar, the context is heterogeneous. The extent of homogeneity or heterogeneity describes a spectrum from all stimuli being completely identical to all stimuli being different (or being completely randomly arranged).*

suggest that different processing modes are at work for textures with few and textures with many items. A more local processing mode, based on single items in the visual field, may be most efficient for contexts with few elements because they can each be examined more thoroughly. However, local processing suffers from an increased set size (number of distractors) because more items have to be searched for and lateral masking effects (i.e., reciprocal inhibition of objects of high proximity) may further hamper target detection (Schubö et al., 2004; see also Yeshurun & Rashal, 2010 for related 'crowding' effects). To resolve this, when more distractors are presented within the visual field, processing may switch to a global mode that allows for efficient grouping. Because an increase in the number of items strengthens grouping processes (e.g., Sagi & Julesz, 1987), weight linkages become stronger and suppression of the distractors becomes more efficient, making the global processing mode more efficient for homogeneous contexts (Schubö et al., 2004; see also 2007).

The grouping process has also been shown to strengthen with an increase in context homogeneity (Ben-Av & Sagi, 1995; Nothdurft, 1993). This was explored further in a subsequent study by Schubö et al. (2007; see also Schubö et al., 2011) in which the number of stimuli within a context was fixed but three levels of homogeneity were used. Firstly, a perfectly homogeneous context of only vertical or horizontal lines, secondly, a context grouped in two halves with one group consisting of vertical and the other group consisting of horizontal lines, and thirdly, a random context in which horizontal and vertical lines were randomly arranged, were used (for grouped and random contexts see Figure 2C). Schubö et al. (2007) found that participants performed best with homogenous contexts, followed by grouped, and then random contexts. This order of performance is in accordance with the *Attentional Engagement Theory* which describes a special case of perfect homogeneity: "…when nontargets [distractors] are all identical, responses can sometimes be based on direct coding of homogeneity or heterogeneity at the level of the whole-array unit." (Duncan & Humphreys, 1989, p. 449)". In other words, reducing the heterogeneity of distractors increases search efficiency, because homogeneous elements are being grouped, and grouping reduces the number of perceptual units that have to be searched in order to find the target. In the homogeneous condition, only one unit has to be searched for a target and a global processing mode is favorable, whereas two units have to be searched in the grouped condition making a global processing mode less efficient. In the random condition, grouping is inefficient (or even absent) and thus many units have to be searched in order to find a target. In this case, global processing may not be feasible anymore and local processing needs to be applied. Since local processing is based on single elements, it is rather slow for contexts comprising many elements (see also Schubö et al., 2004). As a result, high stimulus homogeneity allows for more efficient grouping, and thus accelerates visual search via efficient global processing in both the rejection of distractors (on target absent trials) and the singling out of the target element that does not belong to the uniform structure (in target present trials).

While it is quite evident from previous studies that the strong impact of context homogeneity on attention deployment arises from more efficient processing of *grouped* stimuli (Ben-Av & Sagi, 1995; Duncan & Humphreys, 1989; Meinecke & Donk, 2002; Nothdurft, 1992; Schubö et al., 2011, 2004, 2007), it is less understood which processing stages of visual attention are affected by context homogeneity. For example, since perceptual grouping of elements into larger units happens at early stages of visual perception, prior to (Nothdurft, 1992) and not requiring (Humphreys, 1998) focal attention, it may determine what is subsequently attended (Li, 2002; Nothdurft, 1992; Schubö et al., 2011). Accordingly, Study I of this dissertation aimed to examine how contexts modulate the shape of the attentional focus and which parts of the visual field are attended. Study II investigated sustained effects of context homogeneity on the deployment of visual attention and Study IV looked at even more progressed stages of visual processing and determined how context homogeneity could affect implicit learning. Another aspect that is not yet well understood is how processing of salient irrelevant information depends on context homogeneity. This will be examined in Study III. Before aim and scope of the present dissertation will be further explained, in the following section event-related potentials (ERP) of the EEG will be introduced that are indicative of attention processes and that were used in the present dissertation.

1.3 Neurophysiological correlates of attention deployment

Event-related potentials (ERPs) of the electroencephalogram (EEG) have shown to be very useful for investigating selective visual attention because they allow a more precise measure of cognitive processes than possible with purely behavioral measures and even allow an investigation of covert cognitive processes that often remain inaccessible by behavioral measures. For example, with purely behavioral methods, it may be possible to show that attention deployment was sufficient to allow target detection, and that attention deployment happened until a certain point in time, e.g., because a target could be identified successfully within given exposure duration. However, data may not be very conclusive about *how* efficient attention deployment was, and about the time course of attention deployment, especially *when* attention deployment was initiated. ERP measures, however, allow for the investigation of brain activity underlying attentional mechanisms from stimulus onset onward, and thus, make it possible to track various selection mechanisms online and prior to an overt response, such as a button press.

In visual search tasks, the N2pc component is often used as a neurophysiological indicator of attention-related information processing. The N2pc appears usually between 180 and 280 ms post stimulus as a negative deflection at occipito-posterior sites contralateral to attended stimuli (Brisson, Robitaille, & Jolicœur, 2007), see Fig. 3A. Typically, an N2pc is observed in visual search tasks when a lateral target is embedded in a configuration of distractors. It is assumed that the N2pc component mirrors attention deployment towards a target (Eimer, 1996; Hopf, Luck, & Girelli, 2000; Luck & Hillyard, 1994), identification and localization of a target (Mazza, Turatto, Umiltà, & Eimer, 2007), and/or attentional re-deployment within the visual field (Woodman & Luck, 2003). An N2pc is elicited by both task-relevant (Holguín, Doallo, Vizoso, & Cadaveira, 2009; Wykowska & Schubö, 2011), and by task-irrelevant, salient stimuli (Hickey, McDonald, & Theeuwes, 2006; Luck & Hillyard, 1994; but see Kiss, Jolicoeur, Dell'acqua, & Eimer, 2008; Schubö, 2009). The N2pc *amplitude* is often used as an index of the amount of attention allocated to a stimulus (Luck, 2005), whereas the N2pc *latency* is thought to reflect the point in time of attention deployment (Brisson et al., 2007).

More recently, it has been found that the distinct processes underlying efficient attention deployment, namely target prioritization and distractor suppression, may be reflected in two subcomponents of the N2pc (Hickey, Di Lollo, & McDonald, 2009). To demonstrate this, Hickey et al. (2009) used an additional singleton paradigm, a visual search task in which a target and a salient but behaviorally irrelevant singleton are presented among less salient distractors (e.g., Theeuwes, 1994). Hickey et al. (2009) presented participants with either a lateral target and a nonlateral (vertical midline) salient singleton, or with a lateral salient singleton and a nonlateral target. Because nonlateral stimuli usually do not elicit lateralized ERP components, any lateralized activity elicited by the target solely reflects prioritization of behaviorally relevant information. Similarly, any lateralized activity elicited by the salient singleton solely reflects the suppression of irrelevant information. Hickey et al. found a positive deflection of the ERP contralateral to the distractor (distractor positivity; P_D) and a negative deflection of the ERP contralateral to the target (target negativity; N_T) that are presumably subcomponents of the N2pc (Hickey et al., 2009; see also Munneke, Fait, & Mazza, 2013). When both target and distractor are located laterally, P_D and N_T would presumably sum up to the N2pc, however not allowing to disentangle target- and distractor-related activity.

Another component of the ERP that has been shown to be an informative marker of attentional processes is the P1. The P1 component is especially useful in paradigms that use the presentation of rapidly succeeding stimuli or stimulus configurations. The abrupt onset of a salient task-irrelevant stimulus (Eimer & Kiss, 2008; Henderson, 1991; Müller & Rabbitt, 1989; Ruz & Lupiáñez, 2002; Woodman & Luck, 1999; Yeshurun, Montagna, & Carrasco, 2008), or the onset of a stimulus made relevant through task-instruction (Kim & Cave, 1995; Wykowska & Schubö, 2011) can improve the processing of subsequently presented stimuli at the same location. This facilitation is accompanied by a positive deflection in the ERP elicited by the second stimulus, usually in the P1 range and starting as early as 80 ms post stimulus (Doallo et al., 2004; Luck & Hillyard, 1994; Luck, Woodman, & Vogel, 2000; Mangun & Hillyard, 1991), see Fig. 3B. It has been argued that the enhanced performance for the second stimulus is due to a sensory gain that arises when a stimulus falls into the current attentional focus; if the second stimulus is presented shortly after the first stimulus it can thus benefit from the attentional focus still dwelling at the location of the first stimulus (Itti & Koch, 2000; Posner et al., 1980). Sensory gain is reflected in increased firing rates for neurons with receptive fields in the

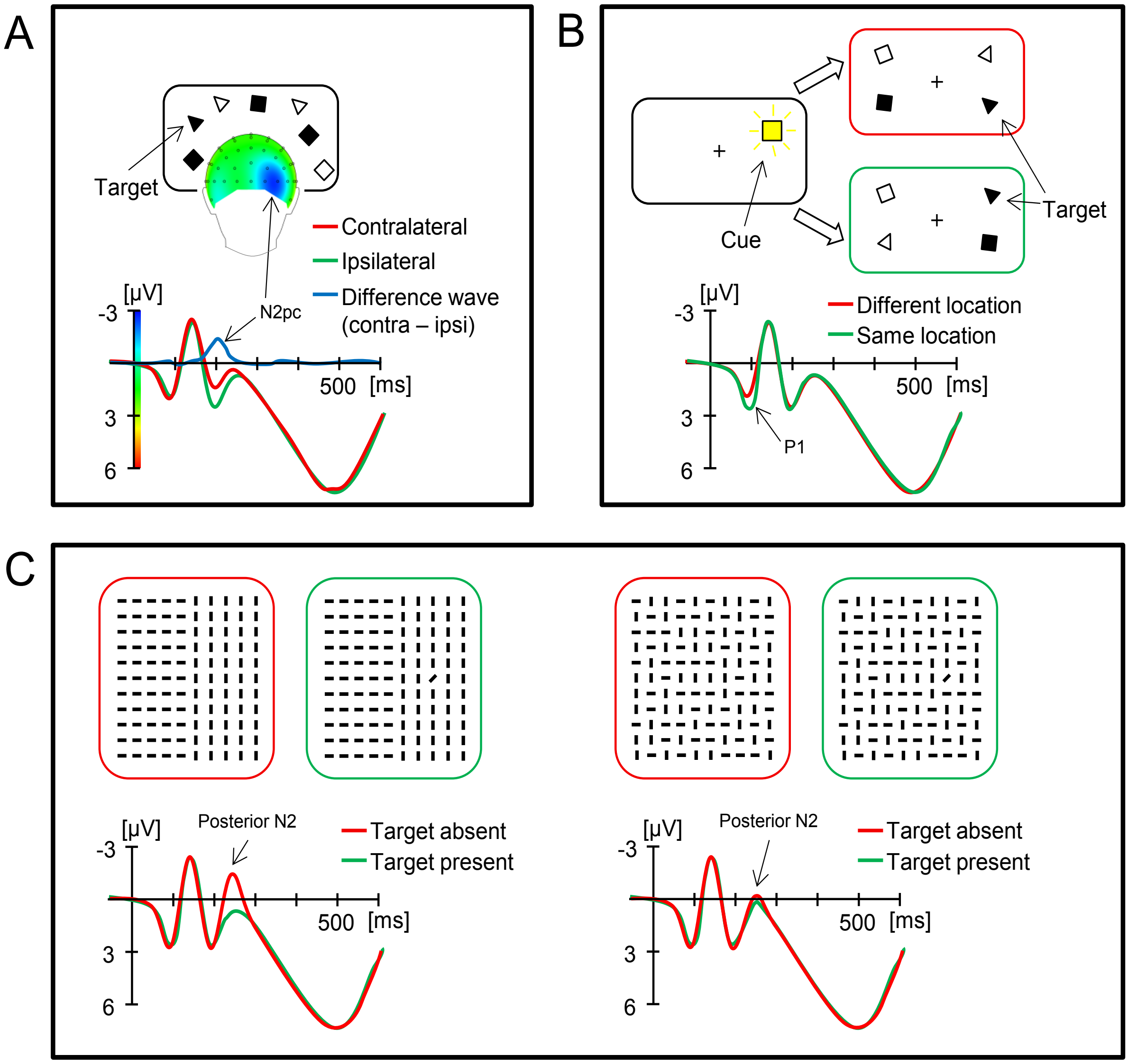


Figure 3. *Overview of event-related potentials (ERPs) used in this dissertation.* ***(A)*** *shows the N2pc component, a negative deflection in the ERP contralateral to attended locations in the visual field. In this example, the black triangle serving as the target is attended. As the target is presented in the left visual field, a negative deflection (blue spot in topographic map) is elicited in the right hemisphere. This can also be observed in the ERP: the contralateral (red) waveform is more negative than the ipsilateral (green) waveform, resulting in a negative difference waveform (blue), reflecting the N2pc. The onset of the N2pc waveform indicates when attention is deployed towards a target while the amplitude (area under the blue line) indicates the amount of attention deployed towards a target. The N2pc is presumably comprised of two subcomponents, the* P_D *and the* N_T*, not shown in this figure.* ***(B)*** *shows the P1, an early component of the ERP, indicative of sensory gain. The P1 component is typically enhanced when the attentional focus is already at the location where the stimulus that elicits the P1 is presented. For example, when a brief increase in luminance, serving as the cue (yellow patch in the figure), is presented shortly before a search display, the target elicits a more pronounced P1 when presented at the cued location (green waveform) than when presented at a different location (red waveform). This is presumably due to the cue attracting attention and the subsequent target benefitting from a sensory gain at the previous cue location (c.f., Luck et al., 2000).* ***(C)*** *shows the posterior N2 component which mirrors grouping processes. The left panel shows a condition in which stimuli can be easily grouped (c.f., Schubö et al., 2007). In this more homogeneous condition, target-absent contexts elicit a more pronounced N2 (red waveform) than target-present trials (green waveform). The right panel shows a condition in which stimuli can hardly be grouped. In this more heterogeneous condition, the N2 does not show any differences between target-present and target-absent trials. Note that A, B, and C do not represent actual data but schematic results that serve illustration purposes.*

attended location (for an overview, see Carrasco, 2011) and such sensory gain is also reflected in an enhanced P1 component of the ERP (e.g., Luck & Hillyard, 1994). Consequently, the P1 component has been used as an indicator of sensory gain due to previous attention deployment towards clearly defined locations in the visual field. The basic principle in such paradigms is that the first stimulus is presented to attract attention and the second stimulus follows at varying inter-stimulus intervals to allow for the examination of the sensory gain that reflects the previous attention deployment. Varying stimulus intervals allow examining the progress of attention deployment at several points in time. Due to its early onset, the P1 is well-suited to examine early stages of selective attention (Hillyard, Vogel, & Luck, 1998; Luck & Hillyard, 1994; Luck et al., 2000).

The perceptual grouping of similar stimuli associated with the more efficient processing of homogeneous contexts has also been found to be reflected in the ERP of the EEG signal. For perfectly homogeneous contexts that consisted of numerous nontarget stimuli, the posterior N2 was shown to be enlarged on target-absent compared to target-present trials (Schubö et al., 2004, 2007), see Fig. 3C. This differential N2 amplitude was smaller for grouped contexts and absent for random contexts. This finding suggests that the posterior N2 mirrors grouping processes: Grouping is most efficient in homogeneous contexts in target-absent trials (Duncan & Humphreys, 1989) eliciting a pronounced N2 amplitude whereas targets disrupt this grouping process and elicit a much smaller N2 amplitude. Grouped contexts that do not consist of completely homogeneous stimuli allow for less efficient grouping which results in a less pronounced N2 amplitude in target-absent trials compared to the homogeneous contexts. For grouped contexts, the N2 amplitude is also reduced by target presence, but not as much as for homogeneous contexts, as it already has a relatively lower amplitude. In random contexts, finally, grouping is very inefficient (or even impossible) resulting in low N2 amplitudes for target-absent trials. In random contexts, the presence of a target, therefore, does not further hamper grouping processes and does not reduce the N2 amplitude accordingly (Schubö et al., 2004, 2007).

1.4 Aim and scope of the present dissertation

The present dissertation aimed to better understand the role of context homogeneity in guiding attention in the visual field. Although there is a large body of evidence that more homogeneous contexts enhance visual search, less is known about the time course of attention deployment and the shape of the attentional focus in contexts of varying homogeneity. Also, little is known about how long attention deployment is affected by the context and if even more persistent effects, such as in visual long-term memory, may be evident. Further, present research has mainly been focused on how context homogeneity *enhances* processing of behaviorally *relevant* stimuli (e.g., targets in visual search tasks), but not on how context homogeneity affects behaviorally *irrelevant* but highly salient stimuli (e.g., singleton distractors).

Study I

As outlined above, enhanced attention deployment towards targets in homogeneous contexts has often been explained by grouping processes. It was argued that stimuli with similar physical features are grouped into larger perceptual units, causing improved target detection and fast distractor rejection (Ben-Av & Sagi, 1995; Nothdurft, 1992; Schubö et al., 2007). According to the *Attentional Engagement Theory*, the more similar stimuli are, the more efficiently they are grouped to one structural unit. When similar enough, the visual system can process them as one homogeneous unit (Duncan & Humphreys, 1989). Although previous results suggest that targets in homogeneous contexts receive more attention, little is known about how such early grouping processes affect attention deployment to other locations or other stimuli in the context. Study I used a variation of the spatial cueing paradigm (Müller & Rabbitt, 1989; Posner et al., 1980) to look at the time course and distribution of attention in contexts of varying homogeneity and varying border contrast. This allowed for conclusions on how attention spread within contexts thus facilitating processing of larger units of stimuli. The displays consisted of two distinct, yet homogeneous contexts of horizontal and vertical line elements. A specific location within one of these two contexts was cued with a peripheral abrupt onset (exogenous cue) or central arrow pointing towards a specific location (endogenous cue). A subsequent probe was presented at the same cued location (valid trials), at a different location but inside the same context (invalid-inside trials), or at a different location and outside the context (invalid-outside trials). Best performance was expected for valid trials, replicating earlier studies (e.g., Ruz & Lupiáñez, 2002). If attention spread context-wise, i.e., from the cued location to other locations that are part of the context, probes at invalid-inside locations should yield better performance than probes at invalid-outside locations because the former are within the attentional focus whereas the latter are not. By varying the inter-stimulus interval, the distribution of attention in the visual field could be measured at various points in time. In additional experiments, the context border contrast and the context homogeneity was varied independently to assess the individual contribution of these factors to the distribution of the attentional focus in space and time.

Study II

Study II built on Study I by further investigating the time course of attention deployment in contexts. But rather than looking at how attention spreads from one location to other locations of a context over time, Study II looked at how persistently attention was maintained at a particular location over time, i.e., how sustained attention deployment was. More specifically, Study II aimed at pinpointing the time course of differential attention deployment towards target locations in contexts of varying homogeneity. Although previous results clearly speak in favor of more efficient attention deployment towards stimuli surrounded by more homogeneous stimuli due to grouping processes (Duncan & Humphreys, 1989; Li, 2002; Nothdurft, 1992; Schubö et al., 2004), the sustained effects of grouping on attention deployment are less understood. To investigate the sustained impact of context homogeneity on attention deployment, in Study II a paradigm was used that combined a visual search task with a (subsequent) probe discrimination task. The visual search displays consisted of contexts of varying degrees of homogeneity: simple line elements were either arranged in two homogeneous groups or were arranged randomly resulting in a more heterogeneous context. A probe was presented after a short or long inter-stimulus interval either at the same location as a previously presented target or at a different location. A better search performance, as well as a larger N2pc component, for targets in grouped than in random contexts were expected, indicating enhanced attention deployment towards targets in homogeneous contexts (e.g., Schubö et al., 2007). Further, a larger posterior N2 amplitude for target-absent trials than for target-present trials in grouped but not in random contexts was expected. This would indicate that grouping processes were only available in the more homogeneous contexts (e.g., Schubö et al., 2004). Critically, the P1 component was used as an indicator of sensory gain due to prior attention deployment towards targets in grouped vs. random contexts. In case enhanced attention deployment for targets in grouped contexts was sustained and caused an enhanced sensory gain at the previous target location, the P1 elicited by probes should be enlarged when probes followed a grouped context compared to when probes followed a random context. Short and long ISIs (time between context offset and probe onset) allowed for the investigation of the effects of grouping on the deployment of attention at two successive points in time.

Study III

Efficient selective attention requires prioritizing relevant and suppressing irrelevant information (Carrasco, 2011; Wolfe, 2007). While Study I and II investigated how selection of behaviorally *relevant* information is accelerated in homogeneous contexts, Study III focused on how efficiently behaviorally *irrelevant* information can be suppressed in homogeneous or heterogeneous contexts. There may be situations in which it is not the behaviorally relevant stimulus that stands out from its surrounding, but a salient yet behaviorally *irrelevant* stimulus that is potentially attracting attention and thus impeding visual processing. Little is known about differential suppression of such stimuli in homogeneous vs. heterogeneous contexts. It is possible that a salient but behaviorally irrelevant stimulus might also benefit from context homogeneity, i.e., is processed preferentially (more likely to be selected) in homogeneous contexts when compared to heterogeneous contexts. Alternatively, one could assume that a salient item is suppressed more easily (less likely to be selected) in homogeneous contexts than in heterogeneous contexts, because the target is more likely to ‘pop out’ (Wolfe, 1994) which would enable earlier inhibition of the distractor. In Study III, the additional singleton paradigm was adapted to examine these alternative accounts, and to investigate prioritized processing of a target and suppression of a salient singleton embedded in homogeneous vs. heterogeneous contexts. Similarly to Hickey et al. (2009), the target and the salient distractor singleton were either presented both laterally, or one was presented on the vertical midline and the other one laterally. The target and the singleton were always embedded in a large context of simple horizontal and vertical lines that were either completely homogeneous (vertical or horizontal lines only) or heterogeneous (horizontal and vertical lines randomly arranged). Of particular interest was whether the varying degree of context homogeneity affected the attention-related ERP components P_D and N_T and, moreover, whether they were affected in a similar manner. By the use of these components it was intended to disentangle prioritized processing of the target (as reflected in the N_T component) and inhibition of a distractor (as reflected in the P_D component), which may be modulated differentially by context homogeneity.

Study IV

While Study I – III focused on how context homogeneity affects attention deployment, Study IV also took interactions of long-term memory and attention into consideration. More precisely, Study IV used a *contextual cueing paradigm* to investigate whether prior knowledge about stimulus configurations differentially affects attention deployment within contexts of varying homogeneity. Contextual cueing paradigms allow investigating how implicit learning of regularities in the visual field can help guiding attention efficiently. The typical contextual cueing task is a variation of the visual search task; participants have to search for a pre-defined T-shaped target stimulus embedded in contexts of L-shaped distractors. While some of the contexts are being repeated in some trials (including the associated target location), in other trials contexts are randomly created and thus novel to observers. The standard finding in contextual cueing experiments is that response times for targets progressively decrease throughout the experiment when the target is presented in repeated compared to novel contexts (Chun & Jiang, 1998; Chun, 2000; Kunar & Flusberg, 2006). The term ‘contextual cueing’ reflects the common interpretation of such results, namely that the context serves as a spatial cue for a specific target location associated with that context, implicitly learned during the experiment. As a result, repeatedly presented contexts accelerate the search process, presumably due to attentional guidance to the target location (Chun & Jiang, 1998; Ogawa, Takeda, & Kumada, 2007; Schankin & Schubö, 2009; Zhao et al., 2012). Although the role of stimulus homogeneity in visual search has been demonstrated numerous times (Duncan & Humphreys, 1989; Meinecke & Donk, 2002; Schubö et al., 2007), its role in implicit learning as evident in contextual cueing paradigms has received far less interest. The homogeneity among L-distractors (i.e., the similarity of Ls) may affect implicit perceptual learning because varying distractor homogeneity changes how well distractors can be grouped. In accordance with this assumption it was previously found that learning is more efficient when visual spatial information can be grouped (Brady, Konkle, & Alvarez, 2009; Gobet & Simon, 1996; Luck & Vogel, 1997; Woodman & Luck, 2003).

Study IV investigated the effect of context homogeneity on implicit learning by using Ls of one, two, or four orientations, or by using Ls of one, two, or four colors. It was hypothesized that internal representations of homogeneous contexts (e.g., contexts with one L type only) were learned more efficiently compared to heterogeneous contexts (e.g., contexts with four L types) because groups of context elements rather than single context elements needed to be learned. It was expected that the contextual cueing effect was more pronounced the more homogeneous contexts were. Furthermore it was investigated whether differential contextual cueing for homogeneous and heterogeneous context configurations depended on whether homogeneity was varied on a task-relevant dimension.

2 CUMULATIVE THESIS

Note: This chapter presents an overview of the research question, the paradigm used and the main measures for each individual study (see Table 1 below), and a summary (extended abstracts) follows in subchapters 2.1- 2.4 for each individual study. For reasons of comprehensibility, each summary includes a figure which briefly explains stimulus setup and most important results. Detailed information about the studies can be found in the original articles in the Appendix.

	Research question	**Paradigm**	**Main measures**
Study I	What is the time course and shape of the attentional focus in homogeneous contexts?	Spatial cueing (exogenous & endogenous)	Accuracy
Study II	How sustained is attention deployment towards target in contexts of varying homogeneity?	Successive displays (search task + probe discrimination task)	ERPs (N2pc, posterior N2, P1), accuracy, response times
Study III	How does context homogeneity affect suppression of salient stimuli?	Additional singleton paradigm	ERPs (P_D, N_T, N2pc), response times
Study IV	How does homogeneity of a context affect implicit learning?	Contextual cueing paradigm	response times (response time benefit for repeated contexts)

Table 1. *Overview of the studies that are part of this dissertation*

2.1 Study I: Textures shape the attentional focus

Reference

Feldmann-Wüstefeld, T. & Schubö, A. (in press). Textures shape the attentional focus: Evidence from exogenous and endogenous cueing. *Attention, Perception & Psychophysics.* doi: 10.3758/s13414-013-0508-z
(for original article, see Appendix, pp. A1-A23)

Summary

The spatial cueing paradigm (Posner, 1980) has often been used to study the time course of selective visual attention from pre-attentive processing to the deployment of visual attention. Study I used a variation of the spatial cueing paradigm in which cue and probe were embedded in contexts of simple line elements. In a series of 8 experiments it was investigated whether spatial cues would not only enhance processing of probes presented at cued locations, but also enhance processing of the entire context in which the cues were presented. Contexts typically consisted of 10 x 10 horizontal and vertical lines arranged in two homogeneous halves (see Fig. 4). An oblique line served as an exogenous cue and a blue or green line (highlighted with a dotted circle in Fig. 4A and 4B) served as a probe. First, a cue display was presented. After a varying inter-stimulus interval (ISI), a search display containing a probe followed, see Fig. 4A. The probe appeared either at the same location as the cue (valid trials), at a different location but within the same context (invalid-inside) or at a different location outside the cued context (invalid-outside), see Fig 4B. Participants had to indicate the probe color; cues and contexts were not behaviorally relevant.

Results (see Fig. 4C) showed highest accuracy for valid trials (green line), a replication of the traditional cueing effect (Posner, 1980). More importantly, invalid-inside trials (blue line) showed higher accuracy than invalid-outside trials (red line). The difference between invalid-inside and invalid-outside trials suggests that attention was not limited to the cued location but spread to some extent to the entire cued context. This context advantage disappeared with time while the traditional cueing effect (advantage for valid trials) was preserved.

The data shown in Fig. 4C were derived from Experiment 1 in which cues were ‘informative’, i.e., they correctly predicted the probe location in 73% of the trials. However, a similar context advantage (higher accuracy for invalid-inside than for invalid-outside) was found when cues were uninformative, i.e., when their location was uncorrelated to the subsequent probe location (Experiment 4). In Experiments 2 & 3, centrally presented small arrows indicated the subsequent probe location, serving as endogenous cues. A context advantage was also observed for endogenous cues, however at longer latencies than for exogenous cues. In Experiment 8, *orientation contrast* at the border between contexts and *context homogeneity*, two factors potentially contributing to the context advantage were systematically varied. Contexts with high homogeneity were sufficient to evoke a context-advantage,

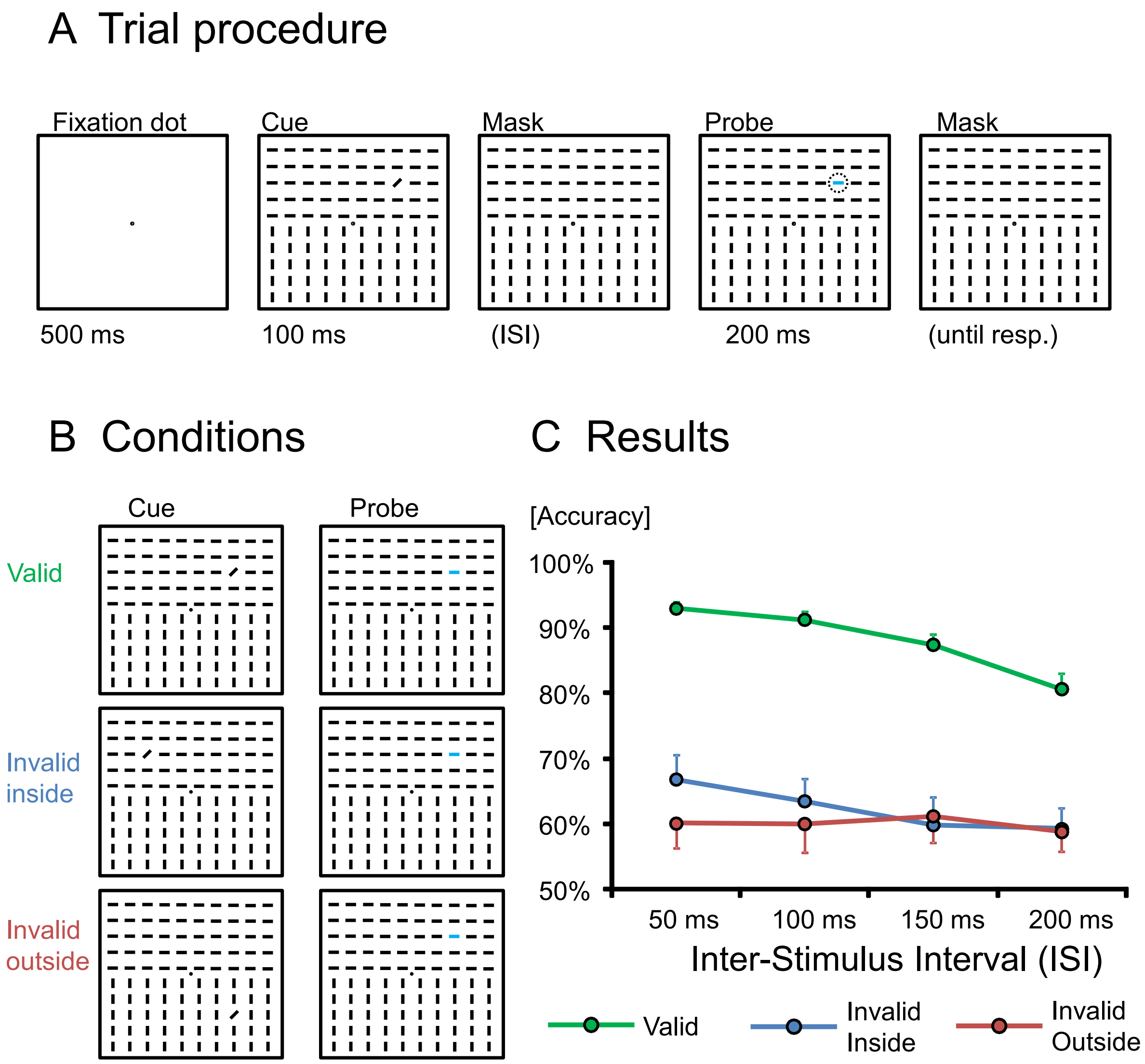


Figure 4. *Excerptions of figures from Study I.* ***(A)*** *shows the trial procedure of Experiment 1 that is representative of Study I.* ***(B)*** *shows the essential conditions used in Study I: in valid trials, the probe followed the cue at the same location. In invalid-inside trials, the probe was presented at a different location as the cue but within the cued context. In invalid-outside trials, the probe was presented at a different location as the cue and in the uncued context.* ***(C)*** *shows the results of Experiment 1 that are representative of Study I: Valid trials yielded best performance (green line), replicating the traditional spatial cueing effect. For short ISIs, invalid-inside trials (blue line) yielded better performance than invalid-outside trials (red line), suggesting a context advantage. For more details, see original article in Appendix.*

regardless the degree of border contrast. Contexts with low homogeneity could only yield a small context advantage when border contrast was high and no context advantage when border contrast was low.

Further control experiments were conducted to substantiate findings from these experiments. When the arrangement of contexts changed from an upper and lower context to a right and left context (or vice versa) between cue and search display, the context advantage disappeared (Experiment 5). Similarly, when the arrangement stayed the same but the context element identity was swapped (from horizontal to vertical and vice versa) between cue and search display, no context advantage could be observed (Experiment 6). However, when the context element identity changed gradually, context advantage could still be observed (Experiment 7). Experiments 5-7 thus suggest that gradual changes in orientation within a context did not disrupt grouping processes whereas abrupt changes in orientation disrupted grouping processes and eliminated the context advantage.

In sum, Study I shed new light on the way attention is deployed in a structured visual field. It was found that pre-attentively grouped context elements shape the focus of attention induced by spatial cues. Results showed that not only locations, but entire contexts can benefit from a cue which manifested itself in the context advantage. Therefore, one may conclude that attention spread context-wise across the visual field, at least for the first 100 ms after exogenous and 200 ms after endogenous cues. The homogeneity within contexts contributed more to the context advantage than the orientation contrast at the context border.

2.2 Study II: Context heterogeneity has a sustained impact on attention deployment

Reference

Feldmann-Wüstefeld, T., Wykowska, A. & Schubö, A. (2013). Context heterogeneity has a sustained impact on attention deployment: Behavioral and electrophysiological evidence. *Psychophysiology, 50,* 722-733. doi: 10.1111/psyp.12061
(for original article, see Appendix, pp. A25-A36)

Summary

In visual search, efficiency of finding a target increases with homogeneity of the context in which the target is embedded. Study II used a combined visual search task and probe discrimination task to investigate sustained effects of context homogeneity on deployment of visual attention. The search display comprised of 10 x 10 horizontal and vertical lines, arranged to form a context of two homogeneous halves or a heterogeneous context in which lines were randomly arranged (see Fig. 5B). An oblique line served as a target and observers had to report the orientation of that target. After a short (30 ms) or long (90 ms) inter-stimulus interval (ISI), a probe display was presented that comprised of 10 x 10 asterisks (see Fig. 5A for complete trial procedure). One of the asterisks was colored green or blue, serving as the probe, and observers had to indicate the probe color. The probe could be presented at the same or different location as the target.

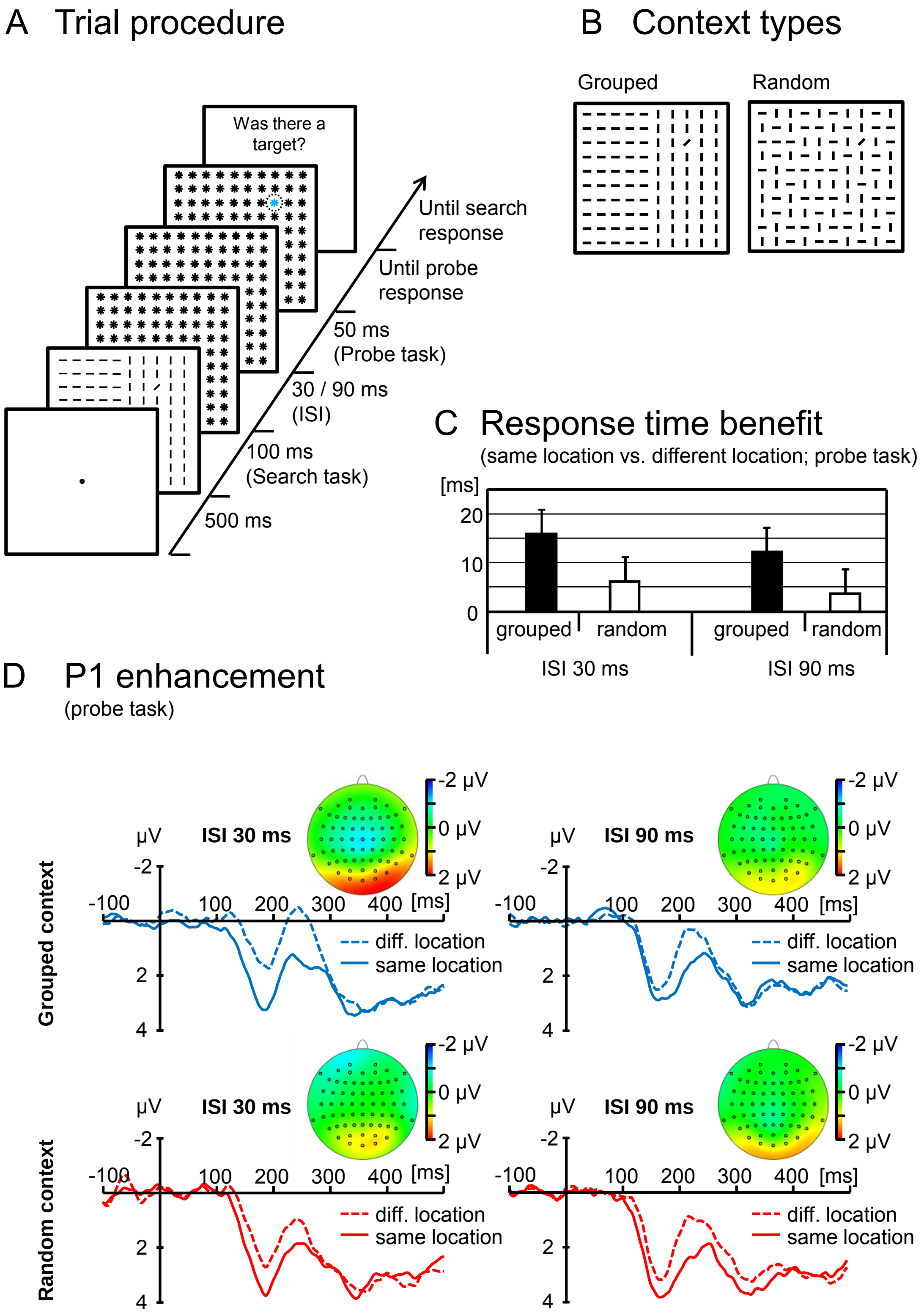


Figure 5. *Excerptions of figures from Study II.* ***(A)*** *shows the trial procedure. Participants had to first search for the oblique line serving as the target (search task) and then respond to the probe as quickly as possible (probe task). After probe response, target presence was prompted on the screen and required an unspeeded response by participants.* ***(B)*** *shows a grouped context and a random context as used for the search task.* ***(C)*** *shows the response time benefit for probes presented at the same location as the target compared to probes presented at different locations. Response time benefit was more pronounced for grouped than for random contexts, especially at an ISI of 30 ms.* ***(D)*** *shows the ERP elicited by probes; P1 was more pronounced for probes presented at target locations compared to different locations. After an ISI of 30 ms, this P1 enhancement was more pronounced in grouped contexts (upper left panel) than in random contexts (lower left panel). After an ISI of 90 ms, the P1 enhancement was comparable in size for grouped (upper right panel) and random contexts (lower right panel). For more details, see original article in Appendix*

Targets in homogeneous contexts yielded higher accuracy and larger N2pc amplitudes than targets in heterogeneous contexts, indicating more efficient selection in the former (not shown in Fig. 5). Subsequently presented probes yielded shorter response times (‘response time benefit’) and a larger P1 component in the ERP (‘P1 enhancement’) when presented at the same location as the previous target location compared to other locations. Both RT benefit (Fig. 5C) and P1 enhancement (Fig. 5D) were more pronounced in homogeneous than in heterogeneous contexts when the probe was presented shortly after the context (ISI of 30 ms) but not when the probe was presented at longer latencies after the context (ISI of 90 ms). Results from Study II thus demonstrated that homogeneous contexts had a more sustained effect on visual attention than heterogeneous contexts and enhanced visual processing for some time after contexts were presented.

2.3 Study III: Context homogeneity facilitates both distractor inhibition and target enhancement

Reference

Feldmann-Wüstefeld, T. & Schubö, A. (2013). Context homogeneity facilitates both distractor inhibition and target enhancement. *Journal of Vision*, 13 (3), 11, 1-12. doi: 10.1167/13.3.11
(for original article, see Appendix, pp. A37-A48)

Summary

Homogeneous contexts were shown to result in prioritized processing of embedded targets compared to heterogeneous contexts (Duncan & Humphreys, 1989). Efficient deployment of visual attention, however, does not only require prioritizing relevant, but also suppression of irrelevant information. Study III used behavioral and ERP measures to disentangle these two processes and thus systematically analyze how context homogeneity affects processing of embedded targets and salient distractors.

Search displays comprised of contexts of 17 x 27 simple line elements which were all identical (homogeneous contexts) or randomly arranged (heterogeneous contexts), see Fig. 6A. All contexts embedded an oblique line, serving as the target, and a red line aligned to the context, serving as a salient distractor. Observers had to report the target orientation while ignoring the salient distractor. In some trials, targets were presented laterally and salient distractors were presented on the vertical midline. In other trials, salient distractors were presented laterally and targets were presented on the vertical midline. Since stimuli presented on the vertical midline do not elicit lateralized components in the ERP, this setup allowed for disentangling target- and distractor-related activity. More precisely, two subcomponents of the N2pc were isolated; a target-negativity (N_T), reflecting prioritized

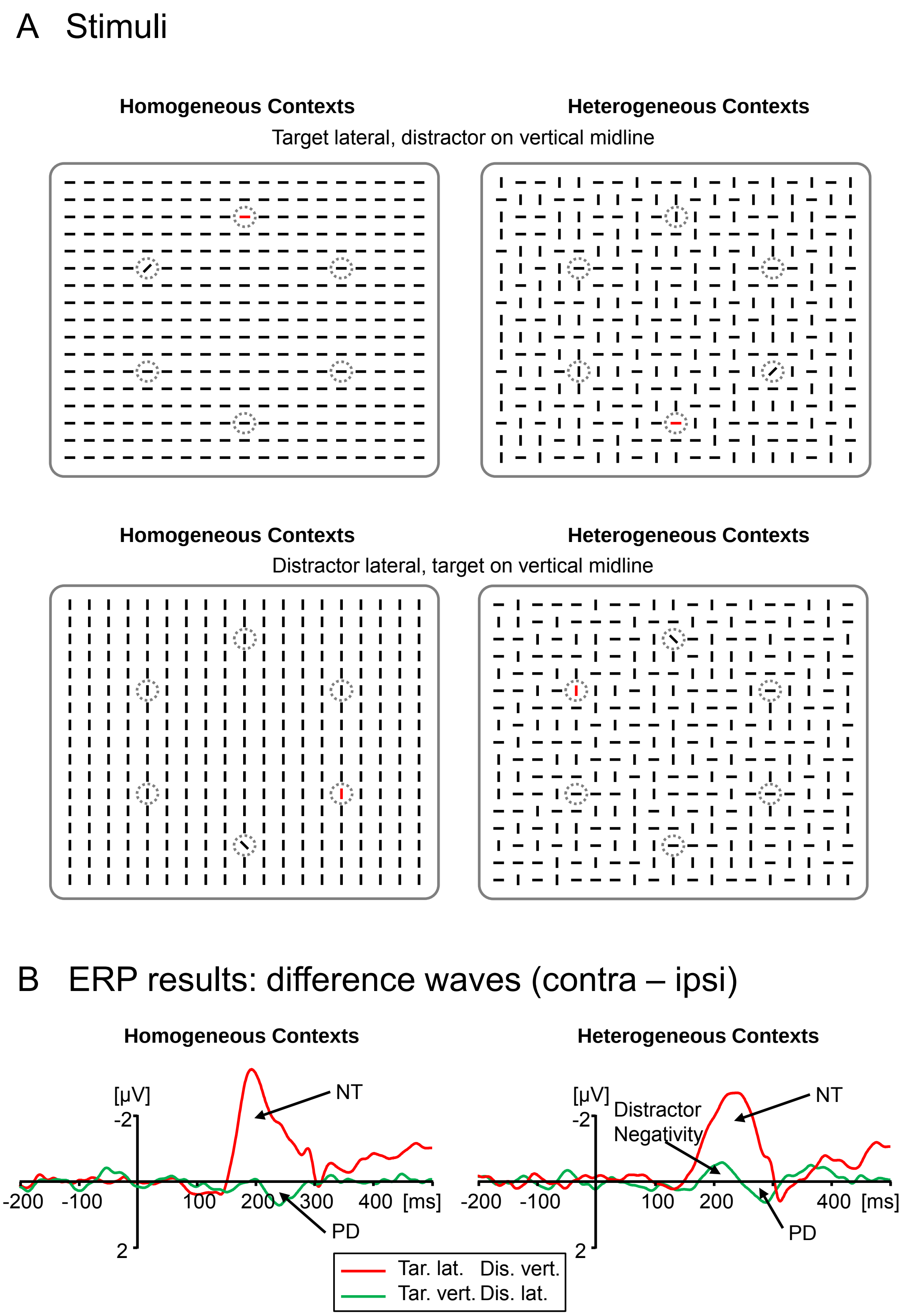


Figure 6. *Excerptions of figures from Study III.* ***(A)*** *shows exemplary search displays. In the left panels, target (oblique line) and salient distractor (red line) are embedded in a homogeneous context of vertical or horizontal lines. In the right panel, target and distractor are embedded in a heterogeneous context of randomly arranged vertical and horizontal lines. Participants were to indicate the orientation of the target (leftward vs. rightward) while ignoring the distractor and the context. Dashed circles illustrate the possible target and singleton locations and were not visible to participants. The target could be presented in a lateral position and the distractor on the vertical midline (upper panel), or vice versa (lower panel) which allowed disentangling target- and distractor related processing in the lateralized ERP.* ***(B)*** *shows the ERPs elicited by lateral targets, reflecting prioritized processing of relevant information (N_T; red lines) and by lateral distractors, reflecting suppression of irrelevant information (P_D; green lines) for homogeneous (left panel) and heterogeneous (right panel) contexts. For more details, see original article in Appendix.*

processing of relevant information and a distractor-positivity (P_D), reflecting suppression of irrelevant information (Hickey et al., 2009). Response times for targets in homogeneous contexts were shorter than for targets in heterogeneous contexts, suggesting more efficient attention deployment towards targets in homogeneous contexts (not shown in Fig. 6). Importantly, neurophysiological measures revealed that this more efficient attention deployment may have been caused not only by differential processing of targets, but also by differential processing of salient distractors in contexts of varying homogeneity: In homogeneous contexts, targets elicited an more pronounced N_T component than in heterogeneous contexts (red lines in Fig. 6B), showing more efficient prioritization of targets in homogeneous contexts. The P_D component elicited by salient distractors occurred earlier in time in homogeneous compared to heterogeneous contexts, suggesting more efficient suppression of salient distractors in homogeneous contexts (green lines in Fig. 6B). Distractors in heterogeneous contexts elicited a contralateral negativity prior to the P_D, indicating attentional capture of the distractor prior to active suppression. In sum the present results suggest that both enhanced prioritization of relevant and suppression of irrelevant information contributed to more efficient attention deployment in homogeneous contexts. Since in Study III, targets were related to top-down processing while salient distractors were related to bottom-up processing, results indicate more pronounced top-down control of attention in homogeneous compared to heterogeneous context.

2.4 Study IV: Stimulus homogeneity enhances implicit learning

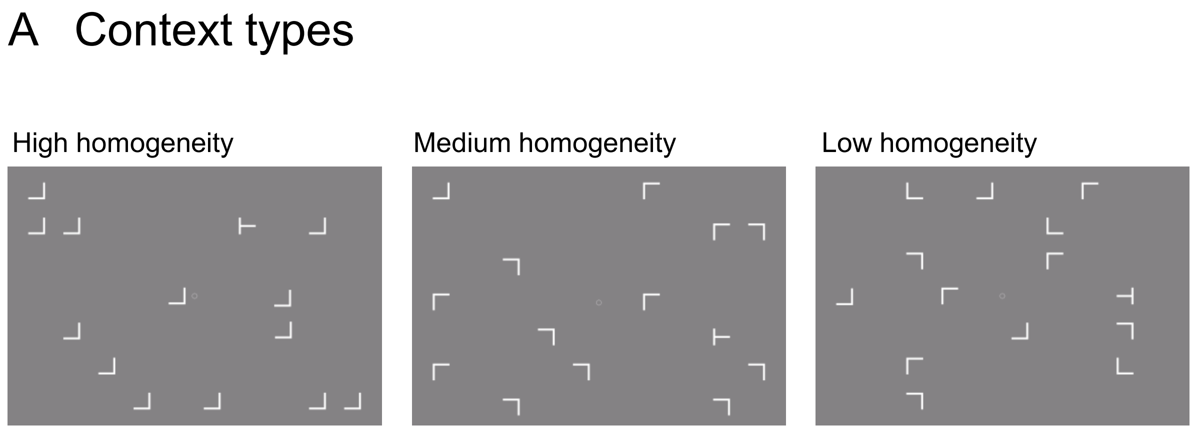
Reference

Feldmann-Wüstefeld, T. & Schubö, A. (submitted). Stimulus homogeneity enhances implicit learning: Evidence from contextual cueing.
(for submitted manuscript under review, see Appendix, pp. A51-A71)

Summary

Visual search for a target is faster when the target is embedded in a repeatedly presented context of invariant distractor configurations, an effect called ‘contextual cueing’ (Chun & Jiang, 1998). Contextual cueing is presumably based on enhanced implicit memory representations for repeated contexts. Study IV investigated in a series of three experiments how context homogeneity affects memory-related processes as evident in contextual cueing.

Search displays comprised of contexts of 14 stimuli, 13 L-shaped distractors and a T-shaped target. Participants had to indicate the orientation of the target while ignoring the distractors. Context homogeneity varied on three levels: All distractors were identical (high homogeneity), distractors were of two types (medium homogeneity) or of four types (low homogeneity), see Fig. 7A. In half of the trials, contexts were repeatedly presented, i.e. identity and location of the stimuli were identical throughout the experiment (‘old contexts’). In the other half of the trials, contexts were newly created and novel to observers (‘new contexts’). Contextual cueing denotes the typically observed shorter response times for old compared to new contexts. Results from Study IV demonstrated a contextual cueing effect in all three homogeneity conditions. More importantly, the contextual cueing effect was most pronounced for contexts with high homogeneity, followed by contexts with medium and low homogeneity (see Fig. 7B). Figure 7 shows displays and results from Experiment 1 of Study IV in which context homogeneity varied on the dimension ‘orientation’. Orientation was a *task-relevant dimension* as observers had to indicate the orientation of the target. In two control experiments (Experiment 2 and 3), context homogeneity varied on three levels of the dimension ‘color’ that was *task-irrelevant* as observers did not need to consider color in order to solve the task. In both



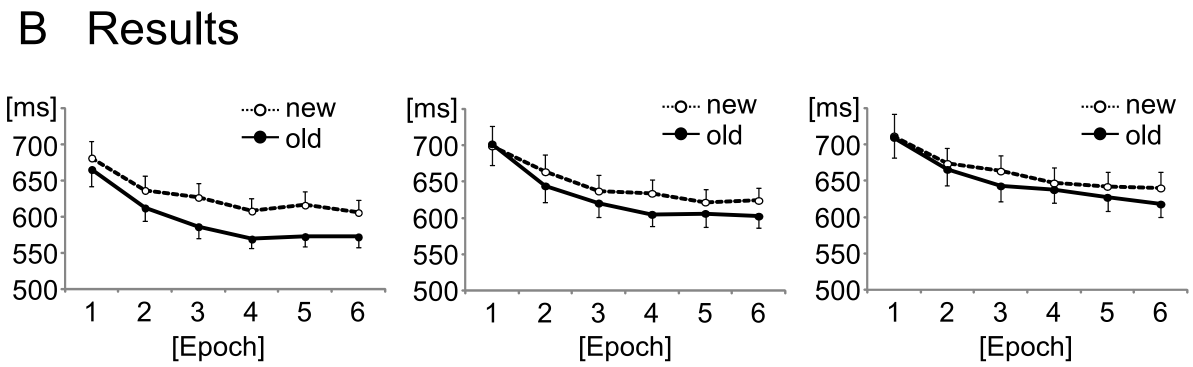


Figure 7. *Excerptions of figures from Study IV.* ***(A)*** *shows contexts used in Experiment 1. Participants had to indicate the orientation of the T-shaped target while ignoring L-shaped distractors. In the high homogeneity condition, all distractors were identical (left panel). In the medium homogeneity condition, two distractor types were used (middle panel). In the low homogeneity condition, four distractor types were used (right panel).* ***(B)*** *shows results of Experiment 1. When contexts were repeatedly presented (old), RTs were faster than when contexts were novel to observers (new). This denotes the ‘contextual cueing’ effect that was most pronounced for highly homogeneous contexts and decreased with decreasing homogeneity. For more details, see original article in Appendix.*

Experiment 2 and 3, no modulation of contextual cueing due to different levels of color homogeneity was observed (not shown in Fig. 7). One may conclude that memory representations of contexts are more easily acquired when contexts can be processed as larger perceptual units based on grouping of homogeneous stimuli. However, it seems that grouping processes can only boost contextual cueing when grouping is based on a task-relevant dimension (here: orientation) but not on a task-irrelevant dimension (here: color). In sum, Study IV showed that stimulus homogeneity is likely not only to affect visual search but also subsequent memory-related processes such as implicit learning.

3 GENERAL DISCUSSION

In four studies it was examined how the context that structures the visual field affects the deployment of visual attention. Results showed that context homogeneity plays a crucial role in attention guidance towards behaviorally relevant stimuli at various processing stages: it determines how attention spreads from a cued location to other locations in the visual field (Study I), how sustained the attentional focus remains at a certain location to facilitate processing of subsequent stimuli (Study II), and how efficiently representations of stimulus configurations are stored in memory (Study IV). Furthermore, context homogeneity does not only determine how efficiently behaviorally relevant information is prioritized, but also how efficiently behaviorally irrelevant, interfering information is suppressed (Study III).

3.1 The role of context homogeneity in deployment of visual attention

3.1.1 Stimulus prioritization and suppression in contexts of varying homogeneity

In Study I, II, and III, contexts presented to participants were comprised of simple horizontal and vertical line elements which contained an odd element, an oblique line, to serve as a behaviorally irrelevant spatial cue (Study I), or a behaviorally relevant target in a visual search task (Study II and III). Study IV used slightly more complex contexts of conjunctions of two line elements (L-shapes) that contained a T-shaped target. Results from all four studies showed that the context homogeneity tremendously affect the way we select embedded visual information. The present results demonstrated that participants more efficiently detected a target (Study II) or identified a target (Study III & IV) in case it is embedded in a homogeneous context compared to a heterogeneous context. Additionally, it was found in Study II that the better performance for targets in homogeneous contexts was accompanied by a more pronounced and earlier N2pc, an ERP component indicative of attention deployment (e.g., Luck & Hillyard, 1994; Mazza et al., 2007; Schubö, 2009). In accordance with these findings, Study III showed that targets in homogeneous contexts elicited an earlier and more pronounced N_T component, a subcomponent of the N2pc indicative of prioritized processing of relevant information (Hickey et al., 2009). N2pc and N_T results suggest that in homogeneous contexts attention deployment occurred earlier in time and was more pronounced than in heterogeneous contexts. This suggests that the better performance for targets in homogeneous contexts was due to differential attention deployment in contexts of varying homogeneity. Moreover, Study III provided evidence not only for enhanced processing of relevant, but also for suppression of irrelevant information. The P_D component which was elicited by salient distractors and is indicative of active suppression of such irrelevant information (Hickey et al., 2009), had a shorter latency and was more pronounced in homogeneous than in heterogeneous contexts. The P_D results suggest that not only prioritizing relevant information, but also active suppression of salient distracting information, was more efficient in homogeneous than in heterogeneous contexts. Furthermore, the results of Study III showed that salient distractors elicited a contralateral negative deflection in the ERP prior to the P_D when presented in heterogeneous contexts but not when presented in homogeneous contexts. This negative deflection indicates attentional capture by salient distractors (e.g., Hickey, McDonald, & Theeuwes, 2006; Schubö, 2009) was only evident in heterogeneous contexts and not in homogeneous contexts, suggesting that in heterogeneous contexts suppression of irrelevant information is less efficient.

3.1.2 Sustained effects of context homogeneity in deployment of visual attention

The current data also suggest that the structure of the visual field had sustained effects on attention deployment. The visual contexts determined how attention spread over time (Study I), had a persistent effect on attention deployment towards embedded stimuli (Study II), and even influenced the way visual spatial information was represented in long-term memory (Study IV). In Study I, a variation of the spatial cueing paradigm (Müller & Rabbitt, 1989; Posner et al., 1980) was used to investigate how visual attention was deployed in a visual field structured by contexts of homogeneous simple line elements. Line elements had no imperative character for observers because they were behaviorally irrelevant. Results showed that an odd element in an otherwise homogeneous context (oblique line amongst horizontal or vertical lines), serving as a cue, could induce greater accuracy for probe stimuli subsequently presented at the same location as the odd element, similarly to valid cues in traditional cueing experiments (for a review see Ruz & Lupiáñez, 2002). Even when the cue was uninformative of the probe location (i.e., the cue and probe location were uncorrelated), it caused enhanced probe performance up to at least 200 ms after cue offset, suggesting sustained attention deployment towards the odd element in the context. Similarly, in Study II, an odd element in a context, serving as a target in a visual search task, resulted in shorter response times (RTs) for probes subsequently presented at the same location as the target compared to other locations in the visual field. This RT benefit was evident up to at least 190 ms after the onset of the target, indicating a similarly sustained attention deployment as in Study I. In Study II, the RT benefit was complemented by a more pronounced P1 component in the ERP elicited by probes presented at the same location as the target compared to probes presented at other locations. This P1 enhancement indicates that the facilitated processing of probes was due to a sensory gain for probes presented at target locations caused by previous attention deployment towards the targets (Luck & Hillyard, 1994). Importantly, the RT benefit and P1 enhancement were both more pronounced when probes followed homogeneous contexts than when probes followed heterogeneous contexts. This suggests that the sensory gain for probes at previous target locations depended on the homogeneity of the context in which the target was embedded. When a target was presented in a homogeneous context, attention deployment towards the target was not only earlier and more pronounced, but also caused a more sustained sensory gain at the target location, facilitating subsequent probe identification.

While findings from Study I and II suggest that context homogeneity affects attention deployment in a sustained manner, results from Study IV indicate that the homogeneity of stimulus configurations may have even longer lasting effects that carry forward to long-term memory. In Study IV, a contextual cueing paradigm was employed, in which participants had to search a target in a context of distractor configurations. Some of the contexts were repeatedly presented throughout the experiment, while others were randomly created, showing a new distractor configuration in each trial. The results of Study IV showed that *contextual cueing*, i.e., shorter response times for repeated contexts (Chun & Jiang, 1998), was more pronounced for homogeneous contexts than for heterogeneous contexts. It has been argued that contextual cueing is a manifestation of implicit perceptual learning of repeated contexts that happens during exposure in preceding trials (e.g., Chun & Nakayama, 2000). Acquired memory representations then serve as spatial cues and guide attention to locations associated with a specific target location (Chun & Jiang, 1998; Ogawa et al., 2007; Schankin & Schubö, 2010; Zhao et al., 2012). Results from Study IV, by this account, suggest that more homogeneous contexts are not only more efficiently processed during search, but are also more efficiently represented in memory, thus, resulting in enhanced contextual cueing when repeatedly presented.

3.3 Homogeneity enhances visual attention through grouping processes

Enhanced attention deployment towards stimuli embedded in homogeneous contexts has been argued to be due to efficient pre-attentive grouping of similar nearby stimuli (Duncan & Humphreys, 1989; Nothdurft, 1992; Sagi & Julesz, 1987). According to the *Attentional Engagement Theory*, grouping facilitates the search process for embedded information because it reduces the number of perceptual units that have to be searched in order to find the target (Duncan & Humphreys, 1989). The posterior N2 component of the ERP was identified as a neurophysiological marker of such grouping processes (Schubö et al., 2004, 2007). In Study II, the data showed that in grouped contexts, search displays elicited a larger posterior N2 in target-absent trials as compared to target present trials. This was not observed for random contexts, which suggests that grouping was more efficient in more homogeneous contexts than in less homogeneous contexts. A global processing mode may have been employed for grouped contexts, taking advantage of grouping and allowing processing of larger perceptual units (Schubö et al., 2007). Conversely, a more local processing mode may have been employed in random contexts because grouping was not possible. The more efficient grouping in turn may have caused the enhanced attention deployment towards the target, as observed in better performance and shorter / more pronounced N2pc in Study II and N_T in Study III.

Results from Study I were in line with this notion, and further provided evidence that homogeneous contexts are grouped efficiently and spontaneously without any effort to be processed as one perceptual unit. In Study I, performance for targets presented in uncued locations systematically depended on the way the visual field was segmented into contexts: In invalid trials, performance was still better when target and cue were presented inside the same context (invalid-inside), than when they were presented in different contexts (invalid-outside). Because invalid-inside locations were equally far away from the spatial cue and equally likely to show the behaviorally relevant probe as invalid-outside locations, it was not necessarily beneficial for observers to prioritize these locations more than any other (uncued) location. The advantage for locations inside the cued context, thus, suggests a spontaneous involuntary spread of attention from the conspicuous location - where the odd line element was located - to the entire context. It is possible that such a spread of attention, as observed in Study I, resulted in an enhanced attention deployment towards targets in homogeneous compared to heterogeneous contexts, which was demonstrated in Study II.

Grouping processes that lead to larger structural units in homogeneous contexts (Bacon & Egeth, 1991; Duncan & Humphreys, 1989; Nothdurft, 1992; Schubö et al., 2007) as evident in Study I – III may also explain the stronger contextual cueing effects for homogeneous contexts observed in Study IV. When L distractors built a heterogeneous context, single stimuli may have been represented in memory, requiring a relatively high storage capacity. Conversely, when L distractors built a homogeneous context, groups of stimuli may have been represented in in memory, requiring a reduced storage capacity. As a result, in Study IV, homogeneous contexts may have caused an enhanced contextual cueing effect because the more efficiently learned groups of L distractors in homogeneous contexts allowed for a more reliable and faster conclusion about the target location. More efficient learning of homogeneous contexts is in line with findings showing that learning is more efficient when visual spatial information can be grouped based on Gestalt principles (Luck & Vogel, 1997; Woodman, Vecera, & Luck, 2003), when observers have expert knowledge within a visual domain (Gobet & Simon, 1996), or when statistical regularities and associations among stimuli were present (Brady et al., 2009).

In sum, the present series of studies provided further evidence for the predictions of the *Attentional Engagement Theory*, implying that grouping processes have a strong impact on how attention is deployed in the visual field (Duncan & Humphreys, 1989, 1992). It should be noted that the crucial role of stimulus homogeneity in attention deployment, pioneered by Duncan and colleagues, was also implemented in other visual search models (Bundesen, 1990; Itti & Koch, 2000; Wolfe, 1994). For example in the *Guided Search Theory* (Wolfe, 1994, 2007), the strength of the bottom-up signal for a particular stimulus in the visual field (‘salience’) is a function of the stimulus’ difference from all other items in the visual field on all feature dimensions, scaled by the distance between them. By this account, improved processing of targets embedded in a homogenous compared to a heterogeneous contexts can also be explained by *Guided Search Theory*: The more homogeneous a context is, the lower is the salience of each context element due to mutually low differences on various feature dimensions. The target, constituting the only element which is different from the context would receive the highest salience signal and, importantly, would have to compete against less salient elements in homogeneous than in heterogeneous contexts. The implications of the present results for salience models will be further discussed in section 3.5.

3.4 Mechanisms of attentional facilitation in contexts of varying homogeneity

Although there is a broad consensus *that* visual processing is facilitated within the attentional focus (Belopolsky & Theeuwes, 2010; Eimer, 1999; Eriksen & James, 1986; LaBerge, 1983; Müller & Hübner, 2002; Posner et al., 1980), different mechanisms were suggested explaining *how* such prioritization of visual stimuli at attended locations is realized by the visual system. Firstly, according to the *reduction of spatial uncertainty* account, the number of monitored locations in the visual field is reduced by visual attention. As a result, fewer distractors need to be matched with the target template thus decreasing the overall likelihood that a distractor is confused with a target (e.g., Eckstein, Peterson, Pham, & Droll, 2009; Morgan, Ward, & Castet, 1998). Secondly, *sensory gain* may enhance the entire signal at attended locations compared to unattended locations (e.g., Carrasco, Williams, & Yeshurun, 2002; Hillyard et al., 1998). Thirdly, *signal tuning* may occur at attended locations by the application of a local filter that enhances the signal-to-noise ratio (Ling, Liu, & Carrasco, 2009; Lu & Dosher, 1998). Reduced spatial uncertainty, sensory gain and signal tuning were suitable to explain various results from the visual attention literature and may in fact all contribute to enhanced performance for stimuli at attended locations (for a review see Carrasco, 2011).

Which of these mechanisms could contribute to the attentional benefits for homogeneous contexts observed in the present series of studies? Reduced spatial uncertainty is unlikely to explain a higher performance in high homogeneity conditions, because observers had no indication to monitor smaller areas of the visual field in homogeneous compared to heterogeneous contexts in any of the experiments. Regarding the remaining two mechanisms that may account for attentional benefits, Ling et al. (2009) suggest that the relative contribution of sensory gain and signal tuning on improved visual processing at attended locations could be assessed by measuring attentional effects under varying degrees of visual noise. For example, sensory gain is predicted to not be very powerful in high-noise scenarios because sensory gain not only enhances the signal (e.g., the target), but also the noise (distractors) at attended location. In other words, sensory gain does not much improve performance in high-noise scenarios because the signal-to-noise ratio is not improved by sensory gain. In low-noise scenarios, however, sensory gain can enhance performance due to an amplified signal strength without amplifying much noise (for neurophysiological evidence see Martinez-Trujillo & Treue, 2002).

Therefore, if attentional modulation can only be observed when little noise is present, this suggests that sensory gain drives the effect (Ling et al., 2009). Conversely, signal tuning could be especially helpful in high-noise scenarios: signal tuning improves the signal-to-noise ratio which is particularly beneficial in high-noise scenarios because a large portion of noise can be excluded from visual processing. In low-noise scenarios, on the other hand, only a small portion of noise can be excluded by increased signal-to-noise ratio, resulting in smaller benefits due to signal tuning. Therefore, if attentional modulation can only be observed when a lot of noise is present, this would suggest that signal tuning drives the effect (Ling et al., 2009).

In the present series of studies, contexts had different noise levels; heterogeneous contexts involved more noise than homogeneous contexts (Eckstein, 2011; Li, 2002). Accordingly, it is possible to draw conclusions from the present pattern of results in terms of how much sensory gain or signal tuning contributed to enhanced processing of targets within homogeneous contexts. For example, in Study II, when attention was deployed towards the target location, a better probe performance was observed for probes at the same location (‘on target trials’). This attentional benefit was more pronounced after ‘low-noise’ homogeneous contexts than after ‘high-noise’ heterogeneous contexts. Accordingly, one could argue that a sensory gain mechanism was responsible for the sustained homogeneity advantage because attention modulated the low-noise condition more than the high-noise condition. This is also in line with the finding in Study II that the P1 component, indicative of a sensory gain (Hillyard et al., 1998; Luck, Heinze, Mangun, & Hillyard, 1990), was more pronounced for probes after homogeneous than after heterogeneous contexts. As there was also a smaller but substantial on-target advantage after heterogeneous contexts, this could indicate that the noise level in the heterogeneous condition was still low enough so that heterogeneous contexts could benefit from sensory gain to some extent (c.f., Carrasco, 2011). It could also indicate that signal tuning, in addition to sensory gain, is involved in the sustained homogeneity advantage. To further scrutinize the relative contribution of various attentional mechanisms, future research could for example employ more levels of noise to better estimate the contribution of signal tuning (see section 3.6 for operationalization of a continuum of context homogeneity). Furthermore, spatial uncertainty and context homogeneity could be varied systematically to assess whether reduction of spatial uncertainty is also involved in the sustained homogeneity advantage.

3.5 Context representations on salience and priority maps

Several current theories of visual attention assume that deployment of focal attention is based upon a *priority map* that codes the visual field in a topographical manner; the priority map represents all stimuli in the visual field, with a particular activation reflecting the current relevance of a stimulus (Fecteau & Munoz, 2006; Itti & Koch, 2000; Li, 2002; Wolfe, 1994, 2007). The priority map receives bottom-up input from a salience map that is activated by physical stimulus features and highlights those stimuli that are very distinct from other stimuli in the visual field (Itti & Koch, 2000; Li, 2002). These salience computations are for example implemented to constitute a first massive parallel process in *Guided Search* (Wolfe, 2007). The salience map in turn receives input from different feature maps, each representing a specific physical quality of the visual environment (e.g., color or orientation), and sums up these values to determine the distinctiveness of the represented stimulus in a featureless manner (Fecteau & Munoz, 2006; Treisman & Gelade, 1980). The activation pattern on the salience map is available at a very early point in visual processing (Itti & Koch, 2000) and are argued to be based on activations in V1 (Li, 2002), the ventral visual pathway (Mazer & Gallant, 2003), or the oculomotor system including frontal eye fields and the superior colliculi (Bichot & Schall, 1999; Fecteau & Munoz, 2006). The summed bottom-up inputs represented on the saliency map are then weighted by top-down processes (such as an observer’s current goals) and feed forward to build representations on the priority map. The priority map is subsequently used to prioritize those stimuli in the visual field that will receive more elaborated, attentive processing. Potentially interesting objects in the visual field compete for selection and, based on the activation on the priority map, focal attention is deployed to various conspicuous locations occupied by competing items in order of decreasing activation until the relevant information is found (e.g., Wolfe, 1994).

3.5.1 Salience computations in contexts of varying homogeneity: bottom-up processing

How do the results of the present series of studies relate to previous findings regarding computations on salience and priority maps? In Study II and III, targets were equally relevant and physically identical in both homogeneous and heterogeneous context conditions. Firstly, equal relevance presumably balanced the top-down influences, leading to a direct translation of salience signals to priority signals without further weighting, and thus, resulting in guidance of attention on the basis of salience map activation (Fecteau & Munoz, 2006; Itti & Koch, 2001). Secondly, physical identicalness of targets in the homogeneous and heterogeneous condition suggests that any difference in target salience was due to differences in the surrounding context rather than physical features inherent of the target stimuli. Indeed, it has been argued before that the same orientation singleton can have different saliency values depending on the arrangement of the surrounding context elements (Li, 2002; Nothdurft, 1990). In the present experiments, when contexts were homogeneous, the reciprocal neural inhibition of context elements was presumably rather strong because processing of an item most efficiently inhibits processing of other items that share the same physical properties (Li, 2002; Luck et al., 1997). Figure 8 illustrates how this should result in different salience map patterns; relatively low activation for context element representations in homogeneous contexts due to strong mutual inhibition and relatively high activation for context element representations in heterogeneous contexts due to weak mutual inhibition (compare overall activation level in Fig. 8A and 8B). At the same time, in homogeneous contexts a target is presumably inhibited relatively weak and only little ‘noise’ is

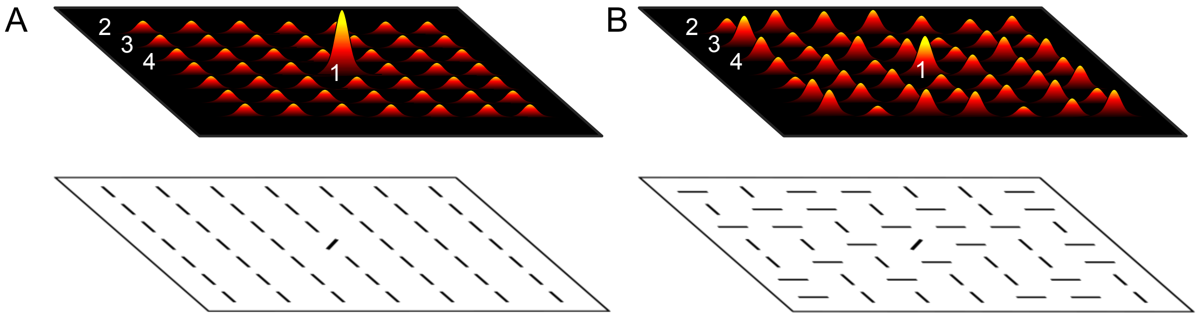


Figure 8. *Salience maps for homogeneous* ***(A)*** *and heterogeneous* ***(B)*** *contexts. Due to high mutual inhibition, homogeneous context elements should receive lower activations than heterogeneous context elements. This is illustrated in the figure by overall lower activation for homogeneous compared to heterogeneous context elements (e.g., the sum of #2, #3, and #4 is smaller in A than in B). Furthermore, heterogeneous context elements should induce more noise on the salience map than homogeneous context elements. This is illustrated in the figure by more variation in activation for homogeneous compared to heterogeneous context elements (e.g., #2, #3, and #4 vary more in B than in A). In both context types, targets should receive highest activation because they are the only oblique lines in the visual field. This is illustrated in the figure by a higher target activation (#1) in the homogeneous (A) than in the heterogeneous (B) context. Note that this figure does not represent actual data; it depicts a model of salience computations that can explain the pattern of results observed in the present series of studies.*

added to context representations compared to heterogeneous context elements (Desimone & Duncan, 1995; Fecteau & Munoz, 2006). On the salience map for a homogeneous context, one would thus expect a clear peak of activation indicating the target location and a smaller peak of activation for heterogeneous contexts (compare activation #1 in Fig. 8 A and B). In addition, one would expect a relatively low variation in activation for context elements in homogeneous contexts and a relatively high variation in heterogeneous contexts (compare variation among #2, #3, #4 in Fig. 8 A and B). As a result, the probability of initial attention deployment towards the target location was presumably rather high in homogeneous contexts because activation for the target (#1 in Fig. 8A) was larger than any other activation most of the time (Itti & Koch, 2001; Wolfe, 1994). Conversely, in heterogeneous contexts, activation for one of the context element could be higher than for the target in a particular trial (e.g., #3 is almost as large as #1 in Fig. 8B), which could explain the higher accuracy for targets in homogeneous contexts (Study II, III and IV) as well as the earlier attention deployment as evident in shorter N2pc latency (Study II) and N_T latency (Study III).

In paradigms that use successive stimulus configurations (e.g., spatial cueing), the enhanced performance for stimuli presented at the same location as previously presented stimuli was explained by cumulative activation on the salience map. For example, probes might be represented with a higher activation in valid compared to invalid trials in spatial cueing tasks. This could be due to a residual cue activation at the probe location in valid trials compared to residual cue activation at a competing location in invalid trials (e.g. Fecteau & Munoz, 2006). Such residual activations on the salience map for cues could explain results from Study I in which probes were presented at the cued location and from Study II in which probes were presented at the previous target location. In both studies, probe performance was better when the probe was presented at the cued location or the previous target location compared to probe presentation at any other location. This could be explained by a benefit from persistent activation from the previous cues / targets, which would lead to an accumulation of more activation than at any other location in the visual field (Itti & Koch, 2001). When probes were presented in a location where no cue / target was initially presented, the representation of the probe location could not benefit from prior activation, and further, had to compete with the activation of the prior cue / target location; hence, probe detection was less efficient. Results from Study I, however, showed that not only the location that a stimulus occupied may have received enhanced activation which can be preserved for subsequent stimuli. Instead, the entire *cued context* (i.e., the context that embedded the cue) received prioritized processing to some extent (as evident in the context advantage observed in invalid-inside trials). This context advantage suggests that representations of all locations that were part of the cued context received more activation on the salience map than locations outside that context (see Fig. 9A). Apparently, the odd element in the context (the oblique line serving as the cue or target) not only induced high activation on the salience map for its very location, but also added some activation to other locations representing stimuli of the same context. This presumably yielded a gradient of activation on the salience map: while the cued location received highest activation, resulting in best performance, the cued context received more activation than the remaining visual field, resulting in better performance for the cued context compared to the uncued context. Time-course-wise, the data from Study I also showed that a context advantage for probes presented in the cued context disappeared after 100 ms (exogenous cues) or 200 ms (endogenous cues). This might

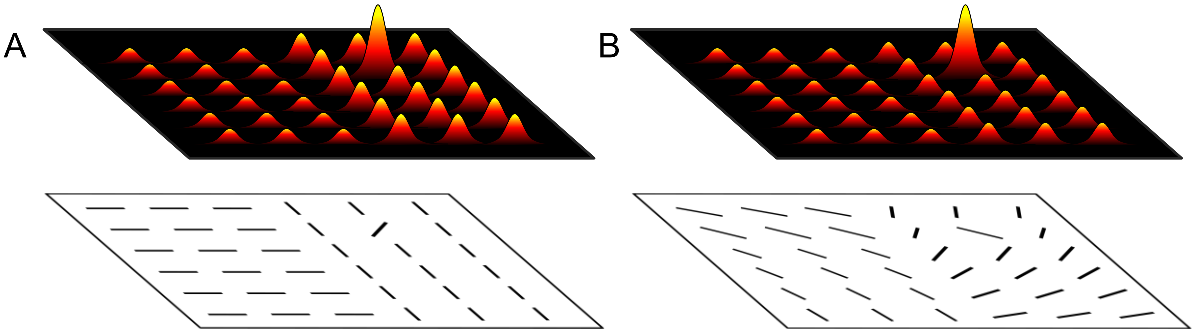


Figure 9. *Salience maps for grouped contexts as used in Study I. The lower panels show a context with homogeneous groups of line elements as for example used in Experiment 1* ***(A)*** *and a context with heterogeneous groups of line elements as for example used in Experiment 8* ***(B)****. An oblique line served as a cue and subsequently presented probes yielded best performance when presented at the same location as the cue. This could be due to residual activation on the salience map, as illustrated in the upper panels of the figure by the highest peak at the cue location. In Study I, probes could be presented in uncued locations, but within the same context as the cue (invalid-inside), yielding better performance than probes at uncued locations outside the context (invalid-outside). This could be due to higher residual activation on the salience map for the entire context in which the cue was presented. This is illustrated in the figure by higher peaks for the right side of the visual field compared to the left side of the visual field (A; upper panel). When context homogeneity was reduced, probe performance was still best for the cued location, but the benefit for invalid-inside trials was less pronounced than for homogeneous contexts (Experiment 8). This could be explained by relatively lower residual activation on the salience map for the cued context when the context was less homogeneous. This is illustrated by less activation for the cued context when the context was heterogeneous (B; upper panel) than when the context was homogeneous (A; upper panel). Note that this figure does not represent actual data; it depicts a model of salience computations that can explain the pattern of results observed in Study I.*

indicate that the gradient of activation on the salience map became sharper over the course of time after stimulus presentation. This might have had the consequence that after some time has passed, only the cued location, not the cued context, benefitted from remaining activation on the salience map. This is in line with previous studies showing a rather flexible deployment of attention in the visual field (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Eimer, 1999) and points towards the necessity of economizing limited attentional resources as revealed by neurophysiological studies (Luck et al., 1997; Reynolds et al., 1999). Since deploying attention towards the invalid-inside and invalid-outside location was equally beneficial for observers (targets appeared at both locations with equal probability), the present results also show that the per se irrelevant context can modulate the use of attentional resources in a predominantly bottom-up manner.

Importantly, present data suggest that decreasing the context homogeneity affected activation on the salience map in a *spatial* and a *time-related* manner. The data from Study I showed that decreased homogeneity within a context eliminated prioritized processing of subsequent stimuli in the cued context but not of subsequent stimuli in the cued location (see Experiment 8). This suggests that residual activation on the salience map is *spatially limited*, which means that it can only spread to locations representing the same context when that context is sufficiently homogeneous. By this account, cues in less homogeneous contexts induced less activation to other locations of the same context on the salience map (see Fig. 9B). Results from Study II showed that probes could benefit more from being presented at the same location as a previous target (RT benefit, P1 enhancement) when the target was embedded in a homogeneous compared to a heterogeneous context, especially at shorter latencies. This suggests that residual activation on the salience map was weaker and more *time-limited* for heterogeneous contexts. It is possible that less reciprocal neural inhibition produced by heterogeneous context elements (less similar stimuli suppress each other less, c.f., Li, 2002) resulted in a smaller, and more likely to fade, peak of activation on the salience map. In other words, more homogeneous contexts lead to more pronounced and longer lasting activation peaks of embedded stimuli on the salience map.

3.5.2 Salience and priority computations: interactions of bottom-up and top-down processing

How are salience signals computed when more than one potentially interesting stimulus is concurrently presented in the visual field? It is usually assumed that concurrently presented stimuli compete for the limited attention resources (Bundesen, 1990; Luck et al., 1997; Wolfe, 1994) and this competition is represented by differential activation levels on the salience or priority map (Fecteau & Munoz, 2006; Itti & Koch, 2000, 2001). In Study I and II, only one salient stimulus was presented at a time, but as argued above, in trials in which the second stimulus (the probe) was presented at a different location as the previous cue / target, there may have been a competition between residual activation of the first stimulus, and the activation of the second stimulus, potentially hampering optimal processing. In Study III, targets were always presented together with a salient singleton that potentially interfered with target processing. This presumably made it necessary to weight salience signals and thus guide attention based on activation on the priority map (see Fig. 10 A-1 and B-1). On the salience map for homogeneous contexts, activations for targets and distractors were comparable (Fig. 10 A-2). A distractor presumably received high activation on a color feature map (see Fig. 10 A-4), because it was the only colored item in the visual field (see Fig. 10 A-5). As argued above, in homogeneous contexts the target should also have received high activation on the salience map due to input from an orientation feature map (Fig. 10 A-3); the target was the only oblique line in the visual field (Fig. 10 A-5). In Study III, the orientation target was behaviorally relevant as participants had to report the orientation in every trial. The color singleton was not behaviorally relevant and participants were instructed to ignore it. Accordingly, the target representation was probably receiving higher activation by specifically giving higher weights to oblique lines (Wolfe, 2007) or the entire orientation feature map (Itti & Koch, 2001). Conversely, to circumvent potential distraction from the goal, activation on the color feature map probably received especially low weights (which is equivalent to suppression; see Fecteau & Munoz, 2006). As a result of the weighting process, one can assume that the activation peaks for the color singleton distractor and the oblique line target on the priority map differed from each other (see Fig. 10 A-1); a larger peak for the target location and a smaller peak for the distractor location would be expected (Serences & Yantis, 2006; see also Fecteau & Munoz, 2006).

Importantly, results from Study III also showed that the extent to which a salient distractor interfered with attention deployment towards the target depended on the homogeneity of the context in which target and distractor were embedded. Both behavioral measures and ERP measures showed that prioritized processing of targets and suppression of singletons was more efficient in homogeneous contexts. This strongly suggests that different patterns of activation on the priority map were induced by homogeneous and heterogeneous contexts (see Fig. 10 A-1 and B-1). The crucial difference between context types may have been the differential activation between targets versus salient distractors, i.e., how much more activation a target (#1 in Fig. 10) received than a salient distractor (#2 in Fig. 10), in trials with homogeneous compared to trials with heterogeneous contexts.

As argued above, targets presumably received lower activation on the orientation feature map when they were embedded in heterogeneous contexts (see Fig. 10 B-3). Conversely, the red singleton, serving as a salient distractor, should have received a similar activation on the color feature map in homogeneous and heterogeneous contexts (compare Fig. 10 A-4 and B-4), because the homogeneity in terms of color was identical in both context types. As a result, on the overall salience map that combines orientation and color, a larger peak of activation may be found for the distractor than for the target location (Fig. 10 B-2). Also in heterogeneous contexts, the behaviorally relevant target should be weighted higher and the irrelevant distractor should be weighted lower on the priority map. However, due to the higher activation of the distractor on the salience map (Fig. 10 B-2), the activation for the target is not so much higher than the activation for the distractor on the priority map

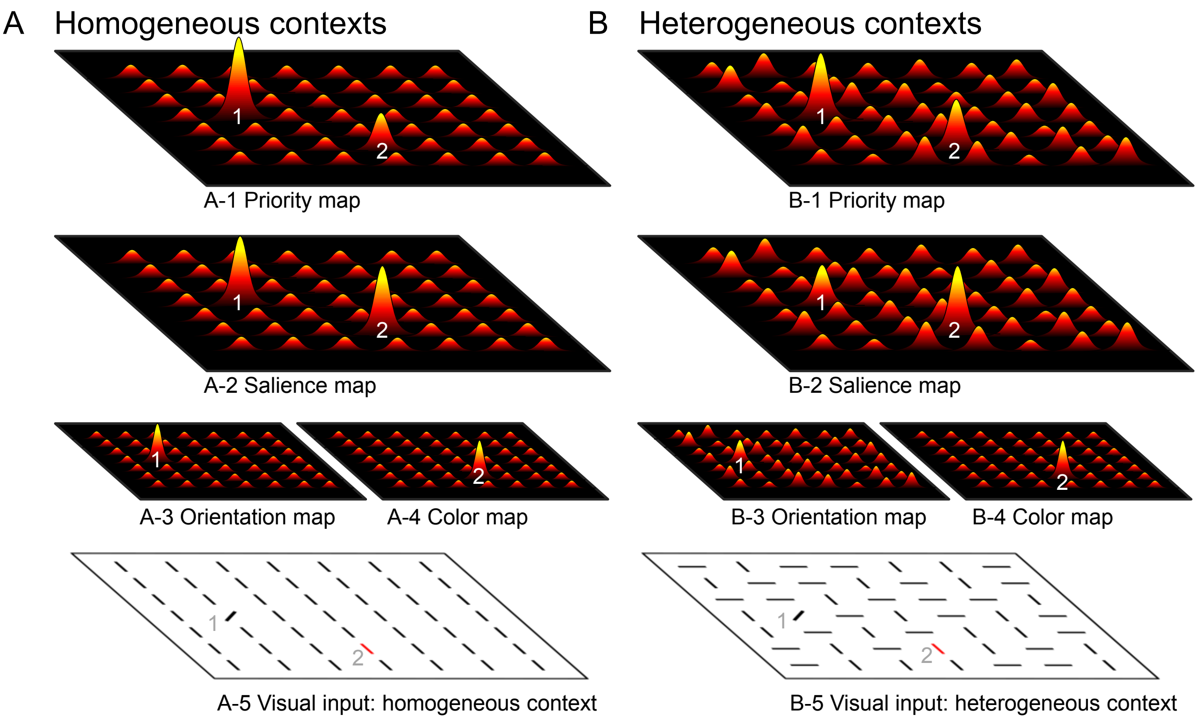


Figure 10. *Salience and priority maps that reflect bottom-up and top-down processes in contexts of varying homogeneity. A-5 shows a homogeneous and B-5 a heterogeneous context as used in Study III. As targets (#1) are the only oblique lines in the context, they should receive highest activation on the orientation feature map in both contexts (A-3 and B-3). As salient distractors (#2) are the only red lines in the context, they should receive highest activation on the color feature map in both homogeneous (A-4) and heterogeneous (B-4) contexts. Due to more suppression of the target, this activation peak should be smaller for targets in heterogeneous contexts (B-3) compared to homogeneous contexts (A-3). Color feature map and orientation feature map feed forward to a combined overall salience map (A-2 and B-2). In homogeneous contexts, target and salient distractor should receive approximately the same amount of activation (A-2) due to similar input from color and orientation map. In heterogeneous context, salient distractors should receive more activation than targets (B-2) because of the reduced activation of the target on the orientation feature map. As observers had the task to report the orientation of the target and ignore the salient color singleton, orientation should be weighted higher and color should be weighted lower. The amplification of the orientation map signal by top-down control should result in highest activation for the target on the priority map (A-1 and B-1). This is very efficient in homogeneous contexts (A-1), because the activation peak for the target on the salience map is relatively large (A-2). In heterogeneous contexts, however, the activation peak for the target is initially smaller than the peak for the distractor on the salience map (B-2). As a result, the difference between the activation of the target and the salient distractor is smaller in heterogeneous (B-1) compared to homogeneous contexts (A-1).Note that this figure does not represent actual data; it depicts a model of salience and priority computations that can explain the pattern of results observed in Study III.*

for heterogeneous contexts (Fig. 10 B-1). The high accuracy rates (> 90%) for both context types in Study III suggest that eventually the target was found most of the times within the limited exposure duration, in both homogenous and heterogeneous contexts.

As there is always additional noise on top of the activation for each location on the priority map, target locations may in general not always be the first locations to which attention is deployed (Wolfe, 1994; Itti & Koch, 2000, 2001). By this account, in heterogeneous contexts the smaller differences in activation for targets and distractors on the priority map may have led to relatively frequent initial attention deployment towards the salient distractor location (attentional capture), as reflected by a distractor negativity (inversed P_D). As a result, in heterogeneous contexts relatively often attention was deployed towards the target location in a later step, reflected by a smaller and later target negativity (N_T) and longer RTs. In homogeneous contexts, however, attention was more likely initially deployed towards the target than in heterogeneous contexts because most of the time the target received higher activation than the salient distractor. This was reflected in an earlier and more pronounced N_T and P_D. The differential activation patterns on the priority map in homogeneous compared to heterogeneous contexts can also be described as enhanced top-down control in visual search for the target (and ignoring the singleton): the visual system was more reliably able to differentiate between target and distractor according to current goals when both were presented in homogeneous compared to heterogeneous contexts (the current goal was to find an orientation singleton while ignoring a color singleton and denotes a top-down signal). This does not necessarily mean that distractor suppression is not based on low-level features, but it suggests that top-down processing might be less vulnerable to interferences from potentially distracting low-level features in homogeneous contexts. At the same time, processing of stimuli embedded in heterogeneous contexts might be more vulnerable to distraction by salient stimuli.

The importance of top-down control in deployment of visual attention within contexts was also observed in Study IV, which showed how prior knowledge can affect the deployment of attention in the visual field. One approach to account for such contextual cueing effects is based on the assumption that the priority map activations can be modulated by prior knowledge. This approach stems from the notion that coarse statistical information about the visual field may be processed very rapidly with unlimited capacity; as a result, this information can be matched with prior knowledge and subsequently allows efficient deployment of visual attention within the visual scene in case prior knowledge allows for conclusions on where to attend (Wolfe, Võ, Evans, & Greene, 2011; Wolfe, 2007). Rapid processing with unlimited capacity may also apply to contexts presented in contextual cueing paradigms and could account for shorter RTs for repeated contexts; amplified activation of target locations on the priority map could be possible through previous implicit learning (Geyer, Zehetleitner, & Müller, 2010). Geyer et al. (2010) argue that during visual processing, activation on a priority map is compared with (implicitly) stored representations of contexts by means of previous activation patterns. In case the current activation pattern matches a prior activation pattern, the target location associated with that activation pattern will receive a higher pre-activation, thus increasing the probability of attention deployment towards the cued location (Geyer et al., 2010; see also Oliva & Torralba, 2007; Torralba, 2003). This seems plausible as a connectionist model has shown that repetitive activation of a given pattern will increase activation for a target location which is consistently associated with that pattern (Brady & Chun, 2007).

Study IV found more pronounced contextual cueing effects for homogeneous than for heterogeneous contexts. Following the logic of Geyer et al. (2010), this suggests that amplification of salience signals, resulting in enhanced activation on the priority map for targets in repeated contexts, was stronger in homogeneous than in heterogeneous contexts. One may speculate that this is due to faster processing of homogeneous stimulus arrangements that can be perceptually grouped (Duncan & Humphreys, 1989), and hence, faster computation of salience signals. As a result, an earlier comparison of the current salience map activation with prior activation patterns, as suggested by Geyer et al. (2010), is possible. One other explanation could be that representations of homogeneous contexts in the 'contextual memory' (Geyer et al., 2010) are represented more efficiently, thus, allowing more reliable comparisons with current activations patterns.

In sum, the present data indicate that both salience computations as well as weighting salience on the priority map are affected by the homogeneity of the context in the visual field. Increased homogeneity reduces the noise on the salience map and thus increases the chance of initial attention deployment towards relevant items. Increased homogeneity makes attention guidance on basis of the priority map particularly efficient, allowing for a better suppression of irrelevant information and the facilitated use of prior knowledge due to previous implicit learning.

3.6 Conclusions and future directions

The present dissertation demonstrated the crucial role of the visual context in the deployment of attention at various stages throughout visual processing. Results from all four studies showed that the contexts that structure the visual field tremendously affect the way we attend, select, and maintain visual information. It was shown that the context modulates early visual processing and can determine the shape and time course of the focus of visual attention: attention spreads context-wise across the visual field. Furthermore, this dissertation has provided evidence for the crucial role of the *homogeneity* of a context for attention deployment in the visual field: more homogeneous contexts accelerate visual search for an embedded target and allow for a more sustained attention deployment than heterogeneous contexts. Moreover, this dissertation demonstrated that not only prioritizing relevant information, but also suppressing irrelevant information boosts efficiency of visual search in homogeneous contexts. Finally, it was investigated in this dissertation how context homogeneity affects later memory-related processes: more homogeneous contexts were shown to enhance the beneficial effect of implicit learning on the deployment of visual attention.

In summary, this dissertation showed that the context of the visual field is a crucial component in the process of efficiently applying the limited resource of selective visual attention. Importantly, the contexts used in the current series of studies were behaviorally irrelevant structures in the visual field – meaning that the individual items that contexts consisted of had no imperative character because observers did not need them in order to solve the task. Results from the four studies, involving data from 223 participants in 13 experiments, complemented and extended previous research on the important role of such task-irrelevant items on how we perceive and attend to information in our visual environment (Bacon & Egeth, 1991; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Nothdurft, 1992; Sagi & Julesz, 1987). The results presented in this dissertation may have important implications for future research as they emphasize the importance of considering the numerous effects that the visual context can induce in models of visual attention: it becomes evident from the present results that *behaviorally irrelevant* stimuli strongly influence the way *behaviorally relevant* items are selected and processed. Importantly, the present data show that the context is important at various processing stages of visual perception. Future research should thus take stimulus configuration, especially context homogeneity, into consideration when examining how attention spreads in the visual field, how sustained attention deployment towards a specific location is, and how attention and long-term memory interact. Moreover, future studies that investigate the inhibition of irrelevant information should take context homogeneity into account.

Ideas for future research

The present dissertation may inspire future research to further explore how contexts affect the deployment of visual attention. For example, the benefit for homogeneous contexts may depend on how demanding visual search is, and how much attention is generally needed to find a target. In Study II, targets embedded in contexts of varying homogeneity had to be *detected*, i.e. participants had to indicate the presence or absence of a pre-defined target (‘was there an oblique line?’). A more attentionally demanding task would be to not only detect a target but to also identify it, i.e., to *discriminate* between two potential targets and then report the respective identity (‘was the oblique line pointing upwards or downwards?’). It was shown that target discrimination is usually more demanding than detection tasks, which results in delayed response times and attention processes for discrimination tasks (Braun & Julesz, 1998; Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997). Thus, the sustained attention deployment towards targets in homogeneous, compared to heterogeneous, contexts may be also delayed when the target has to be discriminated rather than just detected. In future studies, target detection and target discrimination, together with tasks of intermediate attentional demands (e.g., target localization), or even more demanding tasks (e.g., compound search tasks), could be compared regarding the role of context homogeneity. As a consequence, it may be possible to conclude at which stages context homogeneity facilitates attentional processes and to obtain a more fine-grained model of the time course of grouping processes.

Another factor future research should explore, is how varying operationalizations of homogeneity may affect attention deployment in the visual field. In the present dissertation, homogeneity was typically operationalized by using the same stimuli (horizontal and vertical lines) that were arranged differently, for example, in two groups of identical stimuli (more homogeneous context) or in a random pattern (more heterogeneous context). Thus, not only the level of homogeneity, but also the number of perceptual groups varied between contexts of varying

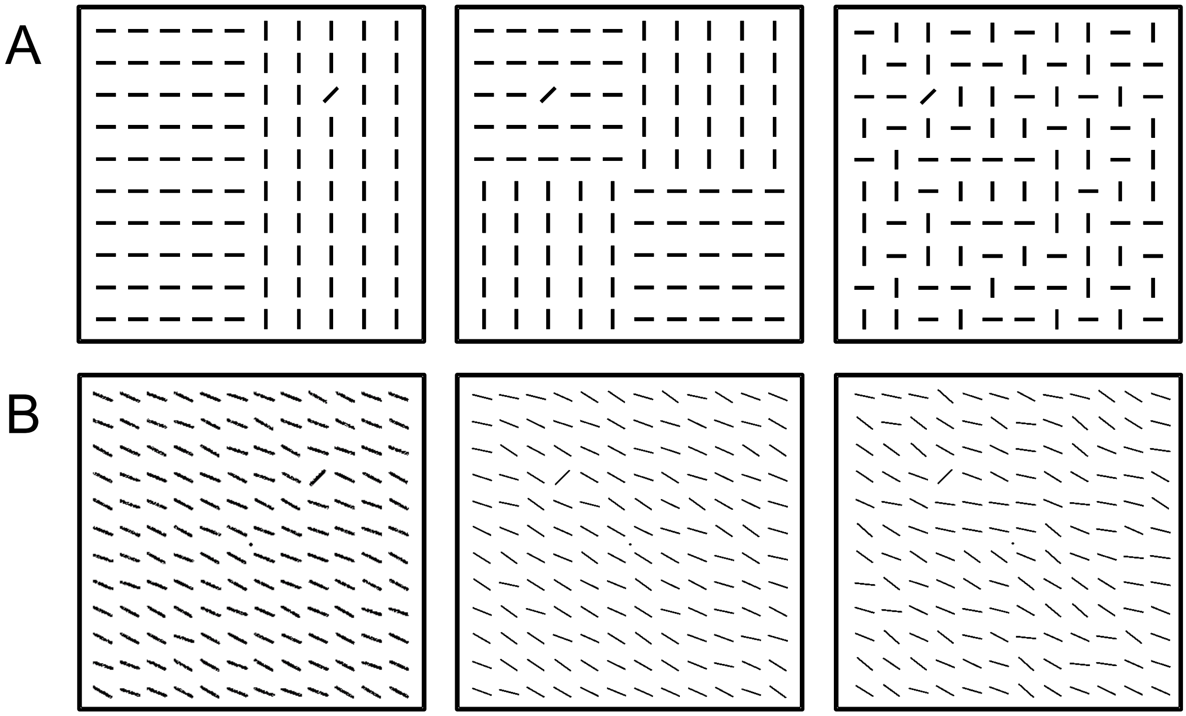


Figure 11. *Different operationalizations of homogeneity; homogeneity decreases from left to right.* ***(A)*** *shows varying levels of homogeneity by arranging the same two line elements (horizontal and vertical) differently. Two large (left panel), four smaller (middle panel) or many very small (right panel) groups of stimuli build the context in which the target (oblique line) is embedded.* ***(B)*** *shows an operationalization of homogeneity that was not used in this dissertation but may be useful for future research. The variation in angle ranges from 12° (left panel) and 24° (middle panel) to 36° (right panel). Note that the same stimulus identities are used in (A) while the number of stimulus identities varies in (B). Conversely, the number of stimulus groups does not vary in (B) while it does in (A).*

homogeneity (see Fig. 11A). By this account, it was possible to use only two context element identities, namely horizontal and vertical lines to control for the number of different context elements in homogeneous and heterogeneous contexts. Homogeneity may, however, also be operationalized by using contexts with lines of varying orientations. For example, lines could vary within 12°, within 24°, within 36°, or within 90° of angle thus imposing varying levels of homogeneity (see Fig. 11B). By this account, there are no borders separating the visual field into different numbers of perceptual groups in contexts of varying homogeneity. This comes with the drawback that the context element identities would not be the same in contexts of varying homogeneity, possibly limiting the use of such contexts to cases in which distractors do not have to be identical between conditions. An obvious advantage of homogeneity variations as shown in Fig. 11B would be that more grades of homogeneity are possible because virtually every variation of angles could be used. More grades of homogeneity would allow for a more fine-grained analysis of the effect of homogeneity on various processing stages of visual attention. For example, the differential modulation of sustained attention deployment (similar to the paradigm used in Study II) could be investigated for ten grades of homogeneity. Similarly, the efficiency of actively suppressing a salient distractor (as in Study III) could be investigated for ten grades of homogeneity. Finally, more grades of homogeneity are equivalent to more grades of noise levels (Eckstein, 2011). Thus, more grades of homogeneity would allow for a better estimation of the

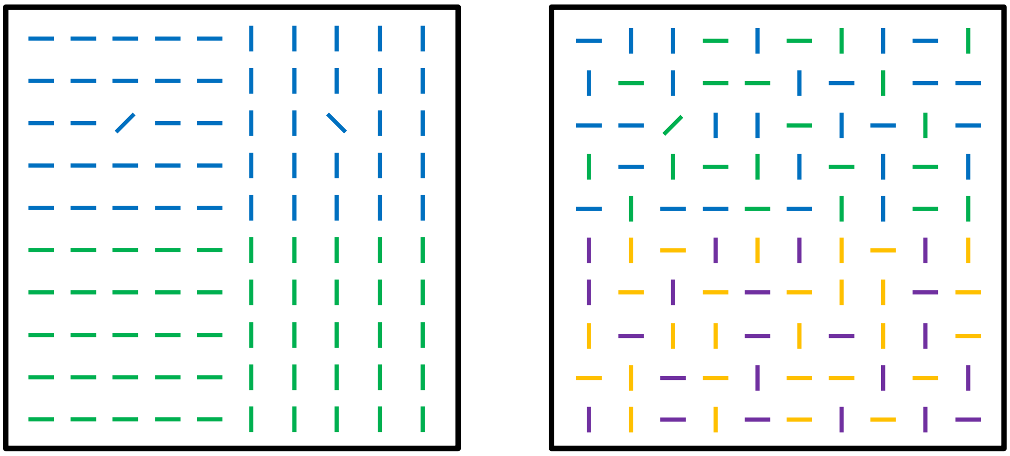


Figure 12. *Contexts with potentially interfering grouping tendencies. In the left panel, stimuli may be grouped according to color in an upper and lower half and the oblique lines, serving as targets would be within the same group, presumably facilitating target processing. Conversely, stimuli may be grouped according to orientation in a left and right half and targets would be in different groups, presumably impeding target processing. Which grouping process is dominant may be determined by various factors. For example, pre-stimulus oscillations (amplitude in a specific frequency range or concentration in a specific phase) may cause grouping by orientation or grouping by color. Moreover, the feature dimension currently relevant to the observer may determine which grouping process wins. For example, orientation may be more relevant because observers need to keep an orientation-defined object in visual working memory. The right panel shows a context that is heterogeneous according to orientation but grouping may be possible according to color. When a green and a blue item need to be kept in visual working memory, grouping of green and blue lines may be facilitated and the oblique target line would be in a grouped half, presumably facilitating target processing. Conversely, when blue and purple items are kept in visual working-memory, blue and purple lines may not be grouped because they do not intermingle to one combined context. Thus, the target would not be in a grouped half, presumably impeding target processing.*

relative contribution of sensory gain and signal tuning to attentional benefits in contexts of varying homogeneity.

While Study IV provided evidence that the homogeneity of contexts in visual *long-term* memory affects visual search, increasing evidence suggests a close relationship between visual *working memory* and attention deployment. For example, it was found that information in the visual field is more likely to be selected if it matches information stored in visual working memory: a red distractor is more likely to capture attention when a stimulus of a similar shade of red has been stored in visual working memory (Olivers & Eimer, 2011). Future research might want to examine visual processing stages prior to deployment of visual attention and investigate whether information stored in memory can also affect the way stimulus configurations in the visual field are grouped. For example, contexts with elements of varying colors may be grouped differently depending on whether one of the colors has to be actively kept in memory (or alternatively, actively suppressed from working memory), see Fig. 12.

In the present dissertation, event-related potentials of the EEG were used as markers for attention processes and have shown to be useful tools in examining the time course and amount of attention deployment towards targets (N2pc, N_T), the inhibition of distractors (P_D), the sensory gain due to previous attention deployment (P1), and in assessing grouping processes (posterior N2). In addition to traditional ERPs, future research could use time-frequency analyses to further explore EEG data and examine differential processing of homogeneous and heterogeneous contexts as a function of frequency band amplitudes and phase locking. This would allow for uncovering the neural basis of differential attention processes that are otherwise obscured by averaging across EEG frequencies in ERP methodology (e.g., Makeig, Debener, Onton, & Delorme, 2004). Related to this, grouping processes as evident in homogeneous contexts may also be affected by the observer's mental state prior to stimulus presentation. There is empirical evidence showing a link between pre-stimulus brain activity and subsequent performance in visual perception and attention tasks (e.g., Busch & VanRullen, 2010). Future research could examine whether pre-stimulus brain activity not only affects which information is detected, but also how visual information is grouped in terms of various Gestalt principles such as context homogeneity, see Fig. 12.

Theoretical implications for future research

One aspect of the present dissertation that may have theoretical implications for future research concerns how the real world is modeled by a visual search task. Whereas visual search tasks typically use search displays comprised of very few and distinct stimuli, the present dissertation used large stimulus configurations. Although a very limited number of stimuli may suffice to examine various research questions, contexts of 100 stimuli or more as used in the present dissertation may be a good way of matching visual search tasks to our every-day visual environment and thus increase external validity. This is especially true given that some properties of the visual field can only be examined from a certain number of stimuli onwards (such as grouping; see Schubö et al., 2004). In order to even further increase external validity, and come closer to a more complete model of the visual world, a recent movement towards presenting real-life objects, photographs, faces, or scenes to participants in psychological experiments can be observed in the literature (e.g., Henderson, Brockmole, Castelhano, & Mack, 2007; Wolfe et al., 2011). This may be a promising approach to further increase external validity, but may also bear the problem of controlling and balancing physical features of stimuli. Visual search tasks should ideally not only model the outside world as correctly as possible but also allow for valid conclusions about the meaning of results obtained from such experiments. Future research should try to strive to the ideal balance between external and internal validity so that obtained results are both reliable and generalizable beyond the study. The strength of the model used in this dissertation lies in increasing external validity through using large stimulus configurations rather than a few stimuli. At the same time internal validity remains high due to the use of standardized stimuli.

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APPENDIX

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Textures shape the attentional focus: Evidence from exogenous and endogenous cueing

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Abstract The spatial cueing paradigm (Posner *Quarterly Journal of Experimental Psychology* 32:3–25, 1980) has often been used to investigate the time course of the deployment of visual attention in space. In a series of eight experiments we investigated whether spatial cues would not only enhance processing of stimuli presented at cued locations, but also enhance processing of the entire texture in which the stimuli were presented. Results showed highest accuracy for responses to stimuli presented at cued locations, a replication of the traditional cueing effect (Posner 1980). Additionally, stimuli presented at uncued locations were responded to with higher accuracy when they were presented inside the same texture as the cued location, as compared with stimuli presented outside the texture with the cued location. To investigate this *texture advantage* for both automatic and voluntary attention deployment, exogenous and endogenous cues were used. The texture advantage was observed for short interstimulus intervals (ISIs) of 50 and 100 ms for exogenous cues and for a longer ISI of 200 ms for endogenous cues. These findings indicate that the arrangement of task-irrelevant visual stimuli also can have a large impact on the cueing effect. This suggests that visual spatial attention spreads texture-wise across the visual field. Control experiments revealed that the homogeneity within texture elements contributes most to the effect but that the texture advantage is a function of both orientation contrast at the texture border and homogeneity within texture elements.

Keywords Attention · Texture · Visual search · Cueing · Textons

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Introduction

Visual selective attention plays an important role in information processing, since it allows filtering relevant from irrelevant information and, thus, ensures efficient analysis of incoming visual information. It is usually assumed that not all parts of the visual field are attended to the same extent but that certain locations receive prioritized processing, as compared with other locations. Visual spatial attention has been conceptualized as a focus that can be adjusted to the requirements of the visual field and facilitate information processing at focused locations (Eimer, 1999; Eriksen & St. James, 1986; LaBerge, 1983; Müller & Hübner, 2002; Posner, 1980; Theeuwes, 2005).

Peripheral and central spatial cueing

Where the focus of attention is located and how it varies over time has been widely studied using the spatial cueing paradigm introduced by Posner (e.g., Cheal & Lyon, 1991; Jonides, 1981; Müller & Rabbitt; 1989; Nakayama & Mackeben, 1989; Posner, 1980; Posner, Snyder, & Davidson, 1980; Yantis & Jonides, 1990). In this paradigm, a task-irrelevant central or peripheral cue precedes a task-relevant target stimulus. A centrally presented symbolic cue (e.g., an arrow) indicates the likely position of the subsequent target. Such a central cue is assumed to induce endogenous (i.e., under voluntary control) shifts of attention that are initiated actively by the observer. On the contrary, an exogenous cue presented in the periphery of the visual field is assumed to capture attention due to its intrinsic properties (e.g., its color, form, or abrupt onset). Peripheral cues can induce exogenous (i.e. involuntary) attention re-allocation in a reflexive manner. Valid cues correctly indicate the target position and cause a benefit (accuracy or response time), as compared with a neutral condition (no cue prior to target), whereas invalid cues indicate an incorrect target position and cause a cost, as compared with a neutral condition. These performance differences are assumed to mirror attention deployment to the cued locations (for reviews, see Klein, 2004; Ruz & Lupiáñez, 2002).

Since uninformative cues (uninformative regarding the target location) can be ignored when the cue is endogenous, but not when it is exogenous (Jonides, 1981), it has been argued that exogenous cues affect the first feedforward sweep of information through the brain in an automatic manner (Lamme, 2000; Marzouki, Grainger, & Theeuwes, 2007). However, since the magnitude of the cueing effect increases also with increasing informativeness of a peripheral cue, it has been argued that an endogenous component may be involved in exogenous cueing as well (Doallo et al., 2004; Müller & Rabbitt, 1989; Wright & Richard, 2000).

Experiments varying the time interval between cue and subsequent (target) stimulus presentation have shown that endogenous and exogenous cues yield attention shifts of different time courses (Eimer, 2000; Funes, Lupiáñez, & Milliken, 2005; Jonides, 1981; Klein, 2004; Müller & Findlay, 1988). For exogenous cues, interstimulus intervals (ISIs) of 50 ms were sufficient to produce a cueing effect, whereas for endogenous cues, an ISI of 200 ms or more is needed in order to observe a cueing effect (Liu, Stevens, & Carrasco, 2007; Yeshurun, Montagna, & Carrasco, 2008). The differential time course might be due to endogenous attention shifts being slower or needing additional time to decode the information carried by the symbolic cue (Eimer, 2000).

The distribution of spatial attention over time

To account for these results and in order to describe the way attention is deployed in the visual field, the metaphor of an attentional "spotlight" was suggested (Eriksen & St. James, 1986; Posner, 1980; Posner et al., 1980). According to this metaphor, attention is limited in size and moves independently of eye movements (covert attention; Posner, 1980; Wright & Ward, 2008) through the visual field. Visual information at locations within this spotlight receives prioritized processing. Later studies suggested that attention is not a strictly delimited area like a spotlight but, rather, a gradient that provides the visual field with various degrees of attention (Downing & Pinker, 1985; Ghirardelli & Folk, 1996; Kravitz & Behrmann, 2008; LaBerge, 1983; Mangun & Hillyard, 1988; Shulman, Wilson, & Sheehy, 1985) and that the "shape" of this gradient may be flexibly adjusted to the needs of a specific task (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Theeuwes, 2004).

Attention distribution depending on the structure of the visual field

There is evidence that the distribution of visual selective attention is shaped by the structure of the visual field. For example, it has been suggested that attention is deployed rather to entire objects than to specific spatial locations in the visual field (Duncan, 1984; O'Craven, Downing, & Kanwisher, 1999). In an experiment by Duncan, two superimposed objects were presented. Each object had two independent attributes. One object was a rectangle that was either small or large and had a gap on either the left- or the right-hand side. The other object was a line that was either dotted or stroked and was tilted to either the left or the right. Observers were to judge attributes of these objects; for example, they had to judge where the rectangle had a gap and/or whether the line was dotted. Participants' performance was equally good for judging one or two attributes of the same object but was impaired for judging two attributes of two different objects (i.e., one attribute for each of the two objects). Because objects were placed at the very same location, Duncan concluded that attention is limited to one object at a time, not a location.

Further evidence for object-based attention stems from a cueing experiment by Egly and colleagues (Egly, Driver, & Rafal, 1994). Stimulus displays consisted of two drawn-out rectangles, arranged in parallel, and the target consisted of a filled square presented at one of the rectangle's ends. Participants had to press a button as soon as they had detected a target. Prior to the target onset, the outline of one of the four ends of the two rectangles showed an abrupt luminance change, serving as a spatial cue. Cue and target appeared at the same location on 75 % of the trials and at different locations on 25 % of the trials. The critical manipulation was on trials with invalid cues: The target could appear at the other end of the cued rectangle, or it could appear at the equidistant end of the uncued rectangle. Egly et al. found the shortest reaction times (RTs) for validly cued targets, indicating spatial cueing. Moreover, targets presented at locations belonging to the cued object yielded shorter RTs than did targets presented at locations belonging to the noncued object, indicating that attention expanded to the entire object on which the cue had been presented (Egly et al., 1994). As a result, stimuli appearing at the cued object were processed more efficiently than stimuli appearing at a location that did not belong to the cued object—evidence for object-based cueing. In this experiment, the visual field was structured by Gestalt principles of colinearity and closure, but similar results were obtained for colinearity alone (Avrahami, 1999; Marino & Scholl, 2005). Furthermore, the attention distribution in the visual field was also shown to be shaped by the similarity of objects: Attention more likely spreads from one object to a group of objects when they are similar enough (Dodd & Pratt, 2005). As was pointed out by Ben-Shahar and colleagues (Ben-Shahar, Scholl, & Zucker, 2007), often, full-fledged, arbitrarily defined objects are used in such experiments, such as bars, rectangles, or circles. However, it is not clear what counts as an object when it comes to the deployment of attention. In the present study, we examined how attention is deployed in the visual field when it is structured not by objects but by basic simple features like *line orientation*, which underlie objects and virtually any everyday visual scene.

Such simple stimuli have been shown to be grouped preattentively and processed as a unit and are called *textons* (Ben-Shahar et al., 2007; Julesz, 1986; Nothdurft, 1992, 1993; Wolfe, 1994). Textons allow a segregation of the visual field into distinct areas in an effortless, spontaneous way without the requirement of focal attention, a process called *texture segregation* (Bergen & Julesz, 1983; Nothdurft, 1992, 1993; Wolfe, 1992). Texture segregation is one of the prime capabilities of the human visual system (Sagi & Julesz, 1987; Schubö, Schröger, & Meinecke, 2007) and is considered distinct from guided or parallel search processes (Wolfe, 1992). Furthermore, it has been shown that observers can divide their attention between two locations within the same texture far better than between two locations within different textures (Ben-Shahar et al., 2007). However, it remains unclear how a visual field that is structured by textures shapes the focus of attention and whether textures induce a gradient of attention.

Rationale of the experiments

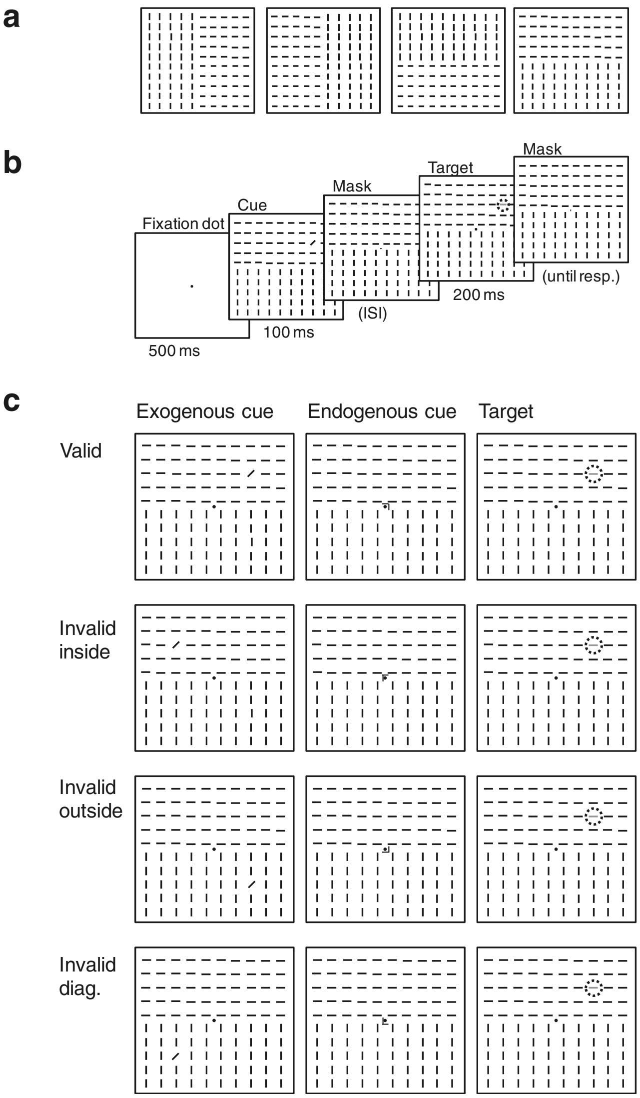
In the present series of eight experiments, we were interested in how attention is deployed in textures of simple oriented lines with texton quality. Since textures can be segregated effortlessly and preattentively (Nothdurft, 1992; Wolfe, 1992), we wanted to examine when and how attention comes into play when observers need to attend particular texture locations. Large arrays of 50 vertical and 50 horizontal lines were arranged in two halves to allow texture segregation on the basis of orientation textons (cf. Fig. 1a). Horizontal and vertical elements were arranged next to each other in such a way that each half consisted of homogeneous elements, resulting in two textures per display. To trigger attention shifts, we employed both exogenous and endogenous cues that are known to enhance processing of stimuli subsequently presented at the cued location for some time (Doallo et al., 2004). We examined whether cues caused enhanced processing at cued locations only or whether the cueing effect would spread to the entire texture to which the cued location belonged. A task-irrelevant oblique line, appearing at one of the four locations, served as an exogenous cue (Experiments 1 and 4). A centrally presented arrow pointing to one of the four positions served as an endogenous cue (Experiments 2 and 3). After a variable time interval, a blue or green line (the task-relevant target) appeared at one of the four locations. The target could be shown at the same location as the cue (valid trials), at a different location than the cue but inside the same texture (invalid-inside trials), or at a different location than the cue and outside the cued texture (invalid-outside trials). In a series of eight experiments, we examined the impact of cue validity (valid vs. invalid-inside vs. invalid-outside) on the search for the target. Informativeness of the cue (the probability that a cue would correctly indicate the subsequent target position) and cue exposure duration were varied to also examine the role of voluntary attentional control, as compared with more spontaneous attention effects.

We hypothesized that cueing should lead to higher accuracy for targets in invalid-inside trials, as compared with invalid-outside trials. This would support the view that attention is not restricted to the cued location but spreads to the entire texture. It would further argue in favor of an attentional gradient between textures. This logic follows that in Egly et al. (1994), but low-level perceptually coherent textures are considered instead of higher-level objects. We further assumed that in line with traditional cueing experiments (Müller & Rabbitt, 1989; Posner et al., 1980; Yantis & Jonides, 1990), performance on valid trials should be better than that on invalid trials. This would argue in favor of an attentional gradient within a texture—that is, more attention at the valid location than at the invalid-inside location. In addition to spatial dynamics, by using several ISIs, we can track down the time course of attention deployment from the starting point (cued location) to various locations in the visual field (e.g., locations inside/outside the texture). In additional experiments, the two determinants of texture segregation, orientation contrast at the texture border and homogeneity within texture elements, were systematically varied (cf. Ben-Shahar et al., 2007; Nothdurft, 1992). Thus, the contribution of both texture properties to shaping the attentional focus in textures could be further assessed.

General method

Participants

One hundred twenty-eight volunteers participated in eight experiments and received payment or course credit. The experiments were conducted with the understanding and consent of each participant. All participants had normal or corrected-to-normal vision and had normal color vision (test-



◀**Fig. 1** **a** Illustration of the four texture arrangements used in Experiments 1–6. Horizontal and vertical lines were arranged in such a way that the line stimulus array consisted of either a left and right texture (left panels) or an upper and lower texture (right panels). All four textures were equally likely to appear. **b** Trial sequence. A trial started with a fixation dot presented for 500 ms, followed by the cue display presented for 100 ms (Experiment 3: 1,000 ms) and a mask display with a standard texture for a variable interstimulus interval (ISI; cf. Table 1 for specific ISI durations in each experiment). Subsequently, the search display appeared for 200 ms and was replaced by a mask display that lasted until the participant made a response. **c** Illustration of the four validity conditions used in Experiments 1–4. On valid trials, the cue and target appeared at the same location. On invalid-inside trials, the cue and target appeared at different locations, and the target was presented inside the same texture. On invalid-outside trials, the cue and target appeared at different locations, but the target was outside the cued texture. Note that the distance between the cue and target was identical on invalid-inside and invalid-outside trials. On invalid-diagonal trials, the cue and target appeared at different locations, and the target was diagonally shifted relative to the cue. Exogenous cues (Experiments 1, 4–8) were diagonal line elements presented at one of four possible peripheral cue locations (left columns). Endogenous cues (Experiments 2 and 3) were centrally presented L-shaped arrows pointing toward one of these four locations (middle columns). Targets were green or blue line elements (a dotted line encircles the target locations for illustration purposes and was not visible to the participants), oriented in the same way as surrounding line elements

ed via a Rodenstock R12 vision tester, with stimuli no.112 for visual acuity and stimuli no.173 for color vision).

In Experiment 1, 16 participants (5 male) were tested; all were right-handed and between 23 and 27 years of age (*M* = 25.4, *SD* = 1.3). Experiment 2 comprised 16 participants (5 male), all right-handed, 20–29 years of age (*M* = 23.2, *SD* = 2.5). Experiment 3 comprised 16 participants (4 male), 12 right-handed, 19–34 years of age (*M* = 26.1, *SD* = 4.1). Experiment 4 comprised 16 participants (5 male), all right-handed, 21–31 years of age (*M* = 24.0, *SD* = 2.9). Experiment 5 comprised 16 participants (5 male), all right-handed, 18–28 years of age (*M* = 21.4, *SD* = 2.9). Experiment 6 comprised 16 participants (4 male), 15 right-handed, 19–35 years of age (*M* = 22.9, *SD* = 4.3). Experiment 7 comprised 16 participants (5 male), 12 right-handed, 18–28 years of age (*M* = 22.6, *SD* = 2.8). Experiment 8 comprised 16 participants (4 male), all right-handed, 19–33 years of age (*M* = 23.3, *SD* = 2.7)

Stimuli and apparatus

Participants were seated in a comfortable chair in a dimly lit, electrically shielded, and sound-attenuated chamber, with an ergonomic gamepad (Microsoft Sidewinder USB) in their hands. Two buttons on the backside of the gamepad had to be pressed with the left and right index fingers. All stimuli were presented on a 19-in. computer screen with a 100-Hz refresh rate placed at a distance of 85 cm from the observer.[1] A light gray served as background for all displays. A trial consisted of two consecutive displays, a cue and a search display. Cue displays consisted of a matrix of 10 × 10 stimuli,

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[1] Due to the fact that both authors changed affiliation during the experimental series, different screens were used in Experiments 1–4 and 5–8. Instead of a 19-in. CRT screen, a 22-in. LCD (TN panel; 100 Hz) screen was used. To maintain the visual angle of all stimuli, the distance to the screen was set to 100 cm. Preliminary tests showed, however, that with these settings, performance was much better than in Experiments 1–4, presumably due to the difference between CRT and LCD screens. Thus, search display duration was decreased and, to further avoid ceiling or floor effects, adjusted for each participant separately in a step function: From a starting point of 100 ms, participants had to perform between 65 % and 85 % correct for two succeeding practice blocks of 32 trials. If performance exceeded this criterion in any single block, search display duration was increased or decreased by 20 ms. The criterion of 65 %–85 % was chosen on the basis of Experiment 4 (here, mean accuracy across all conditions was 75.9 % (±1 *SD* = 10.9 % ≈ 65 %/85 %), which used exogenous uninformative cues like Experiments 5–8.

50 of which were horizontal and 50 of which were vertical dark gray lines. Horizontal and vertical lines were arranged in two halves, with horizontal and vertical lines separated in either an upper and lower or a left and right half of the field (cf. Fig. 1a). Both types of displays (separation into an upper and lower or a left and right half) were presented with equal probability. Line length was 1.1°, and the matrix had a length and height of 14.8°. A single oblique line element, tilted 45° clockwise or counterclockwise, served as the exogenous cue in Experiments 1 and 4-8 (Fig. 1c, left column). A centrally presented equal-sided L-shaped arrow pointing to one of the four quadrants was used as an endogenous cue in Experiments 2 and 3 (Fig. 1b, middle column). The cue indicated one of four positions at 7.7° eccentricity at the center of each of the four imaginary quadrants. Search displays were identical to the cue displays, except that no cue was presented and one of the horizontal or vertical lines was colored either green or blue instead (each 50 %), serving as the target (Fig. 1c, right column). Targets appeared equally often at the four potential cue positions. This led to four possible validity conditions: (1) On valid trials, cues correctly indicated the target position (e.g., Fig. 1b, upper row); (2) on invalid-inside trials, the cue indicated a position different from the actual target position, horizontally or vertically shifted by 15.4° but inside the homogeneous texture (e.g., Fig. 1c, second row); (3) on invalid-outside trials, the cue indicated a position different from the actual target position, horizontally or vertically shifted by 15.4° but outside the cued texture (e.g., Fig. 1c, upper row); (4) on invalid-diagonal trials, the cue indicated a position different from the actual target position, diagonally shifted by 21.8°. After cue offset and after search display offset, a "standard" line array of horizontal and vertical lines was presented without marked cue or target.

Procedure

A trial started with the presentation of a central fixation dot (2 × 2 pixels) that remained on the screen throughout the entire trial (see Fig. 1b for an exemplary trial sequence). After 500 ms, the cue display was presented. Cue presentation time varied between experiments (see Table 1). Subsequently, a standard texture was shown for a variable ISI (see Table 1) to serve as a mask before the search display appeared for 200 ms (see note 1) on the screen and was subsequently replaced by the standard texture, again serving as a mask. Participants were to press one of the response buttons (labeled "GREEN" or "BLUE") in order to indicate the color of the target in the search display; response accuracy was emphasized, and there was no time limit for the response. After a response was given, a blank screen (light gray background) was shown for 300 ms until a fixation cross indicated the beginning of the next trial. Response assignment (left vs. right index finger) was balanced across participants. All four validity conditions (valid, invalid-inside, invalid-outside, and invalid-diagonal) were combined with four ISIs, leading to 16 conditions in each experiment (see Table 1). All types of trials were randomly assigned to blocks of 32 trials each (see Table 1 for number of trials). After each block, performance feedback (response accuracy) was given, followed by a short break of at least 10 s.

Data analysis

Mean accuracy was computed for each participant separately for all 16 conditions, excluding trials with false responses and trials with RTs longer than the participant's mean RT ± 2 *SD*s. For RT analyses, trials with erroneous responses or with RTs longer than the subject's mean RT ± 2 *SD*s were excluded. An ANOVA was calculated with the factors ISI and validity (valid vs. invalid-inside vs. invalid-outside vs. invalid-diagonal) for accuracy and RTs. Greenhouse–Geisser correction was used when appropriate.

Experiment 1

Experiment 1 examined whether performance for targets presented at uncued locations was better when targets belonged to the same texture as the cue. A single oblique line element tilted 45° clockwise or counterclockwise served as an exogenous cue. Targets appeared at the cued location on 72.7 % of all trials (valid trials) and at an uncued location on 27.3 % of all trials (9.1 % for each invalid condition). The ISI between cue and search display was 50, 100, 150, or 200 ms. We expected valid trials to result in the highest accuracy, in compliance with the traditional cueing effect (Posner, 1980). More important, if cues cause enhanced processing not only at the cued locations but also for entire groups of similar stimuli, invalid-inside trials should result in higher accuracies than should invalid-outside trials.

Results

Accuracy (cf. Fig. 2a and Table 2)

Valid cues led to most accurate performance (M = 88.1 %), followed by invalid-inside (M = 62.3 %), invalid-outside (M = 60.0 %), and invalid-diagonal (M = 58.0 %) trials, $F(1.7, 25.3) = 57.37, p < .001, \eta^2 = .79$. The most accurate performance was reached for an ISI of 50 ms (M = 69.8 %), followed by ISIs of 100 ms (M = 68.2 %), 150 ms (M = 66.6 %), and 200 ms (M = 63.8 %), $F(3, 45) = 4.41, p = .008, \eta^2 = .23$. The interaction of both factors also reached significance, $F(9, 135) = 2.19, p = .026, \eta^2 = .13$. Planned contrasts

Table 1 Overview of experimental settings in Experiments 1–8

	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Experiment 6	Experiment 7	Experiment 8
Cue Type	Exogenous	Endogenous	Endogenous	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous
Informativeness	72.7 %	72.7 %	72.7 %	25 %	25 %	25 %	25 %	25 %
Inter-Stimulus Interval [ms]	50/100/150/200	100/200/400/600	100/200/400/600	50/100/150/200	0/50/100 / 150/200	50/100/150/200	150/200	150/200
Cue Duration [ms]	100	100	1,000	100	100	100	100	100
No. of trials (blocks)	1,408 (44)	1,408 (44)	1,408 (44)	1,024 (32)	1,024 (32)	1,024 (32)	1,024 (32)	1,024 (32)
Texture Homogeneity: Cue display	0°	0°	0°	0°	0°	0°	0°	30°/90°
Texture Homogeneity: Search display	0°	0°	0°	0°	0°	0°	30°/90°	30°/90°
Border Contrast	90°	90°	90°	90°	90°	90°	90°	30°/90°
Change of Texture Arrangement	no	no	no	no	yes	no	no	no
Change of Texton Identity	no	no	no	no	no	yes (+90°)	yes (gradual)	no

Note. “Cue Type” describes whether cues were exogenous (diagonal line elements presented at one of four possible peripheral cue locations) or endogenous (centrally presented L-shaped arrows pointing toward one of these four locations). “Informativeness” denotes the probability that the cue correctly indicated the subsequent target location. “Interstimulus interval” marks the time between cue offset and target onset. “Texture Homogeneity: Cue display” denotes the homogeneity within texture elements in the cue display—that is, the orientation variation of line elements within a texture (0° equals no variation). “Texture Homogeneity: Search display” denotes the same variation of homogeneity for the search display. “Border Contrast” describes the orientation contrast at the texture border—that is, the orientation difference of neighboring line elements at the border between textures. “Change of Texture Arrangement” specifies whether the texture arrangement switched from horizontal to vertical (or vice versa) between the cue and search displays or whether the arrangement remained the same. “Change of Texton Identity” specifies whether the identity of all texture elements (the textons) switched from horizontal to vertical (or vice versa) between the cue and search displays or whether all textons remained the same. Bold font indicates that an experimental variation was unique for a particular experiment.

revealed a significant difference in accuracy between invalid-inside and invalid-outside trials for an ISI of 50 ms (M_{inside} = 66.8 % vs. M_{outside} = 60.1 %), $p = .007$, $\varepsilon = 0.99$, but not for longer ISIs (all *p*s > .124).

Reaction times (cf. Table 2)

There was no effect of validity, $F(1.1, 17.1) = 2.84$, $p = .107$, $\eta^2 = .16$. The shortest RTs were found for an ISI of 200 ms (315 ms), followed by ISIs of 150 ms (335 ms), 100 ms (376 ms), and 50 ms (415 ms), $F(3, 45) = 73.21$, $p < .001$, $\eta^2 = .83$. Also, the interaction of both factors reached significance, $F(3.9, 58.6) = 3.32$, $p = .017$, $\eta^2 = .18$, but planned contrasts revealed no significant difference between invalid-inside and invalid-outside trials for any ISI (all *p*s > .05).

Discussion

As was expected, exogenous cues led to higher accuracy for targets presented at the cued location (valid trials), as compared with any other position of the visual field (invalid trials). This shows that the traditional cueing effect (Posner, 1980) can also be evoked by odd elements in otherwise homogeneous textures. Improved performance for valid, as compared with invalid, trials was observed for all ISIs used, although the effect was slightly attenuating from the shortest (50 ms) to the longest (200 ms) ISI. More interesting, however, is that target accuracy on invalid trials also depended on whether target and cued location were part of the same texture: For an ISI of 50 ms, accuracy on invalid trials was higher when the target was presented in the same texture as the cue, as compared with when the target was presented outside that texture. We call this finding the *texture advantage*. For longer ISIs, targets did not benefit from being part of the same texture as the cue.

Experiment 2

Experiment 1 showed that exogenous cues lead to better performance on invalid-inside, as compared with invalid-outside, trials. The aim of Experiment 2 was to examine whether this texture advantage would be observed for endogenous cues as well. Experiment 2 was identical to Experiment 1, except that a centrally presented L-shaped arrow pointing to one of the four target positions served as an endogenous cue and longer ISIs were used that ranged between 100 and 600 ms (see Table 1).

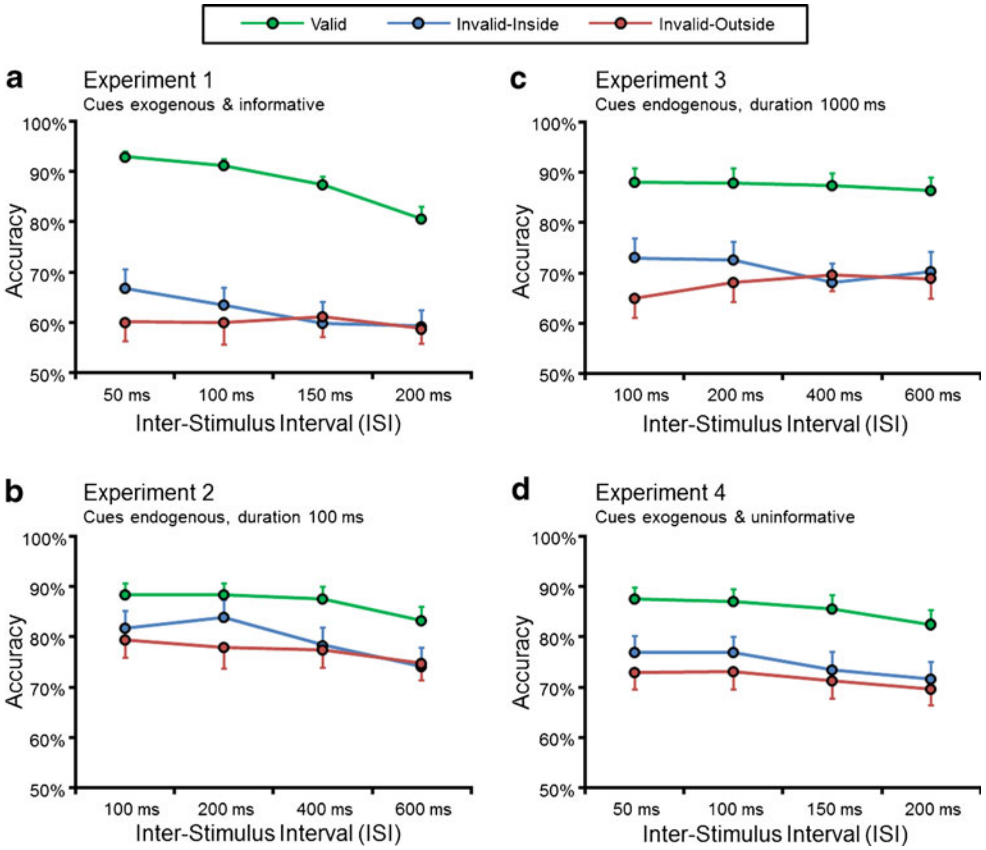


Fig. 2 Mean accuracy in Experiment 1 (upper left panel), Experiment 2 (lower left panel), Experiment 3 (upper right panel), and Experiment 4 (lower right panel). Accuracy is shown as a function of interstimulus interval and validity (valid, green lines; invalid-inside, blue lines; invalid-outside, red lines; for invalid-diagonal trials, see Table 2). Error bars indicate the standard errors of the means

Results

Accuracy (cf. Fig. 2b and Table 2)

As was expected, valid cues led to the best performance (M = 86.8 %), followed by invalid-inside (M = 79.5 %), invalid-outside (M = 77.4 %) and invalid-diagonal (M = 75.8 %) trials, $F(2.1, 31.0) = 7.70$, $p = .002$, $\eta^2 = .34$. Performance was most accurate for an ISI of 100 ms (M = 82.8 %), followed by ISIs of 200 ms (M = 81.2 %), 400 ms (M = 80.0 %), and 600 ms (M = 75.6 %), $F(3, 45) = 11.06$, $p < .001$, $\eta^2 = .42$. The interaction of both factors did not reach significance (p = .153). Planned contrasts, however, revealed a significant difference in accuracy between invalid-inside and invalid-outside trials for an ISI of 200 ms (M_{inside} = 83.8 % vs. M_{outside} = 77.9 %), $p = .003$, $\varepsilon = 1.12$, but not for ISIs of 100, 400, or 600 ms (all $ps > .214$).

Reaction times (cf. Table 2)

Valid cues led to the shortest RTs (507 ms), followed by invalid-inside (606 ms), invalid-outside (609 ms), and invalid-diagonal (613 ms) trials, $F(1.8, 26.3) = 10.91$, $p = .001$, $\eta^2 = .42$. For an ISI of 600 ms, the shortest RT were found (508 ms), followed by ISIs of 400 ms (570 ms), 200 ms (606 ms), and 100 ms (651 ms) [main effect of ISI, $F(1.5, 22.2) = 18.65$, $p < .001$, $\eta^2 = .55$]. The interaction of both factors did not reach significance (p = .376); neither did planned contrasts reveal a significant difference between invalid-inside and invalid-outside trials for any ISI (all $ps > .05$).

Discussion

Similar to Experiment 1, valid cues led to more accurate performance than did invalid cues in Experiment 2, replicating earlier studies (Klein, 2004; Ruz & Lupiáñez, 2002). More important, also endogenous cues yield a texture advantage: Accuracy on invalid trials was higher when the target was presented in the same texture as the cued location, as compared with when the target was presented outside that texture. For endogenous cues, texture advantage was observed much later than for exogenous cues—namely, for an ISI of 200 ms. For the shortest ISI of 100 and the two longer ISIs of 400 and 600 ms, no texture advantage was found. Comparing Experiments 1 and 2, it becomes evident that endogenous cues need more time than do exogenous cues to evoke a texture advantage.

Table 2 Overview of mean accuracy and mean reaction times in Experiments 1–8

				Valid		Invalid-Inside		Invalid-Outside		Invalid-Diagonal	
Experiment 1				Acc (%)	RT (ms}	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	50 ms	92.9	359	66.8	425	60.1	435	59.3	441
			100 ms	91.2	332	63.5	383	60.0	389	58.1	401
			150 ms	87.4	312	59.8	341	61.2	342	58.1	346
			200 ms	80.6	302	59.2	314	58.8	325	56.4	317
Experiment 2				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	100 ms	88.3	572	81.7	668	79.5	693	81.6	672
			200 ms	88.3	524	83.8	626	77.9	623	74.8	649
			400 ms	87.5	472	78.3	613	77.4	593	76.7	603
			600 ms	83.2	461	74.1	515	74.7	527	70.2	530
Experiment 3				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	100 ms	88.0	615	73.0	817	64.9	876	63.5	888
			200 ms	87.8	574	72.6	798	68.0	819	64.9	841
			400 ms	87.3	537	68.0	726	69.6	769	63.2	754
			600 ms	86.4	549	70.2	622	68.8	654	65.2	692
Experiment 4				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	50 ms	87.6	485	76.9	522	72.9	537	73.9	528
			100 ms	87.1	480	77.0	518	73.1	507	71.6	497
			150 ms	85.5	455	73.5	488	71.3	475	72.7	491
			200 ms	82.4	446	71.6	459	69.6	458	68.2	468
Experiment 5				Valid		OLD-Inv.-Inside		NEW-Inv.-Inside		Invalid-Diagonal	
				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	0 ms	90.9	560	87.2	566	85.2	565	84.0	567
			50 ms	90.0	537	83.3	547	84.2	538	84.2	544
			100 ms	87.7	528	79.6	540	80.2	540	76.3	551
			150 ms	81.1	515	76.0	523	75.2	530	73.5	546
			200 ms	78.7	516	72.8	528	72.8	512	71.6	504
Experiment 6				Valid		Invalid-Inside		Invalid-Outside		Invalid-Diagonal	
				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
		ISI	50 ms	90.1	572	83.3	607	84.0	598	82.5	621
			100 ms	83.8	582	81.0	605	79.5	600	79.4	606
			150 ms	84.1	566	80.8	592	81.5	599	77.5	602
			200 ms	80.8	587	77.1	578	78.1	582	79.1	618
Experiment 7				Valid		Invalid-Inside		Invalid-Outside		Invalid-Diagonal	
				Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
Homogeneity of search display	High	ISI	50 ms	85.7	540	77.6	553	73.6	572	76.0	563
			100 ms	78.0	531	66.5	562	66.6	566	65.0	572
	Low		50 ms	84.7	556	80.8	573	77.3	565	79.6	559
			100 ms	74.1	547	70.8	557	70.9	568	70.3	567
Experiment 8				Valid		Invalid-Inside		Invalid-Outside		Invalid-Diagonal	
Border Contrast	Texture Homogeneity			Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)	Acc (%)	RT (ms)
High	High	ISI	50 ms	91.6	492	87.9	545	81.1	525	80.2	545
			100 ms	87.4	498	81.7	536	78.7	538	76.1	539
High	Low		50 ms	94.1	506	86.4	528	82.8	564	83.5	544
			100 ms	88.8	510	80.4	541	77.3	533	76.1	544
Low	High		50 ms	92.7	521	87.8	532	82.2	535	81.4	539
			100 ms	86.6	531	79.9	531	81.4	527	77.7	530
Low	Low		50 ms	93.4	510	84.0	565	81.6	559	81.3	548
			100 ms	86.8	506	81.6	548	80.5	520	77.1	535

Note. The first column to the left indicates the number of the experiment, and the second column indicates the interstimulus interval (ISI). Columns 3–6 show the mean accuracy (Acc) in percent correct and the mean reaction times (RT) in milliseconds across all participants for valid, invalid-inside, invalid-outside, and invalid-diagonal trials. Note that in Experiment 5, texture border switches from horizontal to vertical (or vice versa), resulting in OLD-invalid-inside and NEW-invalid-inside trials (see the Experiment 5 section for details). In Experiment 7, the additional factor “Homogeneity of search display” was varied while the homogeneity of the cue display remained homogeneous (as in Experiments 1–5). High homogeneity denotes an orientation difference of 30° within a texture (low homogeneity: 90°). In Experiment 8, the two additional factors, “Border Contrast” and “Texture Homogeneity,” were varied. High border contrast denotes a 90° orientation difference between neighboring lines at the border of the texture (low border contrast: 30°). High homogeneity denotes an orientation difference of 30° within a texture (low homogeneity: 90°).

Experiment 3

Experiment 2 revealed a cueing effect on valid trials already after an ISI of 100 ms. A texture advantage, however, was observed only later, after an ISI of 200 ms. One may therefore wonder how the texture advantage relates to traditional spatial cueing and what time course both effects follow. One may speculate that a cue presentation time of 100 ms and an ISI of 100 ms were enough time to induce traditional spatial cueing on valid trials but too short to induce a texture advantage. Alternatively, one may assume that the texture advantage may be a by-product of failed spatial cueing; that is, participants may have had problems in focusing their attention on the cued location but have attended the entire texture. Experiment 3 was designed to investigate whether an increase in cue presentation time to 1,000 ms would change the cueing effect pattern and, especially, whether it would modulate the texture advantage. With this increase, participants would have enough time to focus their attention on the cued location and would not need to attend the entire element texture. Contrarily, the presence of a texture advantage with a longer preparation interval would speak in favor of a texture effect independent of traditional spatial cueing.

Results

Accuracy (cf. Fig. 2c and Table 2)

Again, valid cues led to the highest accuracy (M = 87.4 %), followed by invalid-inside (M = 70.9 %), invalid-outside (M = 67.8 %), and invalid-diagonal (M = 64.2 %) trials, $F(1.3, 19.5) = 20.05$, $p < .001$, $\eta^2 = .57$. No other effects reached significance (all ps > .241). Planned contrasts revealed a significant difference for invalid-inside and invalid-outside trials for an ISI of 100 ms (M_{inside} = 73.0 % vs. M_{outside} = 64.9 %), $p = .002$, $\varepsilon = 1.20$, and for an ISI of 200 ms (M_{inside} = 72.6 % vs. M_{outside} = 68.0 %), $p = .003$, $\varepsilon = 1.11$, but not for an ISI of 400 or 600 ms (all ps > .05).

Reaction times (cf. Table 2)

Valid cues led to the shortest RTs (569 ms), followed by invalid-inside (741 ms), invalid-outside (779 ms), and invalid-diagonal (794 ms), $F(1.2, 18.7) = 17.60$, $p < .001$, $\eta^2 = .54$. For an ISI of 600 ms, the shortest RTs were found (629 ms), followed by ISIs of 400 ms (696 ms), 200 ms (758 ms), and 100 ms (799 ms), $F(1.5, 22.3) = 28.09$, $p < .001$, $\eta^2 = .65$. There was an interaction of ISI and validity, $F(4.4, 66.7) = 2.75$, $p = .031$, $\eta^2 = .16$, There was an interaction of ISI and validity, $F(4.4, 66.7) = 2.75$, $p = .031$, $\eta^2 = .16$, and planned contrasts revealed a significant difference between invalid-inside and invalid-outside for an ISI of 100 ms (M_{inside} = 817 ms vs. M_{outside} = 876 ms), $p = .015$, $\varepsilon = 0.84$, but for no other ISI (all ps > .081).

Discussion

As in Experiment 2, ISIs of 400 and 600 ms showed no texture advantage in the present experiment. Interestingly, however, while in Experiment 2 a texture advantage was found for an ISI of 200 ms but not earlier, Experiment 3 showed that an increase in cue presentation time can cause a texture advantage already for an ISI of 100 ms. In both Experiments 2 and 3, an optimal strategy would have been to focus on the cued location (target probability of 73 %), while all other positions were equally “unlikely” to be followed by the target (each 9 %). Even though participants had enough time now to focus their attention accordingly, accuracy was still higher on invalid-inside than on invalid-outside trials. This indicates that the texture had an impact on search performance in addition to the Posnerian cueing effect. In fact, a texture advantage was now observed already after a shorter ISI of 100 ms. The increase in cue presentation time thus did not abolish the texture advantage but, rather, made it appear at an earlier time interval. This strongly speaks in favor of a texture effect independent of traditional spatial cueing.

Experiment 4

Is it possible that the texture advantage observed in the previous experiments was entirely due to endogenous control mechanisms? In Experiment 1, exogenous cues were used that are considered to cause automatic attention shifts (Klein, 2004; Marzouki et al., 2007). However, it is often argued that exogenous cues may also induce endogenous control to some extent when they are informative (Doallo et al., 2004; Müller & Rabbitt, 1989; Wright & Richard, 2000). The aim of Experiment 4 was to test whether a texture advantage is also observed without endogenous control being involved. To do so, the experimental design of Experiment 1 was modified so that the target would appear at each of the four positions with a probability of 25 %. Hence, the cue was uninformative with respect to the location of the subsequent target, and participants would not benefit from attending to one position more than to another, since the target could appear at any position with equal probability.

Results

Accuracy (cf. Fig. 2d and Table 2)

Valid cues led to the best performance (M = 85.6 %), followed by invalid-inside (M = 74.7 %), invalid-outside (M = 71.7 %), and invalid-diagonal (M = 71.6 %) trials, $F(1.3, 19.2) = 21.37$, $p < .001$, $\eta^2 = .59$. Best performance was reached for an ISI of 50 ms (M = 77.8 %), followed by ISIs of 100 ms (M = 77.2 %), 150 ms (M = 75.7 %), and 200 ms (M = 73.0 %), $F(2.0, 30.6) =$

20.46, $p < .001$, $\eta^2 = .58$. There was no interaction of both factors, $p = .857$.

To directly compare accuracy performance between the crucial conditions invalid-inside and invalid-outside, planned contrasts were calculated for each of the four ISIs separately. Accuracy differed significantly for an ISI of 100 ms (M_{inside} = 77.0 % vs. M_{outside} = 73.1 %), $p = .004$, $\varepsilon = 1.08$, and for an ISI of 50 ms (M_{inside} = 76.9 % vs. M_{outside} = 72.9 %), $p = .009$, $\varepsilon = 0.93$, but not for an ISI of 150 or 200 ms (all ps $\geq .05$).

Reaction times (cf. Table 2)

Valid cues led to the shortest RTs (466 ms), while responses differed only slightly between the other three conditions: invalid-inside (497 ms), invalid-outside (494 ms), and invalid-diagonal (496 ms), $F(3, 45) = 10.07$, $p < .001$, $\eta^2 = .40$. For ISIs of 200 ms, the shortest RT were found (458 ms), followed by ISIs of 150 ms (477 ms), 100 ms (500 ms), and 50 ms (518 ms), $F(1.9, 28.1) = 17.94$, $p < .001$, $\eta^2 = .55$. There was no interaction of ISI and validity ($p = .098$), and planned contrasts revealed no significant difference of the means between invalid-inside and invalid-outside for any ISI (all ps > .05).

Comparison of Experiments 1 and 4

To assess possible differences in the texture advantage due to cue informativeness, a post hoc ANOVA with the within-subjects factor validity and the between-subjects factor informativeness (Experiment 1, 73 % validity, vs. Experiment 4, 25 % validity) was conducted separately for the ISIs of 50 and 100 ms. The ISIs of 50 and 100 ms were chosen because significant differences between invalid-inside and invalid-outside were found for these ISIs in at least one the experiments.

ISI of 50 ms

Accuracy was generally higher for uninformative cues (74.9 %; Experiment 4) than for informative cues (63.5 %; Experiment 1), $F(1, 30) = 5.41$, $p = .027$, $\eta^2 = .153$. Additionally, accuracy in both experiments was better on invalid-inside trials (71.8 %) than on invalid-outside trials (66.5 %), $F(1, 30) = 14.27$, $p = .001$, $\eta^2 = .32$. The texture advantage did not differ for informative cues in Experiment 1 (M_{inside} = 66.8 % vs. M_{outside} = 60.1 %), as compared with uninformative cues in Experiment 4 (M_{inside} = 76.9 % vs. M_{outside} = 72.9 %) (interaction of validity and informativeness, $p = .336$).

ISI of 100 ms

The results show the same pattern as for the ISI of 50 ms: Across both experiments, performance was better for uninformative cues (75.0 %; Experiment 4) than for informative cues (61.7 %; Experiment 1), $F(1, 30) = 7.18$, $p = .012$, $\eta^2 = .193$. In addition, accuracy was higher on invalid-inside trials (70.2 %) than on invalid-outside trials (66.6 %), $F(1, 28) = 5.38$, $p = .027$, $\eta^2 = .15$. The texture advantage was of comparable size for informative cues in Experiment 1 (M_{inside} = 63.5 % vs. M_{outside} = 60.0 %) and uninformative cues in Experiment 4 (M_{inside} = 77.0 % vs. M_{outside} = 73.1 %); no interaction of validity and informativeness was observed, $p = .907$.

Discussion

In Experiment 4, the texture advantage was about the same size as in Experiment 1, where the exogenous cue was informative with respect to the subsequent target location. As in Experiment 1, a texture advantage was found for the shortest ISI of 50 ms but not for longer ISIs of 150 and 200 ms. In contrast to Experiment 1, a texture advantage was also found for an ISI of 100 ms. In Experiment 4, exogenous cues were not informative concerning the subsequent target location; one may conclude that a texture advantage can be observed both in exogenous and endogenous cueing and that an endogenous component is not necessary to elicit this effect.

Experiment 5

Experiments 1–4 showed that accuracy on invalid trials depended on the texture to which the cued location belonged: When target and cue were part of the same texture, performance was better than when they were in different textures. In these experiments, the texture segregation was identical in cue and search displays; that is, when the visual field in the cue display was segregated into a left and right texture, this segregation into left and right was left unchanged in the search display. Accordingly, we could determine at what point in time the texture advantage disappeared when the texture arrangements were left *unchanged*. Experiment 5, however, was designed to determine whether and at what point in time the texture advantage would disappear when the segregation *changed*. To that end, Experiment 5 used different texture arrangements in cue and search displays. Different ISIs between the cue and target allowed for measuring for how long a texture advantage could be observed for the cued texture after textures had been changed.

Method

The stimuli and procedure were identical to those in Experiment 4, with the following exception: The texture arrangement changed immediately after the cue offset from vertical to horizontal or vice versa. For example, in cue displays, the visual field was segregated in an upper texture of horizontal and a lower texture of vertical lines. After cue offset, the visual field changed to a left texture of horizontal and a right texture of vertical lines. Line orientation around the cued location was left unchanged. With this change of texture arrangement, the definition of invalid-inside and invalid-outside changed as well: A target that was presented at a location that was part of the cued texture in the cue display (OLD-invalid-inside; cf. Fig. 3a, middle column) could belong to a different texture during its presentation. Alternatively, a target that was presented at a location outside the cued texture in the cue display could belong to the same texture during its presentation (NEW-invalid-inside; cf. Fig. 3a, right column).

To precisely track the point in time at which the texture advantage may disappear, we used an additional ISI = 0 condition in which the search display followed the cue display without delay.

Results

Accuracy (cf. Figure 4a and Table 2)

Valid cues led to most accurate performance (*M* = 85.7 %), followed by OLD-invalid-inside (*M* = 79.8 %), NEW-invalid-inside (*M* = 79.5 %), and invalid-diagonal (*M* = 77.9 %) trials, *F*(3, 45) = 29.24, $p < .001$, $\eta^2 = .66$. The most accurate performance was reached for an ISI of 0 ms (*M* = 86.8 %), followed by ISIs of 50 ms (*M* = 85.4 %), 100 ms (*M* = 80.9 %), 150 ms (*M* = 76.4 %), and 200 ms (*M* = 73.9 %), *F*(4, 60) = 63.35, $p < .001$, $\eta^2 = .81$. There was no interaction of both factors, *p* = .599. Planned contrasts revealed a significant difference in accuracy between OLD-invalid-inside and NEW-invalid-inside trials for an ISI of 0 ms (M_{inside} = 87.2 % vs. M_{outside} = 85.2 %), *p* = .022, $\varepsilon = 0.78$, but not for longer ISIs (all *p*s > .316).

Reaction times (cf. Table 2)

There was no effect of validity on RT, *F*(1.3, 19) = 0.40, *p* = .586, $\eta^2 = .03$. The shortest RTs were found for an ISI of 200 ms (515 ms), followed by ISIs of 150 ms (528 ms), 100 ms (539 ms), 50 ms (541 ms), and 0 ms (564 ms), *F*(4, 60) = 11.36, $p < .001$, $\eta^2 = .43$. The interaction of both factors did not reach significance, *p* = .101.

Discussion

Results showed that only when the ISI was 0 ms—that is, when the target immediately followed the cue—participants were better on OLD-invalid-inside than on NEW-invalid-inside trials. Hence, only immediately after the texture rearrangement could a texture advantage according to the old texture arrangement be observed. With longer ISIs, any texture advantage was lost. At the same time, performance for NEW-invalid-inside trials was not better for any ISI. Thus, although the old texture advantage was lost, no texture advantage according to the novel texture arrangement could evolve once the cue was not visible anymore. Interestingly, the benefit at the cued location (i.e., the traditional cueing effect) persisted throughout all ISIs used, although the texture advantage could not spread to the novel texture.

Experiment 6

In Experiments 1–4, the textures were defined both by the orientation contrast at the texture border and by the contrast within texture elements—that is, homogeneity within the texture elements. Thus, the texture advantage may have resulted from either of these stimulus characteristics, which may, in turn, have triggered different perceptual processes. Although Experiment 6 was conducted to disentangle these two potential mechanisms by changing texton identity between the cue and search displays, while leaving the orientation contrast at the texture border the same (cf. Fig. 3b). If the texture border alone accounted for the texture advantage in the previous experiments, a similar benefit on invalid-inside trials over invalid-outside trials should be observed. Conversely, if texture element homogeneity (i.e., the identity of all textons within a texture) caused the texture advantage, no benefit in invalid-inside trials over invalid-outside trials would be expected.

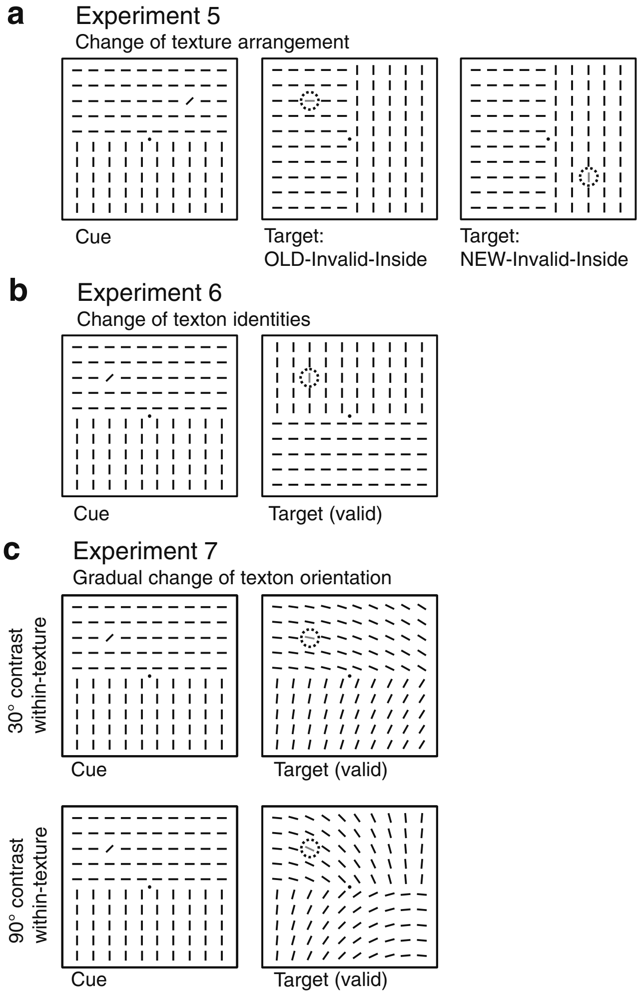
Method

The stimuli and procedure were identical to those jn Experiment 4, with one exception: The identity of the line elements was changed from vertical to horizontal and vice versa with cue display offset. For example, when the upper texture consisted of horizontal and the lower texture of vertical lines in the cue display, the upper texture lines would change to vertical and the lower texture lines to horizontal after cue offset. The texture border was left unchanged.

Results

Accuracy (cf. Figure 4b and Table 2)

Valid cues led to best performance (*M* = 84.7 %), while accuracy differed only slightly between the other three conditions: invalid-inside (*M* = 80.5 %), invalid-outside (*M* = 80.8 %), and invalid-diagonal (*M* = 79.6 %) trials, *F*(3, 45) = 12.55, $p < .001$, $\eta^2 = .46$. The best performance was reached for an ISI of 50 ms (*M* = 85.0 %), followed by ISIs of 150 ms (*M* = 81.0 %), 100 ms (*M* = 80.9 %), and 200 ms (*M* = 78.8 %), *F*(3, 45) = 14.36, $p < .001$, $\eta^2 = .49$. There was no interaction of both factors, *p* = .214. Planned contrasts revealed no significant



◀ **Fig. 3** **a** Illustration of the different texture arrangements in cue and search displays as used in Experiment 5. When the cue display was segregated in an upper texture of horizontal and a lower texture of vertical lines (i.e. horizontal texture border; left panel), the search display (and the standard texture during the interstimulus interval [ISI]) was segregated in a left texture of horizontal and a right texture of vertical lines (i.e., vertical border). Note that this changes the definition of invalid-inside and invalid-outside: A target may be presented at a location that was part of the cued texture in the cue display (OLD-invalid-inside; middle panel) or at a location that would be part of the cued texture if the cue was still present (NEW-invalid-inside; right panel). **b** Illustration of the textures with texton identities changing between cue and search displays, as used in Experiment 6. When the cue displays is segregated in an upper texture of horizontal and a lower texture of vertical lines (left panel), the search display (and the standard texture during the ISI) is segregated in an upper texture of vertical and a lower texture of horizontal lines (right panel). Thus, texton identity changes, while the texture border remains unchanged. The dotted line encircles the target locations for illustration purposes and was not visible to the observers. **c** Illustration of the textures with texton orientation gradually changing, as used in Experiment 7. The cue display comprised horizontal and vertical lines only. In the search display (and the standard texture during the ISI), the orientation of the line elements gradually changed 30° (high homogeneity) or 90° (low homogeneity) from one side of the texture to the other side of the texture. Deviation in orientation (difference in orientation from cue display to orientation in search display) of single line elements increased along the texture border, being small around the cued location and the invalid-outside location and being large around the invalid-inside and invalid-diagonal locations. The increase in deviation was less pronounced in the high-homogeneity condition (upper row) than in the low-homogeneity condition (lower row)

difference for invalid-inside and invalid-outside trials for any ISI (all *p*s ≥ .196).

Reaction times (cf. Table 2)

Valid cues led to the shortest RTs (577 ms), followed by invalid-inside and invalid-outside (each 595 ms) and invalid-diagonal (612 ms), $F(3, 45) = 6.68$, $p = .001$, $\eta^2 = .31$. There were no other significant effects (all ps > .1).

Discussion

If the texture advantage was due to the texture border, the texture advantage should have been left unchanged in the present experiment, because the border contrast was the same on cue and target trials. However, Experiment 6 showed that texture advantage was lost when texton identity changed between the cue and search displays. Performance on invalid-inside trials was not better than on invalid-outside trials for any ISI, although the border was left unchanged, generally allowing the same texture segregation (e.g., upper and lower visual fields) in cue and search displays. Thus, the homogeneity within the texture elements seems the critical aspect determining the texture advantage. The texture advantage seems to be bound to the identity of the homogeneously arranged individual textons. The orientation contrast at the border seems less relevant.

Experiment 7

In Experiment 6, the orientation of each line element changed from horizontal to vertical or vice versa with the cue display offset (i.e., the orientation was swapped for cue display vs. ISI and search display). This resulted in a maximum contrast of 90° at each location in the display, which may have induced some sort of backward mask. Hence, this mask, rather than the texton identity change as such, could have broken up the texture advantage. In Experiment 7, we wanted to test possible masking effects of the transients by gradually varying the deviation in orientation (cue display − search display) within a texture. Invalid-outside trials were privileged over invalid-inside trials by imposing a stronger deviation in orientation at invalid-inside locations. If deviation in orientation served as some sort of mask, this mask should be stronger for invalid-inside, due to the higher deviation in orientation. Let us assume a reliable texture advantage (the advantage for invalid-inside over invalid-outside)

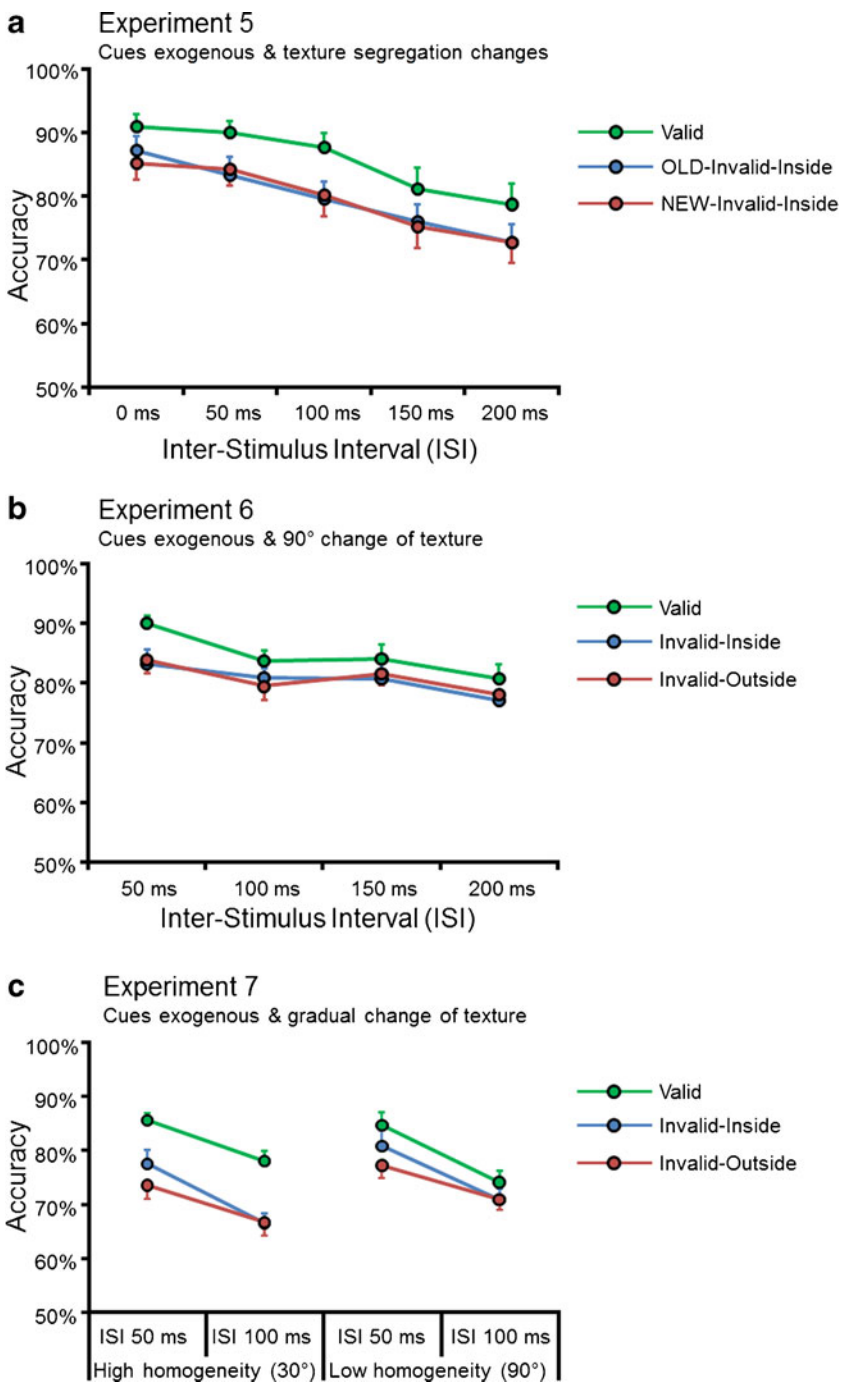


Fig. 4 **a** Mean accuracy in Experiment 5 as a function of interstimulus interval (ISI) and validity (valid, green lines; invalid-inside, blue lines; invalid-outside, red lines; for invalid-diagonal trials, see Table 2). **b** Mean accuracy in Experiment 6 as a function of ISI and validity (valid, green lines; OLD-invalid-inside, blue lines; NEW-invalid-inside, red lines; for invalid-diagonal trials, see Table 2). **c** Mean accuracy in Experiment 7 as a function of ISI, texture homogeneity (30° vs. 90°), and validity (valid, green lines; invalid-inside, blue lines; invalid-outside, red lines; for invalid-diagonal trials, see Table 2). Error bars indicate the standard errors of the means

was still found even when the potential masking for invalid-inside was stronger than for invalid-outside. This would also argue against the idea that the deviation in orientation in Experiment 6 was resulting in some sort of masking, which in turn undermined the texture advantage.

Method

The stimuli and procedure were identical to those in Experiment 6, with one exception: The identity of the line elements was not swapped between the cue and search displays from vertical to horizontal or vice versa (i.e., an all-encompassing change of 90° in orientation) but changed gradually within a texture. Deviation of the line orientation from the cue display increased along the border of the textures, with deviation being smallest at the cued location. This deviation manipulation led to varying differences in orientation between the cue display and the search display for the four quadrants of a display (cf. Fig. 3c). For example, in a horizontally divided display, when the cue was presented in the upper left quadrant, the search display lines on the left-hand side (where the cued location was) deviated less from the lines in the cue display than did the lines on the right-hand side (where the invalid-inside location was). To maintain the contrast of 90° at the texture border, the lower texture changed analogously, leading to a similar gradual deviation in the lower texture from left to right: The search display lines on the left-hand side (where the invalid-outside location was) deviated less from the lines in the cue display than did the lines to the right (where the invalid-diagonal location was). Thus, the deviation manipulation led to the least difference in orientation between the cue display and the search display for valid and invalid-outside trials and to the most difference in orientation for invalid-inside and invalid-diagonal trials. The gradual change from one side of the texture to the other side could be either 30° (high homogeneity) or 90° (low homogeneity) (cf. Fig. 3c). If the change in orientation for the search display serves as a backward mask for the cue display, invalid-inside locations should suffer more from increased within-texture contrast than should invalid-outside, because the single line element at the invalid-inside location deviated more from the single line element at the same location in the cue display.

Results

A two-way ANOVA with the factors validity and within-texture contrast (high vs. low) was run for the ISIs of 50 and 100 ms, separately for accuracy and RTs.

ISI 50 ms: Accuracy. (cf. Fig. 4c, Table 2)

Valid cues led to the best performance ($M = 85.2$ %), followed by invalid-inside ($M = 79.2$ %), invalid-diagonal ($M = 77.8$ %), and invalid-outside ($M = 75.4$ %) trials, $F(3, 45) = 10.24$, $p = .001$, $\eta^2 = .41$. Performance was slightly better for high within-texture contrasts ($M = 80.6$ %) than for low within-texture contrasts ($M = 78.2$ %), $F(1, 15) = 6.76$, $p = .020$, $\eta^2 = .31$. There was no interaction of both factors, $p = .103$. Planned contrasts revealed a significant difference for invalid-inside and invalid-outside trials for low within-texture contrast ($M_{\text{inside}} = 77.6$ % vs. $M_{\text{outside}} = 73.6$ %), $p = .002$, $\varepsilon = 0.79$, and for high within-texture contrast ($M_{\text{inside}} = 80.8$ % vs. $M_{\text{outside}} = 77.3$ %), $p = .018$, $\varepsilon = 0.82$.

ISI 50 ms: Reaction times (cf. Table 2)

There were no significant effects (all ps ≥ .200).

ISI 100 ms: Accuracy. (cf. Fig. 4c, Table 2)

Valid cues led to the best performance ($M = 76.1$ %), while accuracy differed only slightly between the other three conditions: invalid-inside ($M = 68.6$ %), invalid-outside ($M = 68.8$ %), and invalid-diagonal ($M = 67.6$ %) trials, $F(3, 45) = 5.77$, $p = .002$, $\eta^2 = .28$. Performance was slightly better for high within-texture contrasts ($M = 71.5$ %) than for low within-texture contrasts ($M = 69.0$ %), $F(1, 15) = 10.88$, $p = .005$, $\eta^2 = .42$. While valid cues yielded worse performance for high ($M = 74.1$) than for low ($M = 78.0$) within-texture contrast, invalid cues yielded better performance for high ($M = 70.7$) than for low ($M = 66.0$) within-texture contrast [interaction of validity and within-texture contrast, $F(3, 45) = 4.27$, $p = .010$, $\eta^2 = .22$]. Planned contrasts revealed no significant difference for invalid-inside and invalid-outside trials for low within-texture or high within-texture contrast (all ps ≥ .473).

ISI 100 ms: Reaction times (cf. Table 2)

There were no significant effects (all ps ≥ .113).

Discussion

In Experiment 7, the textons' identity varied between the cue and search displays, but in contrast to Experiment 6, their deviation in orientation was not always 90° but depended on the relative position within the texture and was gradually changed. For textons around the cued location and the invalid-outside location, deviation was relatively low, whereas around the invalid-inside location (and the invalid-diagonal location), deviation was relatively high. The results were comparable to those in Experiment 4 (which was similar to Experiment 7, except for the change between the cue and search displays): Invalid-inside trials yielded better performance than did invalid-outside trials for both an ISI of 50 and 100 ms. Valid trials led to best performance. This replication of the texture advantage makes it unlikely that the change in texton identity served as some sort of backward mask that may have broken up the texture advantage in Experiment 6. Since the deviation in orientation from cue display to search display was larger for invalid-inside trials than for invalid-outside trials, presumptive masking should have, if anything, privileged invalid-outside trials, as compared with invalid-inside trials. Quite the contrary was observed: Performance was better on invalid-inside trials than on invalid-outside trials for both high and low homogeneity within textures. This texture advantage was almost the same in size for Experiments 4 and 7 (3.95 % for Experiment 4 and 3.75 % for Experiments 7 across ISIs of 50 and 100 ms).

This finding is particularly interesting because of its implications for the role of texton identity changes in the texture advantage. In Experiment 6, when the texton identities changed from vertical to horizontal and vice versa, no texture advantage was found. In Experiment 7, when the textons identities also changed, but gradually within a texture, a texture advantage comparable in size to that for unchanged textures (Experiment 4) was found. Most interesting, in the low-homogeneity condition of Experiment 7, the deviation in line orientation from the cue to the search display was about the same as in Experiment 6 for the invalid-inside location. Still, there was a pronounced texture advantage for low-homogeneity trials in Experiment 7 and no texture advantage in Experiment 6. Thus, the difference in performance in Experiments 6 and 7 was likely due to the neighboring elements within the texture. These were gradually decreasing in deviation toward the cued location in Experiment 7 or had exactly the same deviation (i.e., 90°) in the entire texture in Experiment 6. Thus, the texture advantage seems not to be bound to the individual identity of the textons. Rather, properties of neighboring textons seem to be crucial for the texture advantage. Results suggest that gradual changes in orientation within a texture do not disrupt processing, whereas abrupt changes in orientation do disrupt processing of the texture. This can lead to differential processing at locations where the actual change of orientation (here, invalid-inside locations) is the same.

Experiment 8

Experiment 6 suggests that the homogeneity within texture elements contributes more to the texture advantage than does the texture border. A comparison of Experiment 6 and Experiment 7 suggests that not the homogeneity per se but, rather, the properties of neighboring textons within a texture determine how a texture is processed. A gradual change in orientation does not disrupt the texture advantage, whereas a uniform change of the entire texture makes the texture advantage disappear. Experiment 8 investigated the respective proportion of texture homogeneity and texture border in more detail by systematically varying border contrast and texture homogeneity. This texture manipulation goes back to a study by Nothdurft (1992) that employed a texture segregation task. Nothdurft (1992) presented a rectangular patch of simple oriented lines on a background of lines with different orientation and varied the homogeneity of the background (high vs. low homogeneity) independently from the border contrast—that is, the orientation difference of neighboring lines at the border (high vs. low contrast). Although texture homogeneity may rely on various local contrasts within the texture and, thus, be comparable to the contrast at the border, we wanted to disentangle these texture-defining determinants to shed light on differential underlying processes. Thus, we used a similar manipulation as Nothdurft (1992) and varied the homogeneity within texture elements and the orientation contrast at the border independently.

Method

Similar to Experiment 7, either texture homogeneity could be 30° (*high homogeneity*), meaning that line elements always varied within a range of 30° within a texture (e.g., from 10° to 40°), or texture homogeneity could be 90° (*low* homogeneity; e.g., elements varied from 10° to 100°). In contrast to Experiment 6, the texton identity did not change between the cue and search displays. Orientation contrast at the texture border could be 30° (*low contrast*), meaning that neighboring lines at each side of the border were 30° different in orientation (e.g., 0° vs. 30°), or border contrast could be 90° (as in Experiments 1–6; *high contrast*; e.g., 0° vs. 90°). This resulted in 2 × 2 possible textures—(1) high homogeneity and high border contrast, (2) high homogeneity and low border contrast, (3) low homogeneity and high border contrast, and (4) low homogeneity and low border contrast (cf. Fig. 5 for an illustration—which were combined with two ISIs (50 vs. 100 ms), and the four validity conditions from Experiments 1–6. Cues were exogenous and uninformative (cf. Table 1 for all experimental settings). Since there were 2,048 trials, participants had to take part in two sessions of 1,024 trials, each of which was at least 24 h apart.

Results

A three-way ANOVA with the factors validity, border contrast (high vs. low), and texture element homogeneity (high vs. low) was run for the ISIs of 50 and 100 ms, separately for accuracy and RTs.

ISI 50 ms: Accuracy (cf. Figure 5 and Table 2)

Valid cues led to the most accurate performance ($M = 92.9$ %), followed by invalid-inside ($M = 86.5$ %), invalid-outside ($M = 81.9$ %), and invalid-diagonal ($M = 81.6$ %) trials, $F(1.6, 23.6) = 11.94$, $p = .001$, $\eta^2 = .44$. No other effects were significant (all ps > .125). Planned contrasts revealed a significant difference in accuracy between invalid-inside and invalid-outside trials when homogeneity was high, both for high border contrast ($M_{\text{inside}} = 87.9$ % vs. $M_{\text{outside}} = 81.1$ %; cf. Fig. 5, upper left panel), $p = .022$, $\varepsilon = 0.83$, and for low border contrast ($M_{\text{inside}} = 87.8$ % vs. $M_{\text{outside}} = 82.2$ % ; cf. Fig. 5, lower left panel), $p = .012$, $\varepsilon = 0.89$. When homogeneity was low, the

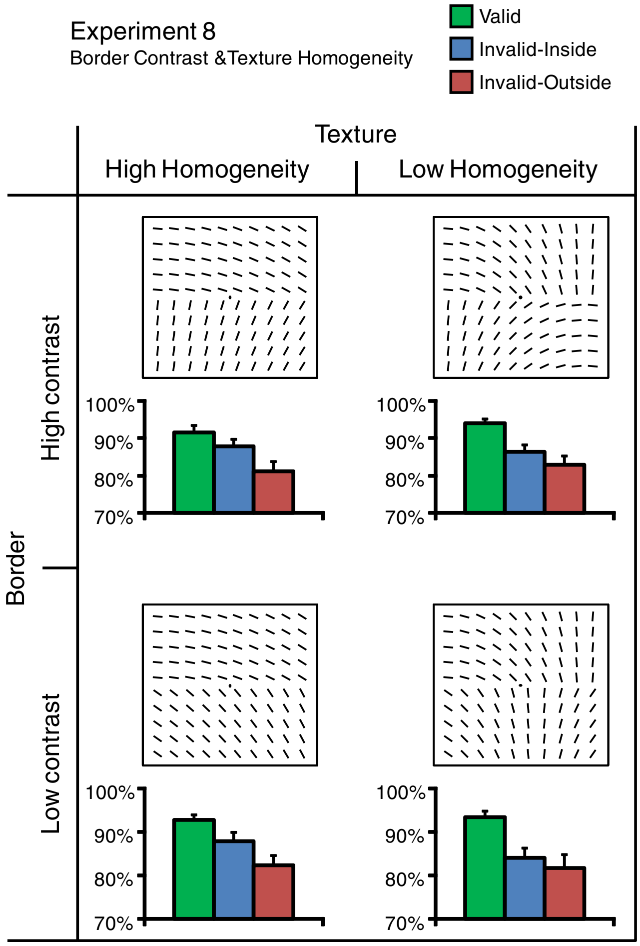


Fig. 5 Mean accuracy in Experiment 8, separately for textures with high (left column) and low homogeneity (right column) and separately for textures with high (upper row) and low border contrasts (lower row). Each of the four panels shows an exemplary texture and the accuracy for each validity condition (valid, green lines; invalid-inside, blue lines; invalid-outside, red lines; for invalid-diagonal trials, see Table 2). The exemplary textures in the four panels all have a "starting angle" of 5° (upper left texture line) to illustrate how the overall orientation difference between neighboring lines (texture homogeneity) and the local shift in line orientation at the texture border (border contrast) was varied. In the experiment, the "starting angle" was randomly chosen on each trial

difference between invalid-inside and invalid-outside just failed to reach significance for high border contrasts ($M_{\text{inside}} = 86.4$ % vs. $M_{\text{outside}} = 82.8$ %; cf. Fig. 5, upper right panel), $p = .086$, $\varepsilon = 0.51$, while no difference was found for a low border contrasts ($M_{\text{inside}} = 84.0$ % vs. $M_{\text{outside}} = 81.6$ %; cf. Fig. 5, lower right panel), $p = .197$, $\varepsilon = 0.31$.

ISI 50 ms: Reaction times (cf. Table 2)

Valid cues led to the shortest RTs (507 ms), while responses differed only slightly between the other three conditions: invalid-inside (542 ms), invalid-outside (546 ms), and invalid-diagonal (544 ms), $F(1.5, 22) = 10.11$, $p = .002$, $\eta^2 = .40$. No other effects were significant (all $ps > .139$).

ISI 100 ms: Accuracy (cf. Table 2)

Valid cues led to the most accurate performance (M = 87.4 %), followed by invalid-inside (M = 80.9 %), invalid-outside (M = 79.5 %), and invalid-diagonal (M = 76.8 %) trials, $F(1.6, 24.4) = 10.07$, $p = .001$, $\eta^2 = .40$. No other effects were significant (all $ps > .186$). Planned contrasts revealed no significant difference in accuracy between invalid-inside and invalid-outside trials for any combination of texture homogeneity and texture border contrast (all $ps > .124$).

ISI 100 ms: Reaction times (cf. Table 2)

There were no significant effects (all $ps > .076$).

Discussion

Experiment 8 systematically varied homogeneity within texture elements and orientation contrast at the texture border. Results showed that textures with high homogeneity (variation within a range of 30°) were sufficient to evoke a texture advantage, regardless of the degree of border contrast. In textures with high element homogeneity, targets that were presented in the cued texture (invalid-inside trials) were more often correctly identified than targets in the uncued texture (invalid-outside trials) both for a high border contrast of 90° (advantage of 6.8 %) and for a low border contrast of 30° (5.6 %). In textures with low element homogeneity (variation of 90°), hardly any texture advantage was observed: The effect just failed to reach significance when border contrast was high, and it was absent when border contrast was low. This further supports the notion that texture homogeneity, rather than the orientation contrast at the texture border, caused the texture advantage, although the border may add an additional benefit to invalid-inside, as compared with invalid-outside, trials. Interestingly, although the search display in the high-homogeneity and high-border-contrast condition in Experiment 8 was identical to the search display in the high-homogeneity condition in Experiment 7, a reliable texture advantage was found only in Experiment 7. The difference between the search displays in both experiments was that the previous cue display was either the same as the search display (Experiment 8) or completely homogeneous (Experiment 7). Apparently, the duration of cue presentation (100 ms) in which the completely homogeneous texture was shown in Experiment 7 was sufficient to induce a pronounced texture advantage that prevailed over the presentation of the less homogeneous search display. When no completely homogeneous texture was shown at all (Experiment 8), the texture advantage could not be fully unfolded.

General discussion

The present results provide evidence for the impact of textures on the deployment of spatial attention in the visual field. The results indicate that both exogenous and endogenous cues not only enhance processing of subsequently presented targets at cued locations, but also enhance processing of the entire cued texture.

Texture advantage for exogenous and endogenous cues

In eight experiments, participants had to identify the color of a target stimulus. Before search display onset, a cue indicated the likely target position; targets could appear at cued or uncued locations. Both exogenous and endogenous cues resulted in higher performance for subsequent targets when they were presented at the same location as the cue (Experiments 1 and 4–8) or when the endogenous arrow cue was pointing to the target location (Experiments 2 and 3). This shows that the benefit on valid trials that has been observed in traditional cueing experiments (for a review, see Ruz & Lupiáñez, 2002) can also be obtained by odd elements in otherwise homogeneous textures.

The novel finding of the present experiments is that performance for targets presented at uncued locations systematically depended on the way the visual field was segregated into textures. On invalid trials, performance was still better when the target and cue were presented inside the same texture (invalid-inside) than when they were in different textures (invalid-outside). Note that the spatial distance between the cued location and the target was the same in these conditions, so that the better performance could be attributed only to the position inside or outside the texture. We refer to the accuracy benefit of invalid-inside over invalid-outside as the *texture advantage*.

We varied the interval between the cue and target (ISI) to track the time course of cueing effects and the texture advantage. When cues were exogenous, the time course of the texture advantage depended on the informativeness of the cue. When the cue was informative, a, texture advantage was found for an ISI of 50 ms, whereas uninformative cues caused a texture advantage for 50 and 100 ms. While it was often argued that exogenous cues can also comprise an endogenous component when being informative (Doallo et al., 2004; Müller & Rabbitt, 1989; Wright & Richard, 2000), Experiment 4 could therefore rule out the possibility that an endogenous component is necessary to cause a texture advantage; exogenous control is sufficient. Interestingly, overall performance was worse when cues were informative than when they were uninformative. This might seem odd at first glance, but note that the difference is clearly on invalid rather than valid trials. This is in line with the recent finding that cueing benefits on valid trials might *not depend* on cue informativeness, whereas costs on invalid trials *do depend* on cue informativeness: Cueing costs are larger for informative cues than for uninformative cues and can sometimes be found for informative cues only (Doricchi, Macci, Silvetti, & Macalusa, 2010; Lasaponara, Chica, Lecce, Lupiáñez, & Doricchi, 2011).

Not only exogenous, but also endogenous cues can trigger a texture advantage as shown in Experiments 2 and 3; however, this effect was observed later than with exogenous cues. For endogenous cues, the time course of the texture advantage depended on the preparation time to deploy attention to a cued location. A texture advantage was found for the shortest ISI of 100 ms only when preparation time was relatively long (1,000 ms; Experiment 1), but not when it was relatively short (100 ms; Experiment 2). Thus, a longer preparation time that allows participants to optimally prepare for the subsequent target stimulus does not abolish the texture advantage but seems to expand it to an earlier point in time. The longer lasting texture advantage for endogenous than for exogenous cues is in line with the finding that endogenous cues need to be decoded by the organism, leading to delayed attention shifts, as compared with the automatically triggered attention shifts observed with exogenous cues (Müller & Rabbitt, 1989).

There has been some debate as to how endogenous control relates to object-based attention. Some studies found that only exogenous cues can trigger a spread of attention to entire objects (e.g., Macquistan, 1997; see also Lauwereyns, 1998). However, it was also found that when task demands or instructions encourage a broader attention focus, endogenous cues also can cause object-based attention (Goldsmith & Yeari, 2003; see also Chen & Cave, 2008). In contrast to these studies, which used rectangular objects in otherwise empty visual fields, we used fully structured visual fields and textures in the present study. These may, as in Goldsmith and Yeari (2003), have caused a tendency in the observer to generally broaden the attention focus (i.e., independently of task demand or instructions) and to attend entire textures rather than single locations. In any case, the present study provides further evidence that object-based attention may also be obtained under endogenous control.

Contrary to accuracy results, RTs did not differ between invalid-inside and invalid-outside trials in the present experiments. This is not surprising, considering that participants were instructed to respond as correctly as possible, neglecting RTs (which were furthermore not displayed in feedback screens). However, valid trials resulted in shorter RTs, as compared with invalid trials in all experiments. Thus, the traditional cueing effect seems much stronger than the texture advantage and has an impact on RTs even though participants did not explicitly try to respond as quickly as possible. Traditional cueing may extend to postperceptual processes such as response selection, while the texture advantage affects mainly perceptual processes.

Attention deployment in a structured visual field

The present results may shed some new light on the way visual selective attention is shaped by the structure of the visual field. It has previously been demonstrated that attention is rather deployed to entire objects than to specific spatial locations (Duncan, 1984; Egly et al., 1994; O'Craven et al., 1999). For example, when a part of a rectangle is exogenously cued, all rectangle locations benefit from cueing. This suggests that attention tends to spread to an entire object when the object is defined by the Gestalt principles of colinearity and closure (Egly et al., 1994). Similar results were obtained when the visual field was structured by colinearity only (Avrahami, 1999; Marino & Scholl, 2005) or by multiple objects that differ in similarity (Dodd & Pratt, 2005).

The present series of experiments extends these findings and shows how attention is deployed on a more fine-grained level. Instead of using full-fledged, rather arbitrarily defined objects that have the shortcoming that is not clear what counts as an object when it comes to the deployment of attention (Ben-Shahar et al., 2007), we structured the visual field with the basic simple feature *line orientation*, which underlies objects in everyday life. These simple *texton* stimuli have the advantage that they can be grouped preattentively to be processed as a unit (Julesz, 1986; Nothdurft, 1992, 1993), which allowed separating the effects of segregating the visual field (preattentively into textures) and the deployment of attention (toward cue/target). The texture advantage we found in several experiments indicates that attention is deployed texture-wise. Positions equidistant to a cued location were *not* provided with the same amount of attention. Instead, targets in the same texture as the cued location were provided with more attention than were targets outside that texture. This is in line with the finding that attention can be divided far better between two locations within the same texture than between two locations within different textures (Ben-Shahar et al., 2007).

The present results show two aspects of the deployment of spatial attention: First, the cued location is provided with more attention than any other location inside or outside its texture, and second, when uncued locations are compared, the texture to which the cued location belongs is provided with more attention than is the other texture. We thus conclude that cueing constituted an *attention gradient* with highest priority directly at the cued location, followed by less efficiency at locations inside the cued texture, with these receiving yet more priority than locations in the remaining visual field.

For object-based attention, it has been found that after prolonged ISIs, invalid locations that are part of a cued object show impaired performance, as compared with invalid locations that are part of another object, while the cued location still shows enhanced performance (i.e., inhibition of return; Weger, Abrams, Law, & Pratt, 2008). This was not the case in the present experimental series: Although valid locations showed highest accuracy throughout all ISIs and any texture advantage disappeared after 100 ms (exogenous cues) or 200 ms (endogenous cues), performance on invalid-outside trials never exceeded that on invalid-inside trials. This difference in the gradient of attention may be due to the fact that *parts* of full-fledged objects like rectangles (Weger et al., 2008) are more likely to be subject to inhibition than are *parts* of a texture (present study). Another reason for not observing inhibition of return in the present experiment may have been the emphasis on accuracy, which usually delays the point in time at which inhibition of return can be observed (Lupiáñez, Milan, Tornay, Madrid, & Tudela, 1997).

Interestingly, the texture advantage followed a different time course than the traditional cueing effect (Posner, 1980). While traditional cueing was observed for basically all cue–target intervals, the texture advantage was present for short latencies only. This indicates a different time course of attention deployment. Attention deployment toward cued locations lasts longer than attention deployment toward textures to which the cued location belongs. Results show different time courses of texture-induced gradients of focal attention for exogenous and endogenous cues: Exogenous cues cause a relatively early spread of attention toward the cued texture and then a focus on the cued location for longer ISIs. Endogenous cues cause a strong gradient of attention first, then a broader gradient encompassing the entire texture. Finally, the focus of attention recontracts around the cued location. The results suggest that the size of the attentional gradient is variable, generally shrinks over time, but is also modulated by exogenous versus endogenous control.

The effect of texture grain on the gradient of attention

To further investigate the texture-induced gradient of attention, we examined whether the grain of the texture affected the way attention was deployed in the visual field. A previous study by Avrahami (1999) has shown that attention deployment in a structured visual field may depend on the grain of the structure. In her experiment, two successive spatially separated stimuli were presented on a grid of long parallel lines that encompassed the entire display. Participants had to respond as quickly as possible whenever they detected the second stimulus. RTs for the second stimulus were shorter when attention had to be shifted parallel to the lines (i.e., a shift "along the grain"; cf. Fig. 6a, upper row), as compared with orthogonal attention shifts (i.e., "against the grain"; cf.

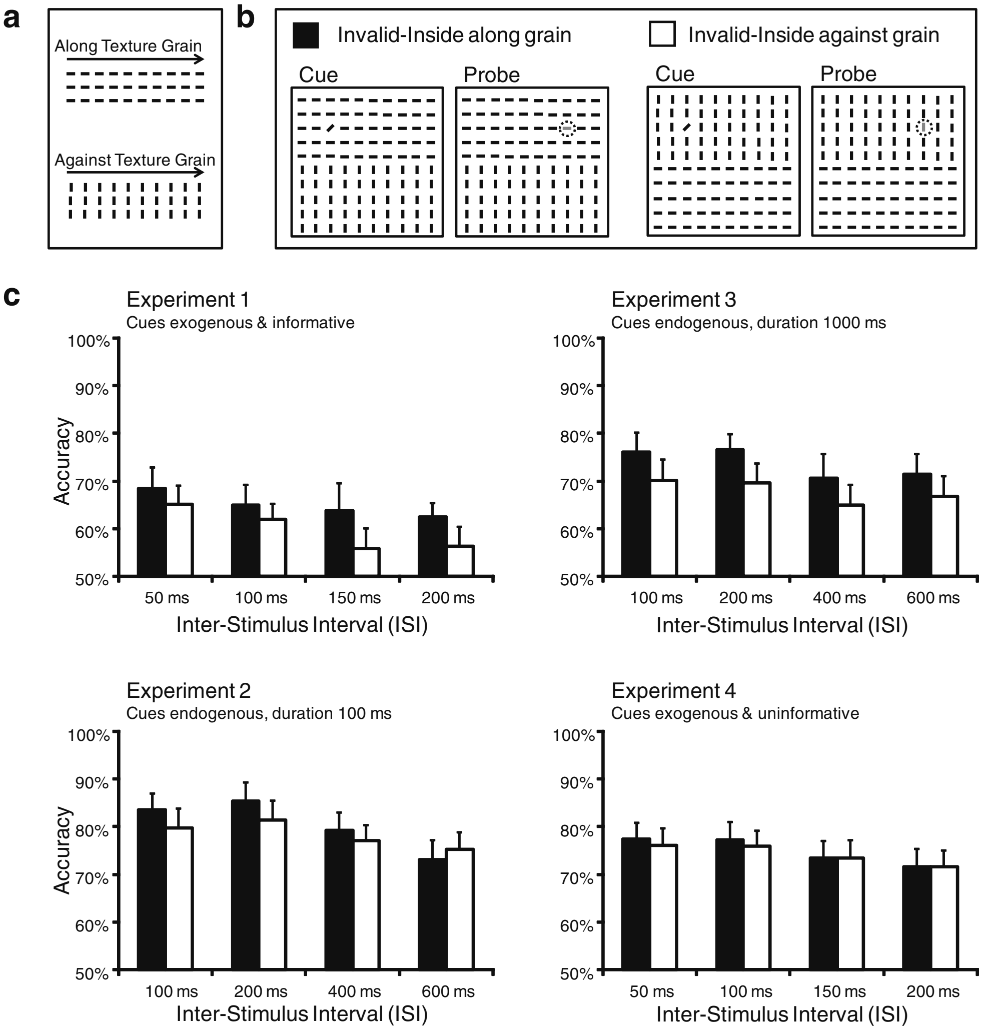


Fig. 6 **a** Illustrative definition of the texture grain. A direction parallel to the orientation of the lines (upper row) is defined as "Along Texture Grain," whereas a direction orthogonal to the orientation of the lines (lower row) is defined as "Against Texture Grain." **b** In invalid-inside trials, attention deployment from the cue to the target could be along the grain (left panel) or against the grain (right panel). The dotted line encircles the target locations for illustration purposes and was not visible to the participants. **c** Mean accuracy for invalid-inside trials in Experiment 1 (upper left panel), Experiment 2 (lower left panel), Experiment 3 (upper right panel), and Experiment 4 (lower right panel). Accuracy is shown as a function of interstimulus interval and attention deployment along the grain (filled bars) versus against the grain (empty bars). Error bars indicate the standard errors of the means

Fig. 6a, lower row; Avrahami, 1999), suggesting more efficient attention deployment along the grain than against the grain. Conversely, the grain of a structure does not modulate attention deployment when two to-be-attended stimuli are simultaneously presented (Ben-Shahar et al., 2007). We conducted a post hoc analysis on invalid-inside trials for Experiments 1–4, separately for cues and targets connected along the grain of the texture versus against the grain of the texture (cf. Fig. 6b). Mean accuracy for invalid-inside trials was collapsed across all ISIs and then compared for grain (along vs. against) with a *t*-test for dependent measures for each experiment. In Experiment 1, accuracy was higher for connections along the grain ($M = 64.9$ %) than for connections against the grain ($M = 59.8$ %), $p = .036$, $\varepsilon = 0.69$. In Experiment 2, accuracy was only marginally higher for connections along the grain ($M = 80.3$ %) than for connections against the grain ($M = 78.4$ %), $p = .088$, $\varepsilon = 0.50$. In Experiment 3, accuracy was higher for connections along the grain ($M = 73.7$ %) than for connections against the grain ($M = 67.9$ %), $p < .001$, $\varepsilon = 1.34$. In Experiment 4, accuracy was about equally high for connections along the grain ($M = 71.7$ %) and for connections against the grain ($M = 71.6$ %), $p = .449$, $\varepsilon = 0.05$.

These results are well in line with earlier findings (Avrahami, 1999) and show that the texture-induced gradient of attention may also be a function of texture grain. The performance difference between valid and invalid-inside trials was smaller when cue and target locations were connected with the grain, suggesting a more balanced attention deployment within the cued context (i.e., a balanced attention gradient). However, for locations connected against the grain, the performance difference between valid and invalid-inside trials was larger, suggesting a more focused attention deployment on the cued location (i.e., a stronger attention gradient). Interestingly, the gradient of attention was modulated by the grain only when cues were informative (Experiments 1, 2, and 3). The differences in invalid-inside trials between “against the grain” and “along the grain” may also be interpreted as a figure–ground effect. It has previously been found that textons parallel to the border are more likely to be perceived as the figure and textons orthogonal to the border are more likely to be perceived as the ground (e.g., Jingling & Zhaoping, 2008). Accordingly, the present results suggest that attention deployment within the figure may be more efficient than attention deployment within the ground.

Representation of texture homogeneity and border contrast on a salience map

Current theories of visual attention often assume that attention deployment is based on a salience map that codes the visual field in a topographical manner; the salience map represents all stimuli in the visual field with a particular activation according to their physical features, such as contrast or similarity (Fecteau & Munoz, 2006; Itti & Koch, 2000; Li, 2002; Wolfe, 1994). The activation pattern on the salience map is available at a very early point in visual processing (Itti & Koch, 2000), may be based on activations in V1 (Li, 2002; Zhaoping, 2003; Zhaoping & Snowden, 2006), and is used to later prioritize those stimuli in the visual field that will receive more elaborated, attentive processing (e.g., Wolfe, 1994). To account for cueing effects, it has been suggested that targets are represented with a higher activation on valid, as compared with invalid, trials, because of the residual cue activation at the same location (e.g., Fecteau & Munoz, 2006). Results from the present study support this assumption but also suggest that targets on invalid-inside trials receive more activation than do targets on invalid-outside trials. Apparently, the texture arrangement adds to the cue-induced activations on the salience map and reflects the gradient of attention. While the cued location receives highest activation, the cued texture receives more activation than does the remaining visual field. Thus, on invalid-inside trials, targets benefited from higher residual activation of the cue display, as compared with targets on invalid-inside trials, resulting in the texture advantage.

This activation pattern seems to be disrupted by dynamic changes in the visual field: When the texture arrangement in cue and search displays was different (Experiment 5), no texture advantage was observed, except for the shortest ISI. Apparently, the texture-induced gradient of activation on the salience map rapidly disappears when a novel texture arrangement is shown. Interestingly, the novel texture arrangement does not seem to induce a new gradient of activation on the salience map, since NEW-invalid-inside trials were not found to show better performance than OLD-invalid-inside trials at any ISI. It may be that subsequent texture representations extinguish each other, leaving a single activation peak at the previous cue location merely preserving the traditional cueing effect.

The texture advantage observed in the present experiments may have resulted from orientation border contrast between the two textures (e.g., Zhaoping, 2003) or the homogeneity of texture elements (Nothdurft, 1992). We disentangled these two potential factors by changing texture element (texton) identity between cue and search displays, while leaving the texture border the same. When the deviation in orientation was 90° (i.e., horizontal and vertical lines were swapped; Experiment 6), results showed that the texture advantage disappeared for all ISIs. When the deviation gradually increased from the cued location to the invalid-inside location (Experiment 7), results showed that this change in identity did not affect the texture advantage. Results from Experiments 6 and 7 suggest that the texture border contrast alone cannot account for the texture advantage. If the texture advantage was due only to the higher activation at the texture border (Zhaoping, 2003), the texture advantage should have been left unchanged in Experiment 6, because the border contrast, inducing higher activation on the salience map (cf. Zhaoping & Snowden, 2006), was the same on cue and target trials. It is also unlikely that masking effects can account for the lack of texture advantage in Experiment 6: In Experiment 7, where the deviation in orientation (cue display − search display) was higher for invalid-inside trials than for invalid-outside trials, presumptive masking should have privileged, if anything, invalid-outside trials, as compared with invalid-inside trials. However, the disruption of the texture advantage due to a change of texton identity depended on the way the search display varied in orientation. When the deviation in texton orientation gradually varied (Experiment 7), texture advantage was stable, while an all-encompassing abrupt change of orientation eliminated the effect. It may be that the presumed spread of higher activation on the salience map from the cued location to all locations that belong to the cued texture was intercepted by the abrupt identity change (Experiment 6), which resulted in lower activation levels at the invalid-inside locations. In Experiment 7, the gradual change in orientation may have allowed a more efficient spread of higher activation from the cued location to all locations that belonged to the cued texture. Results from Experiment 8 showed that such a spread of activation on the salience map within a gradually varying low-homogeneity texture was impaired when the low homogeneity was already present in the cue display. In Experiment 8, orientation contrast at the texture border and homogeneity within texture elements were systematically varied. Even for the maximum border contrast of 90° (also used in Experiments 1–6), only a slight texture advantage was observed when texton homogeneity was low. Conversely, a homogenous texture was sufficient to elicit a texture advantage even for a weak border contrast of 30°. This shows that texture homogeneity had a stronger impact on the texture advantage than did the border.[2] While border contrast may have some general effect on the distribution of activation on the salience map, the impact of homogeneity on salience map activation is more complex. When the initial cue display is completely homogeneous, a subsequent search display with low homogeneity seems to not interrupt the salience increase of the entire texture as long as changes in orientation are gradual (Experiment 7). When the initial cue display also is less homogeneous, the increase in salience for the entire texture is less pronounced (Experiment 8). It has been argued before that similar stimuli may result in stronger linkage (e.g., Duncan & Humphreys, 1989; Meinecke & Donk, 2002; Nothdurft, 1992), which allows grouping into larger perceptual units (Schubö et al., 2004; Schubö, Wykowska, & Müller, 2007). Dissimilar stimuli, on the other hand, may also result in a high-contrast induced activation on the salience map (Li, 2002). As a result, activation on the salience map may spread from the cue location to neighboring elements when these are similar enough or gradually changing in orientation, while activation for elements that are too deviant in orientation (e.g., at the border and beyond; the uncued texture) may be suppressed.

Texture advantage as a result of event integration processes

A different approach to account for exogenous cueing effects is the event integration approach (Lupiáñez & Milliken, 1999; Lupiáñez, Milliken, Solano, Weaver, & Tipper, 2001). The event integration approach suggests that current perceptual information can be integrated with perceptual information the observer was previously exposed to. This happens in such a way that the spatiotemporal match between successive events (e.g., cue and search displays) determines the efficiency of processing of both events (Funes et al., 2005). According to the event integration approach, cue and target have to have a spatiotemporal match in order to be integrated into one single event. This is the case when the ISI is short enough (temporal match) and the cue is valid (spatial match). In this case, location information from the cue can be used to localize the target, leading to improved target processing (Funes et al., 2005). The spatial match may also be flexibly adjusted to the structure of the entire visual field: Since "spatial Stroop," usually reduced by spatial cues, is reduced not only at the cued location, but also for the entire cued object (Luo, Lupiáñez, Funes, & Fu, 2010), it was suggested that all locations of an object can be integrated into one event. In this regard, the texture advantage found in the present series of experiments could be explained in terms of a spatial match assumption. Spatial match between a cue display and a search display is higher when the cue and target locations change within a texture, as compared with a change between textures. In other words, when the target appears in the same texture as the cue, there may be sufficient spatial match for integration. However, when the target appears in a different texture than the cue, they cannot be perceptually integrated, and two "object representations" have to be initiated, one for the cue and one for the target. For longer ISIs, *spatial* match might still be evident on invalid-inside trials, while the degree of *temporal* match would be low on invalid-inside and invalid-outside trials (cf. Luo, Lupiáñez, Funes, & Fu, 2011). Accordingly, invalid-inside and invalid-outside trials may yield similar accuracy rates at longer latencies. Accordingly, the present data can be well explained in terms of the event integration approach and may be suited to extend it from object-based to texture-based attention.

Conclusions

There has been quite some evidence that attention deployment is guided by the structure of the visual scene the observer encounters—for example, by colinearity, closure, or similarity of comprised elements (Dodd & Pratt, 2005; Duncan, 1984; Egly et al., 1994). With a variation of the spatial cueing paradigm (Posner, 1980), the present study investigated in eight experiments how preattentively segregated textures shape the focus of attention induced by spatial cues. Our results showed that not only locations, but also entire textures can benefit from a cue. Whereas highest performance was observed for targets at cued locations (valid trials), a differential performance was shown for invalid trials: for targets presented inside the same texture as the cue, performance was higher, as compared with targets presented outside that texture. This suggests a benefit for stimuli inside the same texture as a previously cued location—that is, a *texture advantage*. For exogenous cues, this texture advantage was found for informative and uninformative cues. For endogenous cues, the texture advantage was evident no matter whether participants had a short (100 ms) or a long (1000 ms) preparation time. Additional experiments revealed that the homogeneity within texture elements may contribute more to this effect than the orientation contrast at the texture border but that, when the orientation changes gradually, a less homogeneous arrangement can still elicit a texture advantage.

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[2] It should, however, be noted that homogeneity and texture border contrast cannot be completely separated. High texture homogeneity may be similar to a low contrast within a texture, and low texture homogeneity may be similar to a high contrast within a texture.

This sheds new light on the way attention is deployed in a structured visual field and helps to explain how the gradient of the attentional focus is shaped by contrast, homogeneity, and gradual changes within a texture.

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Context heterogeneity has a sustained impact on attention deployment: Behavioral and electrophysiological evidence

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Abstract

In visual search, similar nearby stimuli can be grouped and thus enhance processing of an embedded target. The aim of the present study was to examine the time course of attention deployment after a brief presentation of stimulus arrays of different heterogeneity. Targets in less heterogeneous, grouped contexts yielded higher accuracy and larger N2pc amplitudes than targets in more heterogeneous, random contexts, indicating more efficient selection in the former. Subsequently presented probes yielded shorter reaction times and a larger posterior positivity when presented at the target location. This advantage was more pronounced after grouped compared to random contexts at the shorter compared to the longer interstimulus interval. The results show that less heterogeneous contexts that allow for grouping not only enhance processing of stimuli within that context, but have a sustained effect on visual attention.

Descriptors: Visual attention, Distractor homogeneity/heterogeneity, EEG/ERP, Normal volunteers

In everyday life, the human visual system is confronted with an abundance of input at any given moment. An effective process known as *selective visual attention* allows for preferential processing of relevant visual information and/or inhibition of irrelevant information (Duncan & Humphreys, 1989; Eriksen & Yeh, 1985; Treisman & Gelade, 1980; Wolfe, 1994). Thus, only a pertinent amount of information in the visual field is processed and enters visual short-term memory, preventing informational overload (Koch & Tsuchiya, 2007; Posner, Snyder, & Davidson, 1980). It has been suggested that attention is not distributed evenly across the visual field and that attentional selection operates on the basis of spatial locations within a gradient (Eimer, 1999; Ghirardelli & Folk, 1996; Kravitz & Behrmann, 2008; LaBerge, 1983; Mangun & Hillyard, 1991; Posner et al., 1980). Where attention is deployed in the visual field depends upon the visual salience of objects (Itti & Koch, 2001; Nothdurft, 1992; Theeuwes, 2004; Wolfe, 1994) and upon relevance to the observer (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Wykowska & Schubö, 2010, 2011). According to recent models of visual attention, visual salience and current relevance of an object are represented on a priority map, a coarse topographical representation of the visual field, which guides attentional focus to conspicuous locations (Itti & Koch, 2001; Wolfe, 1994).

Attention Deployment and Perceptual Grouping

Visual search tasks have often been used to examine how attention is deployed across the visual field (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Eimer, 1996; Eimer, Kiss, & Cheung, 2010; Found & Müller, 1996; Theeuwes, 1994; Treisman & Gelade, 1980; Wolfe, Võ, Evans, & Greene, 2011; Wolfe, 1994; Woodman & Luck, 2003). In a typical visual search task, participants are requested to indicate whether a predefined target is presented within a set of distracting nontargets that differ from the target in a particular feature (e.g., color or shape) or a combination of such features. It has been shown that both target and nontarget properties influence search performance (Duncan & Humphreys, 1989; Schubö, Wykowska, & Müller, 2007; Wolfe, 1994). In their attentional engagement theory, Duncan and Humphreys (1989, 1992) emphasize the crucial role of nontarget heterogeneity in the deployment of visual attention. They proposed that at an early "parallel" stage of visual coding, incoming visual information is segmented into structural units based on the operation of elementary segmentation and on grouping principles. These structural units form the input for subsequent processing stages on which decisions upon target presence are being made. At this early stage, elements that are similar are linked together to form a larger perceptual unit, which is subsequently processed as one single structural unit. Reducing the heterogeneity of nontarget elements increases search efficiency, because similar (or homogeneous) elements are being grouped, and grouping reduces the number of perceptual units that have to be searched in order to find the target. Similarity grouping

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is thus accelerating both subsequent rejection of nontargets on target-absent trials and singling out the element that does not belong to the uniform structure in target-present trials.

Perceptual grouping of elements into larger units happens at early stages of visual perception and does not require focal attention (Humphryes, 1998). As it is assumed to happen prior to deployment of attention, it may determine what is attended (Li, 2002; Nothdurft, 1992; Schubö, Akyürek, Lin, & Vallines, 2011) and what is suppressed (Feldmann-Wüstefeld & Schubö, 2013). A special status of context heterogeneity was also found to be reflected in the event-related brain potential (ERP) of the electroencephalogram (EEG). For perfectly homogeneous contexts that consisted of numerous nontarget elements, the posterior N2 was enlarged on target-absent compared to target-present trials (Schubö, Schröger, & Meinecke, 2004; Schubö et al., 2007). This suggests that the posterior N2 mirrors grouping processes.

Attention Deployment Toward Successively Presented Stimuli

Previous results clearly speak in favor of a strong impact of nontarget heterogeneity on attention deployment due to more efficient processing of grouped stimuli. However, visual selective attention at any given moment is not constrained to the momentary properties of the visual input, but also results from properties of visual information preceding the given moment in time, and from the interplay between consecutive stimuli (Hommel & Colzato, 2004). It has been shown that attended stimuli do not only influence the current spatial deployment of attention in an array, but also affect attention in subsequently presented sets of stimuli (Found & Müller, 1996; Klein, 2004). For example, it has previously been demonstrated that the abrupt onset of a salient task-irrelevant stimulus (Henderson, 1991; Kiss & Eimer, 2008; Posner et al., 1980; Ruz & Lupiáñez, 2002; Woodman & Luck, 1999; Yeshurun, Montagna, & Carrasco, 2008) or the onset of a stimulus made relevant through task instruction (Kim & Cave, 1999; Wykowska & Schubö, 2011) can improve processing of subsequently presented stimuli at the same location. This has been argued to be due to a sustained effect of the first stimulus on attention deployment towards the second stimulus (Itti & Koch, 2001; Luck & Hillyard, 1994a). Although it has been argued that a stimulus surrounded by less heterogeneous stimuli attracts attention more efficiently than when surrounded by more heterogeneous stimuli (Duncan & Humphreys, 1989; Li, 2002; Schubö et al., 2011, 2007; Wolfe, 1994), it has not yet been examined whether nontarget heterogeneity affects attention deployment in a sustained manner. For example, a stimulus presented shortly after a target within less heterogeneous nontargets may benefit from attention deployment when being shown at the same location as the target, because rejection of grouped nontargets has already terminated. For targets in heterogeneous nontargets, however, this process requires more effort (Duncan & Humphreys, 1989), and it may thus take longer until subsequent stimuli benefit from being presented at the same location. For perfectly homogeneous contexts, it has already been found that deviant elements can induce a sustained attention deployment: In a study by Donk and Soesman (2010), task-irrelevant diagonal lines were presented in otherwise homogeneous contexts of horizontal or vertical line elements. The diagonal lines deviated slightly (20°) or strongly (70°) from the context, inducing different levels of salience. An array of asterisk-like stimuli was presented 42 ms, 158 ms, or 483 ms after context onset, serving as a backward mask. Also, participants had to indicate the location of the one asterisk that differed in color. For the shortest time interval of 42 ms, only reaction times (RTs) for probes presented at locations previously occupied by highly salient singletons were shorter than those occupied by one of the homogenous context elements. For longer time intervals of 158 ms or 483 ms, probe localization was facilitated for both highly salient and moderately salient locations. The authors concluded that once a critical amount of time has passed, the visual system maintains only information concerning the presence of salient objects, lacking all information concerning the specific salience of these objects (Donk & Soesman, 2010; see also Dombrowe, Olivers, & Donk, 2010; Donk & Soesman, 2011). However, in these experiments only perfectly homogeneous contexts were used. By using arrays of grouped versus randomly arranged line stimuli, it is possible to examine whether different degrees of heterogeneity yield facilitation effects of different time course and/or size.

Rationale of the Experiment

The present experiment investigated whether various degrees of heterogeneity have a sustained impact on attention deployment. To this end, a paradigm that combined a visual search task with a subsequent probe discrimination task was designed. The visual search displays consisted of contexts of varying degrees of heterogeneity. The target feature, a diagonal line, was kept constant so that top-down selection criteria would not be altered. Contexts consisted of 50 horizontal and 50 vertical line elements. Varying the spatial arrangement of these line elements allowed for manipulating grouping processes. In a grouped condition, the stimulus array consisted of two groups of homogeneously arranged horizontal and vertical lines (see Figure 1B). In a random condition, the same stimuli were arranged randomly resulting in a more heterogeneous context. A color probe was presented after a short or long interstimulus interval (ISI) either at the same location as a previously presented target or at a different location. Participants had to respond as quickly as possible to the probe's color (blue vs. green).

We assumed different search efficiency for grouped versus random contexts (reflected in better detection performance). Furthermore, we expected that the N2pc, a contralateral ERP component indicative of attention deployment within the visual field (Eimer, 1996; Luck & Hillyard, 1994b; Mazza, Turatto, Umiltà, & Eimer, 2007; Woodman & Luck, 2003), would be enlarged and may occur earlier for targets in grouped compared to targets in random contexts. We also expected to replicate the differential N2 effect (Schubö et al., 2007), that is, larger N2 amplitude for target-absent trials than for target-present trials in grouped but not in random contexts, indicating that processing mode would be different for grouped and random contexts.

We further hypothesized that facilitated deployment of attention to the target in the grouped contexts (relative to random contexts) would also affect processing of the subsequently presented probes. Probes should generally benefit from being presented at the same location as the target because of prior preferential processing at target locations (Donk & Soesman, 2010; Henderson, 1991; Kim & Cave, 1999; Kiss & Eimer, 2008; Luck & Hillyard, 1994a; Posner et al., 1980; Wykowska & Schubö, 2011). This should result in an advantage for probes at the previous target locations (on-target condition) for both grouped and random contexts. If it takes longer until a target can be detected in random contexts due to less efficient nontarget rejection, the on-target advantage should be less pronounced for random contexts than for grouped contexts, especially in the short ISI condition. As a result, probes presented after grouped contexts may benefit to a higher degree from being at the

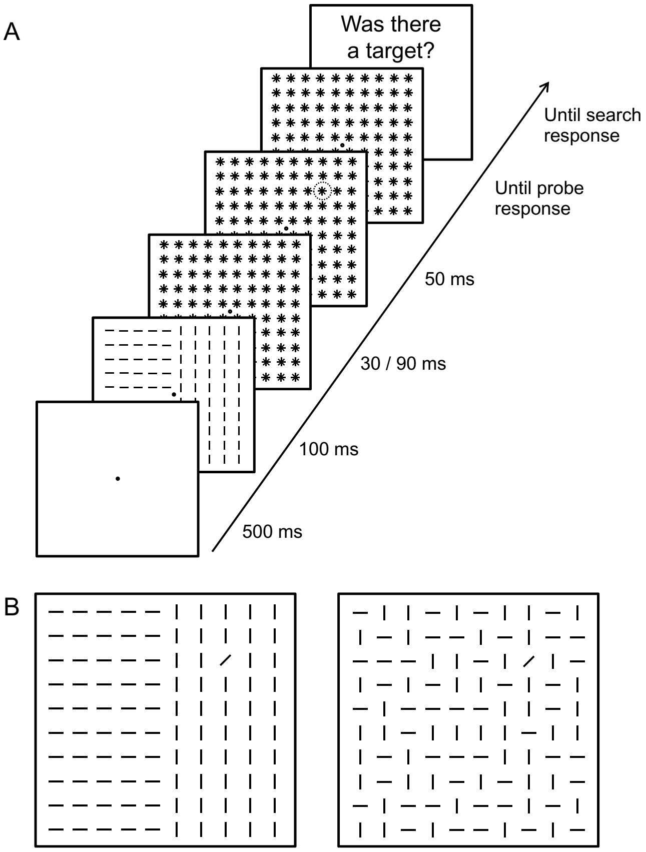

Figure 1. A: Trial sequence. Participants were asked to detect a predefined target (an oblique line of 45°) in a search array of horizontal and vertical lines. Subsequent to search display presentation, all stimuli were masked with asterisks. After 30 ms (short ISI condition) or 90 ms (long ISI condition), one of the asterisks turned green or blue, serving as a probe (circled here with dotted line for illustration purposes). Participants were asked to first respond with the right hand to the probe task (i.e., discriminate probe color). Afterwards, they had to respond with the left hand to the search task (i.e., indicate whether a target was present or not). In 20% of the trials, no probe was presented and the screen prompting for the target presence appeared directly after a mask of 500 ms. B: Display types. (left) Example of grouped context in which horizontal and vertical lines were arranged separately into two visual hemifields. (right) Example of random context in which horizontal and vertical lines were randomly arranged across the entire visual field. Both panels show a trial in which a target (the oblique line) is present.

same location as the previous target compared to probes presented after random contexts, yielding shorter reaction times.

To further elucidate differential processing of contexts of varying heterogeneity and underlying differences in efficiency of attentional deployment, we examined the ERPs elicited by the probes. Previous results have shown that an enhanced positive deflection of the ERP waveform at posterior sites can be indicative of the effects of spatial attention on subsequent sensory processes at the attended location. When focal attention is deployed towards peripheral abrupt onsets, task-relevant stimuli subsequently presented at the same location elicit an enhanced posterior positivity compared to stimuli presented at other locations. This positivity is usually in the range of P1 (Doallo et al., 2004; Luck, Woodman, & Vogel, 2000; Mangun & Hillyard, 1991), but sometimes extends to later components such as the N1 (Heinze, Luck, Mangun, & Hillyard, 1990; Luck, Heinze, Mangun, & Hillyard, 1990). This effect is assumed to mirror sensory gain control (i.e., increase of signal-to-noise ratio by enhancement of processing at the attended locations and/or suppression of processing at other (unattended) locations) at early stages of selective visual attention (Hillyard, Vogel & Luck, 1998; Luck & Hillyard, 1994a; Luck et al., 2000). Therefore, we expected the probe-locked ERP to be generally more positive for probes at target locations compared to probes at non-target locations. Since we expected that target detection in grouped contexts is faster due to faster rejection of nontargets, the resulting sensory gain should be available earlier in time. We thus hypothesized that the positive deflection in the ERP would be more enhanced for probes presented after grouped than after random contexts, paralleling expected behavioral effects.

Using two ISIs allowed for the investigation of effects of grouping on the deployment of attention at two different points in time. Since we were particularly interested in transient, short-lived effects that are likely to be evoked by an oblique line within horizontal and vertical lines (see Nothdurft, 1992; Wolfe, 1994), relatively short ISIs were used, namely 30 ms and 90 ms. We hypothesized that for an ISI of 30 ms, the on-target advantage should be more pronounced for grouped than for random contexts because the target in grouped contexts should be identified earlier due to preattentive grouping (Duncan & Humphreys, 1989, 1992; Nothdurft, 1993) and rejection of fewer groups of nontargets (Schubö et al., 2004). An ISI of 90 ms should be sufficient for targets also in random contexts to summon attention, and therefore a general advantage for probes at previous target locations should be observed in this condition as well.

Method

Participants

Fifteen paid volunteers (5 male) aged 21–28 years ($M = 25$, $SD = 3$) participated in the experiment. All were right-handed and had normal or corrected-to-normal vision. The experiment was conducted with the understanding and consent of each participant.

Stimuli and Apparatus

Participants were seated in a comfortable chair in a dimly lit, electrically shielded, and sound-attenuated chamber, with response buttons under their right index and middle finger (for probe responses) and their left thumb and ring finger (for search responses). All stimuli were presented on a 19-inch computer screen with a 100 Hz refresh rate, placed at a distance of 100 cm from the observers. A light gray hue (65.6 cd/m^2) served as the background color for all displays. Search displays contained a matrix of 10 × 10 stimuli, 50 horizontal, and 50 vertical black lines. Single lines had a length of 1.1° of visual angle, the matrix had a diameter of 14.8°. In the grouped condition, horizontal and vertical lines were arranged separately into two visual hemifields (cf. the examples in Figure 1). In the random condition, horizontal and vertical lines were randomly arranged across the entire visual field. The target (when present) was a single oblique line element tilted 45° with the vertical axis. The target appeared with equal probability at one of four locations replacing a horizontal or vertical line, at the central location of the four imaginary quadrants at an eccentricity of 3.4° from screen centre. Target-present and target-absent trials were equiprobable. The mask, a 10 × 10 array of asterisk-like elements presented immediately after the search array, was con-

Table 1. *Summary of Conditions*

		Probe-present				
		ISI 30 ms		ISI 90 ms		
		ON	OFF	ON	OFF	Probe- absent
Grouped context	Target-present	$n = 96$	$n = 96$	$n = 96$	$n = 96$	$n = 96$
	Target-absent	$n = 192$		$n = 192$		$n = 96$
Random context	Target-present	$n = 96$	$n = 96$	$n = 96$	$n = 96$	$n = 96$
	Target-absent	$n = 192$		$n = 192$		$n = 96$

Note. Columns describe variations in the probe task and rows describe variations in the search task. Probe displays contained a probe in 80% of the trials (left and middle columns) and no probe in 20% of the trials (right column). When a trial comprised both a target and a probe, the probe was presented at the same location as the previous target in half of the trials (dark gray cells) or at a different location in the other half of the trials (light gray cells). The cells depict the number of trials for each combination of conditions.

structed by superimposing horizontal, vertical, left- and rightward-tilted black line elements in each matrix cell. Probe displays were identical to the mask but contained a single asterisk colored either green or blue (each 50%).[1] In trials where a target was present in the search display, probes appeared equiprobably at the target location (ON condition) as at one of the three other locations (OFF condition). If no target was present, probes appeared equally often at one of the four possible target locations.

Procedure

A trial started with the presentation of a central fixation point (2 × 2 pixels) that remained on the screen throughout the entire trial (see Figure 1). After 500 ms, the search display was presented for 100 ms and subsequently masked. After 30 ms (short ISI) or 90 ms (long ISI), the probe replaced one of the asterisks of the mask for 50 ms, whereupon the original asterisk reappeared and the mask stayed on the screen until a response for the probe was given. ISIs longer than 90 ms were not used since the probability of saccades increases especially after 200 ms (search display duration of 100 ms + ISI of 90 ms = 190 ms) (Findlay, 1997). Participants were asked to respond to the probe's color with two horizontally oriented buttons of the keyboard located under the right hand. After probe response, the question "Was there a target?" appeared on the screen, prompting a response to the search display that was presented before the probe. The question remained on the screen until participants responded with the pair of vertically oriented buttons of the keyboard located under the left hand. Subsequently, a blank screen was presented for 300 ms until the next fixation point indicated the beginning of the next trial. If no probe was presented ("catch trials"—20% of all trials), the search display was masked for 500 ms and directly followed by the question display, no probe-related response was required. The catch trials were needed to decontaminate the probe-locked ERP from overlapping ERPs elicited by the preceding targets and to calculate the search-locked ERPs (see below for EEG analysis).

Participants were instructed to respond to the probe as fast as possible while trying to avoid false responses and only then to respond as correctly as possible to the search display. The response assignment for the probe task (index vs. middle finger of the right hand) and for the search task (thumb vs. ring finger) was balanced across participants. All conditions were randomly mixed across 48 blocks (of 40 trials each) except for the context type (i.e., grouped vs. random) that alternated between blocks. The order of contexts was balanced across participants. Every two blocks (i.e., after a grouped and a random block), performance feedback was given to participants. Feedback comprised RT and accuracy for the probe task and accuracy for the search task.

The experiment consisted of 1,920 experimental trials divided into 48 blocks, which were preceded by 6 blocks of practice trials (see Table 1). There were 960 trials for each context type, out of which 192 were probe-absent trials. For ERP analyses, probe-absent trials were split into target-present and target-absent trials. Probe-present trials were further split into ISI conditions (30 ms vs. 90 ms) and target conditions (target-present vs. absent). Target-present trials were further analyzed with respect to the probe location conditions (ON vs. OFF previous target location).

EEG Recording

EEG was recorded with 64 Ag-AgCl electrodes (according to the extended International 10-10 system). Horizontal and vertical electrooculograms (hEOGs, vEOGs) were recorded bipolarly from the outer canthi of the eyes and from above and below the observer's left eye. All electrodes were referenced to Cz and rereferenced offline to the average of all electrodes. Electrode impedances were kept below 5 kΩ. Sampling rate was 500 Hz with a high cutoff filter of 125 Hz.

Data Analysis

Behavioral data. For the search task, mean accuracy was calculated for each participant separately for each context type (grouped vs. random) and each trial type (target-present vs. target-absent) and submitted to a 2 × 2 analysis of variance (ANOVA). For the probe task, mean RTs and accuracy rates were computed for each

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[1] To test whether green and blue probes were of equal salience, a preliminary experiment was conducted with 48 paid volunteers (17 male) aged 20–35 ($M = 25.0$, $SD = 3.4$) years, all normal or corrected-to-normal vision. In each trial, a single display was presented for 50 ms; half of the displays were identical to the probe displays in the present experiment, the other half contained no probe but only black asterisks. Participants were instructed to detect probe presence as fast and accurately as possible while keeping central fixation on a small dot. The preliminary experiment consisted of 384 trials divided in 12 blocks of 32 trials; probe color alternated between blocks. Paired *t* tests for blocks with blue versus blocks with green probes revealed no RT difference for probe color, either in probe-present ($M_{green} = 398.3$ ms vs. $M_{blue} = 397.5$ ms), $t(47) = -0.149$, $p = .882$, $\varepsilon = 0.03$, or in probe-absent trials ($M_{green} = 435.9$ ms vs. $M_{blue} = 436.1$ ms), $t(47) = 0.05$, $p = .961$, $\varepsilon = 0.01$. Paired *t* tests also revealed that accuracy did not depend on the probe color, either in probe-present ($M_{green} = 90.9\%$ vs. $M_{blue} = 90.8\%$), $t(47) = -0.28$, $p = .978$, $\varepsilon = 0.01$, or in probe-absent trials ($M_{green} = 36.7$ % vs. $M_{blue} = 40.3\%$), $t(47) = 0.89$, $p = .559$, $\varepsilon = 0.19$.

participant separately for each context type (grouped vs. random), each probe location condition (ON previous target location vs. OFF), and each ISI (30 ms vs. 90 ms), excluding trials without targets and trials with false responses in the search task. For RT analysis, trials with false responses in the probe task were also removed. Outliers in the probe task (±1 *SD* from mean RT calculated separately for each participant) were excluded from further analysis. ANOVAs were calculated with the factors CONTEXT (grouped vs. random), PROBE LOCATION (ON vs. OFF), and ISI (30 ms vs. 90 ms). As we were particularly interested in transient effects that are expected to be revealed by the two ISIs, separate ANOVAs (Context × Probe Location) were calculated for ISIs of 30 ms and 90 ms.

EEG data. EEG was averaged offline over a 700-ms epoch including a 200-ms prestimulus baseline with epochs time-locked to the search display onset. Only trials with correct search and correct probe responses were analyzed. Furthermore, trials in which EOG electrodes indicated eye movements or blinks (indicated by any absolute voltage difference in a segment exceeding 80 µV or voltage steps between two sampling points exceeding 50 µV) were excluded from analysis. This was the case for 6.7% of the correct trials across all participants. Additionally, channels with other artifacts were excluded if the amplitude exceeded ±80 µV or any activity was lower than 0.10 µV for a 100-ms interval. In order to assess residual gaze-related artifacts after data exclusion, the hEOG (contralateral–ipsilateral channels) locked to probe onset was calculated and averaged for each participant for an interval of 0 ms to 220 ms. The average hEOG activity was −1.2 µV (*SD* = 1.7 µV), which can be considered equivalent to a horizontal eye movements of about 0.075° (Luck, 2005).

ERPs locked to search display onset. For these analyses, ERPs were locked to search display onset and only probe-absent trials were used. For N2 analyses, the EEG was averaged separately for grouped and random contexts and for target-absent and target-present trials, resulting in four waveforms for each participant (cf. Table 1), electrodes PO3, PO7, PO4, and PO8 were pooled, mean amplitudes were calculated for a time window of 200–300 ms. A repeated measures ANOVA was calculated with the factors context and trial type (target-present vs. target-absent). For N2pc analyses, the EEG was averaged separately for grouped and random contexts and for right and left target presentation, only target-present trials were used (cf. Table 1). A left (PO3, PO7) and a right electrode pool (PO4, PO8) were determined, and mean amplitudes were calculated for a time window from 170–220 ms. An ANOVA was calculated with the factors context (grouped vs. random), hemisphere (left vs. right electrode pool), and target location (left vs. right visual hemifield).

A jacknife-based procedure (Miller, Patterson, & Ulrich, 1998) was applied in order to assess onset latency differences elicited by targets embedded in grouped and random contexts observed for the N2pc. The points in time were determined at which the ERP components of 15 grand averages, each excluding one of the 15 participants, reached 50% of the peak amplitude. Subsequently, the jackknife estimate of the standard error of the differences S_D and *t* values were calculated. The difference in onset latencies between waveforms of different experimental conditions was tested by dividing the latency difference with the estimated S_D. The resulting statistics follow the sampling distribution of Student's *t* statistic (for a detailed description of the entire method, see Miller et al., 1998).

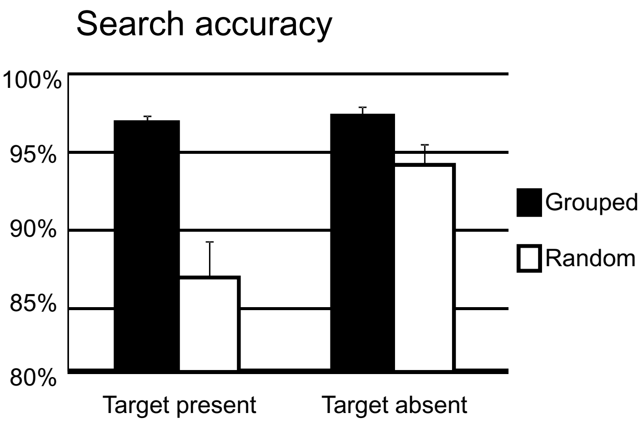

Figure 2. Mean accuracy rates for the search task. Error bars represent standard errors of the mean.

ERPs locked to probe onset. For these analyses, ERPs were locked to probe onset, and only probe-present trials were regarded. In order to extract probe-related activity and to reduce the amount of overlapping ERP activity resulting from the preceding search display presentation, the following subtraction procedure was performed: Average waveforms were calculated time-locked to probe onset, separately for probe-present and probe-absent trials. For probe-present trials, ERPs were averaged separately for each context type (grouped vs. random), each probe location relative to the previous target location (ON vs. OFF), and each ISI (30 ms vs. 90 ms). In this way, eight waveforms were obtained for each participant (cf. Table 1). In addition, the ERP in probe-absent trials was averaged separately for grouped and random contexts and time-locked to the latency of short (30 ms) and long (90 ms) ISIs (cf. Table 1). These four probe-absent waveforms were subtracted from the corresponding probe-present waveforms, which allowed for elimination of overlapping potentials related to search display presentation and for the extraction of potentials purely related to the probes. For example, the probe-absent waveform "grouped, ISI 30 ms" was subtracted from the probe-present waveform "grouped, ISI 30 ms, ON" and from "grouped, ISI 30 ms, OFF." Subsequently, electrodes PO7, PO8, O1, and O2 were pooled, and mean amplitudes were calculated for a time window from 160–220 ms. An ANOVA was calculated with the factors context (grouped vs. random), probe location (ON vs. OFF previous target location), and ISI (30 ms vs. 90 ms).

For all statistical analyses, partial η^2 (ANOVAs) and ε (*t* tests) are reported as a measure of effect size. Greenhouse-Geisser correction was used when appropriate in all statistical tests.

Results

Behavioral Data

Search performance. For search accuracy (see Figure 2), a two-way ANOVA including the within-subject factors context (grouped vs. random) and trial type (target present vs. target absent) revealed generally more correct responses for grouped than for random contexts ($M_{grouped} = 97.0\%$ vs. $M_{random} = 90.1\%$), $F(1,14) = 33.91$, $p < .001$, $\eta^2 = .708$, and more correct responses for target-absent than for target-present trials ($M_{tAbsent} = 95.6\%$ vs. $M_{tPresent} = 91.5\%$),

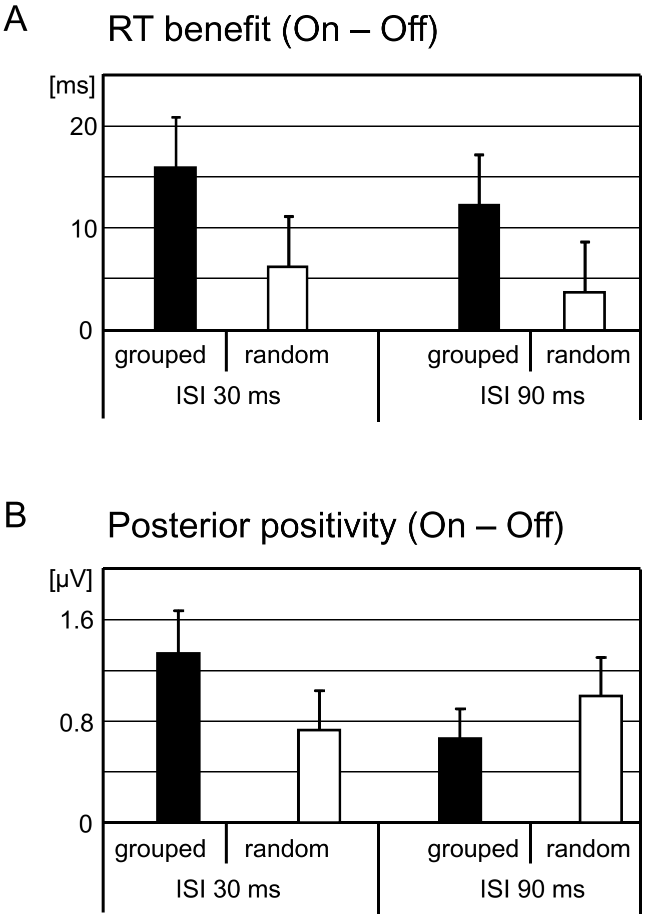

Figure 3. A: Mean RT benefit in the probe detection task for probes appearing ON the previous target location compared to probes OFF target location, calculated through subtraction of mean RT in the ON condition from mean RT in the OFF condition. Error bars represent standard errors of the mean. B: Mean differential amplitude of the posterior positivity (subtraction of ERPs elicited by probes appearing OFF the previous target location from ERPs elicited by probes ON the previous target location) for a time window of 160–220 ms at posterior-occipital sites (pool of O1, O2, PO7, PO8). Error bars represent standard errors of the mean.

$F(1,14) = 6.61$, $p = .022$, $\eta^2 = .321$. In target-present trials, search performance benefited more from a grouped context than in target-absent trials ($\Delta M_{tPresent} = 10.4\%$ vs. $\Delta M_{tAbsent} = 3.3\%$), as revealed by a two-way interaction of context and trial type, $F(1,14) = 8.26$, $p = .012$, $\eta^2 = .371$.

Probe performance. For RT data (see Figure 3 and Table 2), a three-way ANOVA including the within-subject factors ISI (30 ms vs. 90 ms), context (grouped vs. random), and probe location (ON vs. OFF target location) revealed generally faster responses for long ISIs ($M_{30} = 531.2$ ms vs. $M_{90} = 522.6$ ms), $F(1,14) = 5.60$, $p = .033$, $\eta^2 = .286$, and faster responses for probes presented on target locations when compared to probes presented on other locations ($M_{ON} = 522.2$ ms vs. $M_{OFF} = 531.6$ ms), $F(1,14) = 8.07$, $p = .013$, $\eta^2 = .366$. An interaction of the factors probe location and context revealed that the RT benefit for ON vs. OFF was larger in grouped contexts as compared to random contexts ($\Delta M_{grouped} = 14.0$ ms vs. $\Delta M_{random} = 4.8$ ms), $F(1,14) = 6.96$, $p = .019$, $\eta^2 = .332$, see Figure 3. No other effects were significant (all $ps > .279$). Although the interaction was not significant, we analyzed each ISI separately due to our a priori hypothesis (see the Rationale section above). To investigate the benefit for ON target locations separately for short and long ISIs, additional two-way ANOVAs were conducted that included the factors probe location and context. For short ISIs, RT benefit for ON versus OFF was significantly larger in grouped context as compared to random contexts ($\Delta M_{grouped} = 15.8$ ms vs. $\Delta M_{random} = 6.1$ ms), $F(1,14) = 4.75$, $p = .047$, $\eta^2 = .253$, but this difference failed to reach significance for long ISIs ($p = .119$). For accuracy data, analyses revealed no significant effects (all $ps > .159$).

ERP Data

ERPs locked to search display onset

N2 (see Figure 4)**.** Target-absent trials elicited a generally larger N2 than target-present trials ($M_{tAbsent} = 3.12\ \mu V$ vs. $M_{tPresent} = 4.18\ \mu V$), $F(1,14) = 14.41$, $p = .002$, $\eta^2 = .507$. This N2 enhancement was stronger in grouped contexts as compared to random contexts, ($\Delta M_{random} = -0.29\ \mu V$ vs. $\Delta M_{grouped} = -1.83\ \mu V$), as indicated by a significant interaction of trial type and context, $F(1,14) = 20.12$, $p < .001$, $\eta^2 = .590$. To investigate N2 differences between target-present and target-absent trials separately for random and grouped contexts, two-tailed t tests for dependent measures were calculated as follow-up analyses. Target-absent trials did not elicit a larger N2 than target-present trials in random contexts ($M_{tAbsent} = 3.52\ \mu V$ vs. $M_{tPresent} = 3.81\ \mu V$), $t(14) = 1.01$, $p = .332$, $\varepsilon = 0.37$, but did so in grouped contexts ($M_{tAbsent} = 2.72\ \mu V$ vs. $M_{tPresent} = 4.55\ \mu V$), $t(14) = 5.04$, $p < .001$, $\varepsilon = 1.84$.

N2pc. A three-way ANOVA with the factors context (random vs. grouped), hemisphere (left vs. right electrodes) and target location (left vs. right hemifield) revealed that the N2pc was larger for targets in grouped than for targets in random contexts, which was reflected by a significant three-way interaction, $F(1,14) = 5.10$,

Table 2. *Performance in the Probe Discrimination Task*

		Accuracy (%)		Reaction times (ms)	
Condition		OFF	ON	OFF	ON
ISI 30 ms	Grouped context	97.5 *(0.7)*	96.9 *(0.9)*	538.8 *(28.8)*	523.0 *(26.7)*
	Random context	96.1 *(1.1)*	97.0 *(0.9)*	534.5 *(26.9)*	528.4 *(26.2)*
ISI 90 ms	Grouped context	97.3 *(0.6)*	96.5 *(1.3)*	526.4 *(28.9)*	514.3 *(25.2)*
	Random context	96.5 *(1.0)*	96.7 *(0.8)*	526.7 *(26.8)*	523.1 *(26.1)*

Note. ON depicts trials in which target and probe were presented at the same location, and OFF depicts trials in which target and probe were presented at different locations. Standard errors of the mean are expressed in italics.

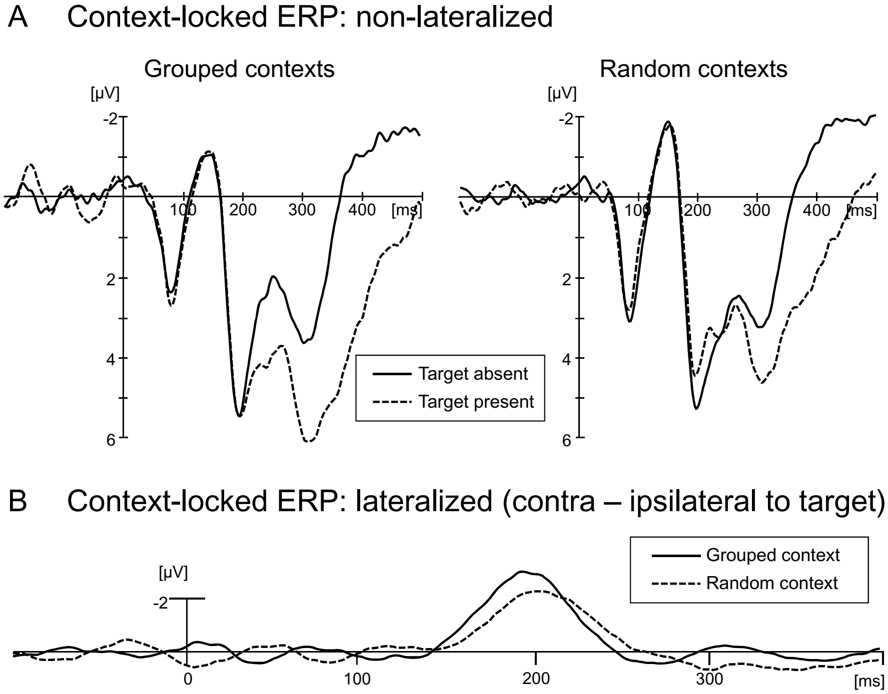

Figure 4. A: Grand average ERPs at posterior-occipital electrode sites (locked to the onset of contexts; pool of PO3, PO7, PO4, PO8). B: Difference waves (contra-ipsilateral electrode sites relative to the target, representing the N2pc) of the grand average ERPs recorded at posterior-occipital electrode sites (pool of PO3, PO7, PO4, PO8). For illustration purposes, EEG waveforms were low-pass filtered at 35 Hz using digital filtering.

$p = .040$, $\eta^2 = .267$. A planned comparison of N2pc mean amplitudes in both context conditions confirmed a more pronounced N2pc for grouped ($M_{grouped} = -2.55$ µV) than for random contexts ($M_{random} = -1.98$ µV), $t(14) = 2.26$, $p = .020$, $\varepsilon = 0.83$. The jackknife-based procedure for latency measurement of N2pc onset (Miller et al., 1998) showed that the target-elicited N2pc revealed an earlier onset in grouped compared to random contexts ($\Delta = 8.2$ ms, $t(14) = 2.78$, $p = .007$).

ERPs locked to probe display onset. The ERP observed 160–220 ms after probe onset was generally more positive for probes presented at target locations than for probes presented at other locations ($M_{ON} = 2.24$ µV vs. $M_{OFF} = 1.30$ µV), $F(1,14) = 40.16$, $p < .001$, $\eta^2 = .742$ (cf. Figure 5). Whether this posterior positivity for ON versus OFF was enhanced in grouped contexts as compared to random contexts depended on the ISI, as indicated by a significant three-way interaction of ISI, context, and probe location, $F(1,14) = 5.39$, $p = .036$, $\eta^2 = .278$. To further investigate this differential effect, two-way ANOVAs including the factors probe location and context were conducted separately for short (30 ms) and long (90 ms) ISIs. For the short ISI, the posterior positivity for ON versus OFF was larger in grouped contexts as compared to random contexts ($\Delta M_{grouped} = 1.35$ µV vs. $\Delta M_{random} = 0.73$ µV), interaction of probe location and context, $F(1,14) = 7.51$, $p = .016$, $\eta^2 = .349$. There was no difference for the long ISI ($p = .198$, $\eta^2 = .116$).[2]

Discussion

The present study examined sustained effects of attention deployment after contexts of varying heterogeneity. The key finding of the present experiment was that the heterogeneity of contexts has an impact on both efficiency of attentional deployment to the target within that context and on the efficiency of attentional deployment toward subsequently presented stimuli. Our paradigm combined a visual search task and a subsequent probe discrimination task and showed that the degree of context heterogeneity in the search task influenced both search task and probe task performance. Results in the search task showed that participants were more often correctly indicating target absence and presence in grouped than in random contexts. This effect was accompanied by a decrease in N2pc amplitude and an increase in N2pc latency for random contexts relative to grouped contexts. In addition, in grouped contexts search displays elicited a larger posterior N2 in target-absent trials as compared to target-present trials. This was not observed for random contexts.

Most interestingly, however, context heterogeneity had also an impact on performance in subsequent probe discrimination—after context information was not available anymore. In general, participants were faster in discriminating probe colors when probes were

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[2] From Figure 5, it is evident that the positivity for on- versus off-target trials is not restricted to the typical P1 interval but extents to the N1 interval. In order to investigate this effect further, we conducted an analysis analogous to the earlier time window (160–220 ms) for a later time window of equal length (220–280 ms). Similar to the earlier time window, the ERP observed 220–280 ms after probe onset was generally more positive for on versus off ($p = .016$, $\eta^2 = .347$), and there was a significant three-way interaction of probe location, context, and ISI ($p = .016$, $\eta^2 = .348$). While for the ISI of 30 ms the posterior positivity was more pronounced for grouped than for random contexts ($p = .004$, $\eta^2 = .458$), this was not the case for the ISI of 90 ms ($p = .133$, $\eta^2 = .153$). Thus, the effects are very similar to the ones observed in the earlier time interval from 160–220 ms. Such parallel results for P1 and N1 time windows have been found before, see Heinze et al. (1990).

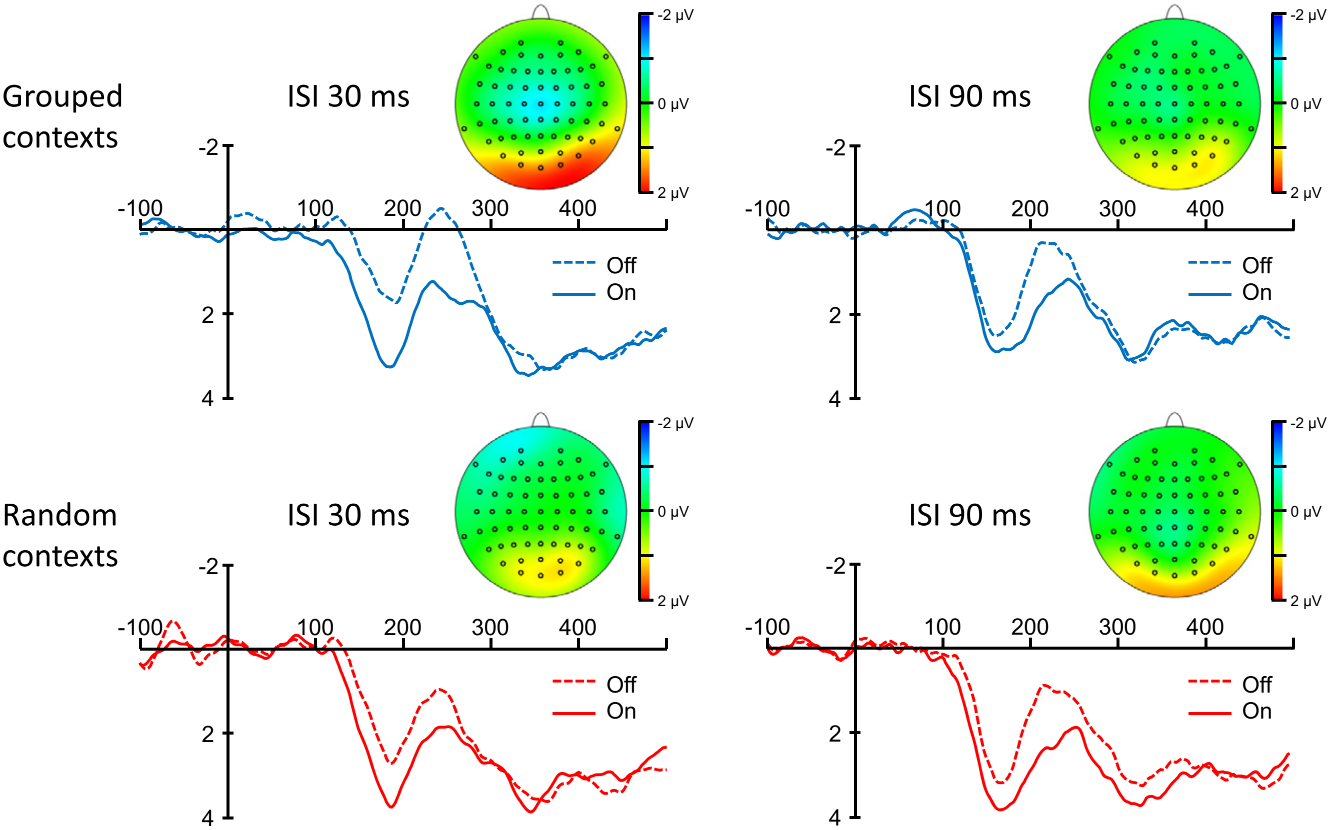

Figure 5. Grand average ERPs at posterior-occipital electrode sites (locked to probe display; pool of O1, PO7, O2, PO8). The difference between on-target and off-target trials reflect the posterior positivity. For illustration purposes, averages were low-pass filtered at 35 Hz using digital filtering. Topographical map insets were constructed using spherical spline interpolation and represent the mean posterior positivity for an interval around the average maximum of the P1 component (180 ms–200 ms).

presented at the same location as the previously presented target, relative to when probes were presented at other locations. This on-target advantage was also mirrored in the probe-locked ERP: probes appearing at locations previously occupied by targets yielded an enhanced positive deflection at posterior sites compared to probes appearing at different locations. The crucial finding of the present experiment was that for the shorter ISI of 30 ms, this modulation of the ERP was larger for grouped contexts than for random contexts. For an ISI of 90 ms, no reliable difference for the posterior positivity was found. These results were paralleled by a similar pattern in the behavioral data (RT benefit).

Sustained Efficiency in Attentional Deployment to Relevant Locations after Grouped and Random Contexts

Better performance together with shorter and more pronounced N2pc for grouped contexts (relative to random contexts) replicate earlier findings showing more efficient attention deployment in less heterogeneous stimulus arrangements. Most interestingly, RT and ERP results indicate that differential attention deployment induced by context heterogeneity was not limited to processing of the context itself but sustained until subsequent probes were presented. We found an on-target advantage, that is, shorter RTs for probes presented at the same location as the previously presented target (ON), relative to probes presented at other locations (OFF). This is well in line with previous results from a large variety of studies showing facilitated processing of stimuli due to previously attended stimuli at the same location (Eimer & Kiss, 2008; Kim & Cave, 1999; Müller & Rabbitt, 1989; Posner et al., 1980; Wykowska & Schubö, 2010, 2011). In the present study, the on-target advantage was also reflected in an enhanced positive deflection of the probe-locked ERP for ON compared to OFF trials. The on-target positivity exceeded the typical P1 interval and continued until later components such as the N1 (Heinze et al., 1990). Former studies have suggested that once attention has been deployed to a specific location in the visual field, a preset facilitation of information processing for these locations yields prioritized processing of subsequent stimuli (LaBerge, 1983; Posner et al., 1980). Stimuli presented at already attended locations benefit from sensory gain, which is reflected in both a posterior positivity and in enhanced behavioral performance (Doallo et al., 2004; Luck, Woodman, & Vogel, 2000; Mangun & Hillyard, 1991). Accordingly, the on-target advantage in the present experiment speaks in favor of enhanced processing at previous target locations.

The novel finding of the present study is that sensory gain depended on the context in which targets were shown: The on-target advantage reflected in the RT benefit and the posterior positivity was enhanced when preceding targets were embedded in grouped compared to random contexts. This sustained context-related enhancement shows that the impact of context heterogeneity was not restricted to attention deployment within a particular context but extended to subsequently presented probes. The present results thus suggest that deployment of attention towards salient stimuli (Eimer, & Kiss, 2008; Müller & Rabbitt, 1989; Theeuwes, 1994) can be strongly influenced by a previously presented context, presumably due to more efficient grouping of less heterogeneous contexts (e.g., Schubö et al., 2007) or an enhanced local feature contrast at target locations in grouped contexts (Fecteau & Munoz, 2006; Schubö et al., 2011). Importantly, the probe stimuli themselves were unrelated to the previous context: the probes were not presented in grouped or random contexts, but in a stimulus array that consisted of homogeneous asterisks and was thus the same in all conditions and could not be predicted from the preceding context structure. Furthermore, the target embedded in the contexts was identical in all conditions. Thus, the differential efficiency in attention allocation toward probes can be most likely attributed to sustained aftereffects of the arrangement of the previously presented nontargets.

The higher accuracy for targets in grouped contexts and the coinciding earlier and stronger N2pc suggest that the differential sensory gain resulted from attention being allocated faster and more efficiently towards targets in grouped compared to random contexts. The differential N2pc and behavioral effects are in line with previous studies showing that the efficiency of attention deployment depends on background heterogeneity and that targets are processed with priority in less heterogeneous contexts (Julesz, 1981; Mazza et al., 2007; Nothdurft, 1992, 1993; Schubö et al., 2004, 2007) while salient but task-irrelevant distractors are more efficiently suppressed in less heterogeneous contexts (Feldmann-Wüstefeld & Schubö, 2013). While it is still under discussion whether the N2pc reflects target enhancement or nontarget suppression (Hickey, Di Lollo, & McDonald, 2009), the present experiment provides further evidence that the N2pc can vary dependent on nontarget properties. Previous studies have shown that homogeneously arranged vertical and horizontal line elements allow for efficient grouping while the same elements do not when randomly distributed (Schubö et al., 2007), and that grouping leads to more efficient target detection as well as fast rejection in the case of target-absent trials (Meinecke & Donk, 2002; Schubö et al., 2004, 2007). According to the attentional engagement theory (Duncan & Humphreys, 1989, 1992), the more homogeneous the nontargets, the easier or more “efficient” is search performance (see also Theeuwes, 2010; Wolfe, 1994). Duncan and Humphreys (1989) argue that already in an early “parallel” stage of visual coding nontargets can be grouped to structural units based on texture segmentation and Gestalt principles (see also Bacon & Egeth, 1991). The authors assume that the more features are shared by stimuli, the stronger they are linked and the easier they are rejected as a single unit by means of “spreading suppression” (for neural evidence, see Chelazzi, 1999; Desimone & Duncan, 1995).

In the present experiment, behavioral and ERP results provided converging evidence of more efficient processing of grouped relative to random contexts that outlasts the context and is transferred to subsequently presented stimuli. Faster rejection of nontarget elements being possible in grouped contexts (as reflected in the differential posterior N2) resulted in prioritized processing of targets (as shown by higher accuracy, larger N2pc amplitudes, and earlier N2pc onsets) and in prioritized processing of probes at locations previously occupied by targets in grouped contexts (as indicated by the more pronounced posterior positivity and RT benefit).[3]

The improved probe performance and associated posterior positivity enhancement may also reflect temporal integration of the probe and target presented at the same location. Time intervals between onset of the search array and the offset of the probe array were 180 ms (ISI 30) or 240 ms (ISI 90) and thus fell within the range that is commonly associated with temporal integration (Akyürek & Hommel, 2005; Akyürek, Toffanin, & Hommel, 2008). This may have resulted in processing of target and probe as a singular event and thus improved performance for the latter in case both are presented at the same location (Akyürek, Schubö, & Hommel, 2010). The presently observed context-related enhancement in turn may indicate that temporal integration of successive events is impaired if the local feature contrast at the to-be-integrated location is relatively low (random contexts) compared to high local contrast (grouped contexts). However, since there was a task switch and a backward pattern mask between search and probe display, temporal integration might be a less likely explanation. Further research may experimentally test this with a design that would contrast target-probe stimuli that could integrate easily with pairs that would not.

Salience Computations of Stimuli Within and Following Contexts of Different Heterogeneity

A differential sensory gain for targets in grouped and random contexts is in line with the idea that heterogeneity is an important determinant in salience computation (Duncan & Humphreys, 1989; Li, 2002). But how could salience computation of targets and probes have resulted in a sustained context-related enhancement? In general, stimuli presented at locations previously occupied by salient stimuli receive prioritized processing when the salience value of the former stimulus persists for some time and may therefore be added to the salience value of the later stimulus (Itti & Koch, 2001). It was also argued that the same orientation singleton can have different salience values depending on the arrangement of context elements (Li, 2002; Nothdurft, 1990). In the present experiment, targets were physically identical and equally relevant in both context conditions. This should have balanced top-down influences and should have resulted in guidance of attention on the basis of salience map activation (Fecteau & Munoz, 2006; Itti & Koch, 2001). For grouped contexts with less heterogeneous context elements, one would expect that a clear peak of activation indicated the target location at the salience map because the reciprocal neural inhibition of context elements was rather strong (Li, 2002) and nontargets added only little “noise” to stimulus representations (Duncan & Humphreys, 1992; Fecteau & Munoz, 2006). As a result, the probability of initial attention allocation toward the target location was rather high (Itti & Koch, 2001; Wolfe, 1994). In on-target trials, subsequently presented probes added some additional activation to the persistent activation of the previous targets, thus facilitating probe perception. In off-target trials, the activation of the novel probe location had to compete with the activation of the target location; hence, probe detection was less efficient. As targets in grouped contexts had a higher activation on the salience map than targets in random contexts, probes benefited more from grouped contexts in the

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[3] It should be noted, however, that context effects always implicate properties of the target as well, as targets can only be defined in relation to the context. In target-present trials, this becomes evident at the direct target location surround, as local feature contrast of the oblique target and horizontal and vertical context lines. Hence, context and target should not be considered entirely independent factors, and the differential sustained effects on probes may partially be described as a function of the context-target relation.

on-target condition. As more target-related activation was persistent at the former target location, probe perception was facilitated in ON trials. In random (heterogeneous) contexts, however, the peak of activation indicating target location at the salience map was far less pronounced, because nontarget elements produced less reciprocal neural inhibition. Hence, there was also less persistent activation on former target locations. As a result, probe processing benefited to a lesser extent in the on-target condition.

The Time Course of Context-Induced Salience

In the present experiment, the sustained context-related enhancement for grouped versus random contexts was examined at two different points in time. RT results seemed to reflect sustained context-related enhancement for the shorter ISI (30 ms) while no reliable context-related enhancement was found for 90 ms, revealing that this differential effect tended to disappear over time. Furthermore, also the size of the differential probe-locked ERP effect (difference between ON and OFF) was modulated by context only at the shorter ISI of 30 ms. With an ISI of 90 ms, neither RT results nor posterior positivity showed differences between grouped and random contexts. These results elucidate the time course of context-induced salience: context-related enhancement (reflecting the differential efficiency in attentional deployment in grouped vs. random contexts) seemed to be attenuated some time between 30 and 90 ms after context offset. Even though the context-dependent modulation of the on-target advantage was observed mainly for the short ISI, this advantage effect was in general observable for both ISIs. This suggests that the differential efficiency in attentional deployment at locations previously occupied by targets versus nontargets seemed to persist over time. However, as RT and posterior positivity results for the longer ISI of 90 ms are not entirely consistent, further research employing longer ISIs is needed.

The time course of sustained context-related enhancement in the present experiment is in line with previous studies by Donk and colleagues (Dombrowe et al., 2010; Donk & Soesman, 2010). These studies varied target salience by changing the tilt of a diagonal target line that was presented within an unaltered homogeneous context (Donk & Soesman, 2010). The orientation singleton's salience was varied by high (70°) or low (20°) deviation from context elements. Results showed that probes presented 42 ms after singleton onset were only benefiting from being at a previous singleton location when that singleton was highly salient. Probes presented 158 ms or 483 ms after singleton onset were benefiting to an equal amount from being at a previous singleton location, regardless of its salience. Thus, both salience signals showed persistence but had differential effects in time: benefits resulting from relative target salience were short lived, while the general on-target benefit that resulted from target-context contrast sustained. In the present experiment, the local contrast target-context (and hence the salience of the target; see Li, 2002) was varied by using contexts of different heterogeneity instead of manipulating properties of the target itself. ERP effects showed that probes presented 30 ms after the context offset were benefiting more from being at a previous orientation singleton when that singleton was presented within a grouped context due to a sensory gain at that location (indicated by the posterior positivity, see Figure 3 and 5). However, probes presented 90 ms after the context offset were equally benefiting from being at locations previously occupied by singletons in grouped or random contexts. Thus, the information *where* salient stimuli were presented persists in the visual system (the local feature contrast), but the information *how* salient these singletons were (the differential local feature contrast induced by tilted targets (Donk & Soesman, 2010) or varying heterogeneity (present study)) is transient. This suggests that once a critical amount of time has passed, the visual system only holds information concerning the location of salient objects, without information concerning the specific dimension at which salient signal occurs.

Conclusions

So far, studies varying the context heterogeneity in visual tasks have shown that less heterogeneous stimulus arrangements facilitate processing of embedded stimuli (Duncan & Humphreys, 1989, 1992; Mazza et al., 2007; Schubö et al., 2007). The novel finding of the present experiment is that the heterogeneity of contexts has a sustained impact on attention deployment. This shows that the effect of grouping on efficiency of attentional deployment is not constricted to the context itself but is persistent over time. This sustained impact of stimulus heterogeneity is an important factor that should be considered in cueing or visual search tasks that aim at modeling efficiency of attentional deployment depending on context heterogeneity.

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Context homogeneity facilitates both distractor inhibition and target enhancement

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Homogeneous contexts were shown to result in prioritized processing of embedded targets compared to heterogeneous contexts (Duncan & Humphreys, 1989). The present experiment used behavioral and ERP measures to examine whether context homogeneity affects both enhancing relevant information and inhibiting irrelevant in contexts of varying homogeneity. Targets and distractors were presented laterally or on the vertical midline which allowed disentangling target- and distractor-related activity in the lateralized ERP (Hickey, diLollo, & McDonald, 2009). In homogeneous contexts, targets elicited an N_T component from 150 ms on and a P_D component from 200 ms on, showing early attention deployment at target locations and active suppression of distractors. In heterogeneous contexts, an N_T component was also found from 150 ms on and P_D was found from 250 ms on, suggesting delayed suppression of the distractor. Before 250 ms, distractors in heterogeneous contexts elicited a contralateral negativity, indicating attentional capture of the distractor prior to active suppression. In sum the present results suggest that top-down control of attention is more pronounced in homogeneous than in heterogeneous contexts.

Introduction

One of the prime capabilities of the visual system is to filter relevant from irrelevant information in the visual environment within milliseconds. Theories which model *visual search*, i.e., the search for potentially interesting stimuli among other distracting stimuli, often conceptualize this selection to be based upon activation patterns on a "priority map." The priority map is assumed to code information about selection relevance of objects or items in the visual field in a topographical manner (Fecteau & Munoz, 2006; Itti & Koch, 2000; Li, 2002; Wolfe, 1994; Yantis & Jones, 1991). The activation pattern coded on the priority map is a combination of both an item's salience and its relevance in the current task: The priority map receives bottom-up input from a salience map that is activated by physical stimulus features such as contrast or similarity (Itti & Koch, 2000; Li, 2002). The bottom-up input is then weighted by top-down processes such as an observer's current goals (Fecteau & Munoz, 2006; Wolfe, Butcher, Lee, & Hyle, 2003; Wykowska & Schubö, 2011). The activation pattern on the priority map is used to select those objects in the visual field that will receive more elaborated, attentive processing: Based on the activity on the priority map, focal attention is deployed to various locations in the order of decreasing activation (e.g., Wolfe, 1994).

Bottom-up and top-down processes in visual search

There is an ongoing debate on the relative contribution of bottom-up salience and the observer's top-down goals or intentions (Awh, Belopolsky, & Theeuwes, 2012; Bacon & Egeth, 1991; Folk, Remington, & Johnston, 1992; Theeuwes, 1992, 2004, 2010; Wykowska & Schubö, 2011). Support for the view that physical salience can barely be overruled by volitional control comes from experiments in which a salient distractor is presented in addition to a less salient target ("additional singleton paradigm"; Theeuwes, 1992). For example, when observers search for a shape singleton target, a color singleton distractor can slow down response times whereas search for a color singleton is not slowed down by a shape singleton distractor (Theeuwes, 1992). Theeuwes concluded that focal attention is captured by the first feature encoded during the pre-attentive stage (color earlier than form)

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regardless of its importance for the current task. Accordingly, supporters of the attentional capture account demonstrate that intentional control may only take over after some time has passed and the initial phase of salience-based attentional processing is completed (Theeuwes, Atchley, & Kramer, 2000; see also Kim & Cave, 1999; Van Zoest & Donk, 2004).

However, there is also a large proportion of data supporting the view that top-down information is available at the very first sweep of visual processing, meaning that salient but irrelevant objects do only capture an observer's attention when they are contingent on the observer's current task set (Bacon & Egeth, 1991; Folk et al., 1992; Folk, Leber, & Egeth, 2002; Kim & Cave, 1999; Leblanc, Prime, & Jolicoeur, 2008; Wykowska & Schubö, 2010; 2011). Instead, it has been suggested that irrelevant singletons do not capture attention but produce nonspatial filtering costs (Folk, Leber, & Egeth, 2002; Folk & Remington, 2006). Additionally, the interplay of bottom-up and top-down processing seems to strongly depend on several factors such as the attentional demands (Kiss, Grubert, Petersen, & Eimer, 2012) or the value of a stimulus (Anderson, Laurent, & Yantis, 2011).

Context homogeneity determines visual search efficiency

Another factor that may determine how much top-down influence is involved in visual selection is context homogeneity (i.e., how physically distinct the non-singleton distractors are). In fact, the homogeneity of task-irrelevant stimuli can largely affect the efficiency of searching for an embedded task-relevant stimulus. The more similar distractors are, the faster will observers detect an embedded target (Akyürek, Vallines, Lin, & Schubö, 2010; Duncan & Humphreys, 1989; Meinecke & Donk, 2002; Schubö, Wykowska, & Müller, 2007). According to the *Attentional Engagement Theory* (Duncan & Humphreys, 1989) stimuli are grouped according to their shared physical features already in an early parallel stage of visual coding (see also Bacon & Egeth, 1991). The more similar distractors are, the stronger they are linked and grouped to a single structural unit, resulting in fast detection of the target. Perfectly identical distractors may even enhance target processing when they are numerous enough (Schubö et al., 2004; Wolfe, 1994). The present experiment investigated whether a salient distractor singleton that is potentially interfering with target processing (e.g., Theeuwes, 1992) may also benefit from distractor homogeneity; that is, whether a salient distractor singleton is processed preferentially in homogeneous contexts when compared to heterogeneous contexts. Alternatively, one may assume that a salient distractor is suppressed more easily in homogenous contexts than in heterogeneous contexts, because the target is more likely to "pop out" (Wolfe, 1994) and inhibition of the distractor is possible earlier in time.

Neural correlates of target enhancement and distractor inhibition

To examine neural processes associated with target processing and distractor inhibition, we used a technique grounded in work by Hickey and colleagues (Hickey, McDonald, & Theeuwes, 2006; see also Hickey, Di Lollo, & McDonald, 2009; Woodman & Luck, 2003) which investigated the sequence of attention deployment towards targets and towards more salient singleton distractors. The crucial manipulation of the stimuli was their relative position: Target and distractor were presented either both laterally, or one was presented laterally and the other one on the vertical midline (i.e., unlateralized). Since unlateralized stimuli can usually not elicit a lateralized ERP component, target- and distractor-evoked potentials could be analyzed independently. Both target and distractor elicited a contralateral negative deflection in the ERP (i.e., an N2pc) when presented laterally with the other one on the vertical midline. The authors concluded that attention can be deployed to the target but may also be captured by the distractor (Hickey et al., 2006). When target and singleton distractor were presented in opposite hemifields, a negative deflection in the ERP first appeared ipsilateral to the target (reflecting an N2pc elicited by the singleton distractor) and only then contralateral to the target (i.e., a target N2pc). This order of negative deflections argues in favor of attention being deployed first to the most salient item (the distractor), before it is then focused on the target (but see Eimer & Kiss, 2008; Wykowska & Schubö, 2010, 2011 for diverging results). In a more recent study, Hickey et al. (2009) tried to further disentangle target enhancement and distractor inhibition and refined the usage of the N2pc as an indicator of attention deployment. They used a distractor that was less salient than the target and found a positive deflection of the ERP contralateral to the distractor (distractor-positivity, P_D) when the target was presented on the vertical midline. Again, a negative deflection of the ERP contralateral to the target was found (target-negativity N_T), when only the target was presented laterally. Hickey et al. (2009) argued that these components may be considered subcomponents of the N2pc. The results suggest that distinct neural processes are involved in enhancing relevant (N_T) and inhibiting irrelevant information (P_D). A similar technique has been used to dissociate target- and distractor-related processes in fast versus slow attention shifts (Hickey, van Zoest, & Theeuwes, 2010) and in inter-trial priming (Hickey, Olivers, Meeter, & Theeuwes, 2011). As mentioned above, although context homogeneity is known to play a crucial role in how attention is deployed in the visual field, it is still unclear in how far context homogeneity mediates the interplay of these processes.

Rationale of the present experiment

The present experiment investigated whether and how context homogeneity affected enhancing relevant information as reflected in the N_T and inhibiting irrelevant information as reflected in the P_D. Similarly to Hickey et al. (2009), target and salient distractor singleton were either presented both laterally, or one was presented on the vertical midline and the other one laterally. Unlike in previous experiments, target and singleton were always embedded in a large context of 456 vertical and horizontal lines. These were either completely homogeneous (vertical or horizontal lines only) or heterogeneous (horizontal and vertical lines randomly arranged). We were particularly interested in how the varying degree of context homogeneity affected the attention-related N2pc subcomponents P_D and N_T and, more importantly, whether they would be affected in a similar manner. We intended to disentangle prioritized processing of the target (as reflected in the N_T component) and inhibition of a distractor (as reflected in the P_D component) which may be modulated differentially by context homogeneity.

Method

Participants

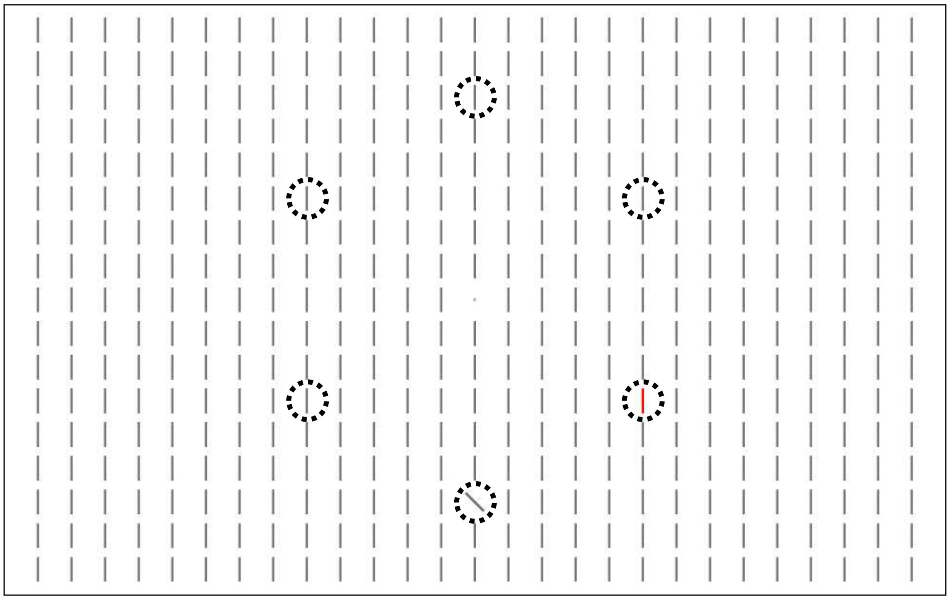
Twenty-one volunteers naive to paradigm and objective of the experiment participated for payment or course credit. One participant had to be excluded due to excessive eye movements (see below for criteria). The remaining 20 subjects (seven male) were aged 18–32 years ($M = 21.5$, $SD = 3.6$). All were right-handed and had normal or corrected-to-normal vision. The experiment was conducted with the understanding and consent of each participant.

Stimuli and apparatus

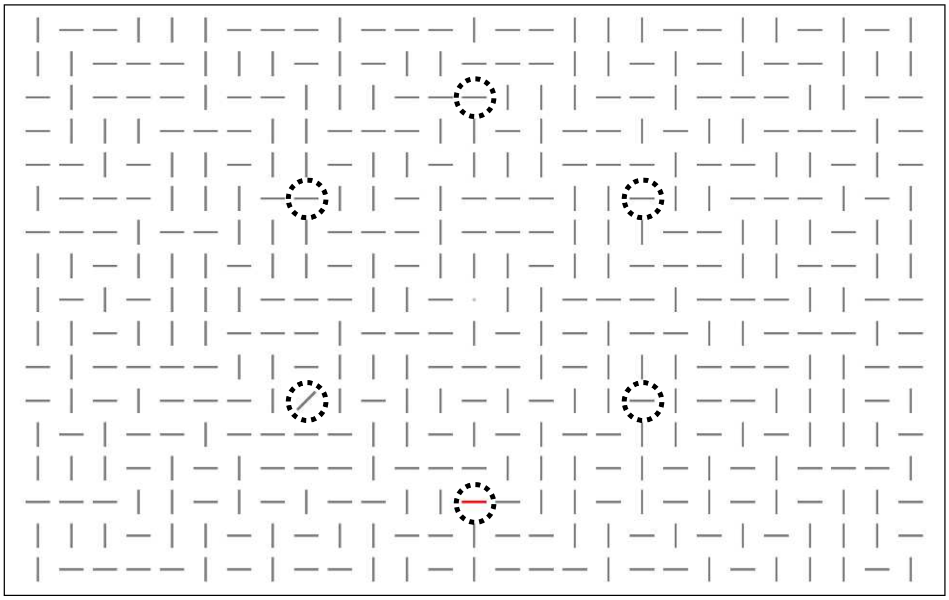
Participants were seated in a comfortable chair in a dimly lit, electrically shielded and sound attenuated chamber, with an ergonomic gamepad (Microsoft Sidewinder USB) in their hands. Participants had to use their left and right index finger to press two buttons on the back of the gamepad. Stimulus presentation and response collection were controlled by a *Windows* PC using *E-Prime* routines. All stimuli were presented on a LCD-TN screen (*Samsung Syncmaster 2233*) placed 100 cm away from participants. Search displays with 458 line elements arranged in a matrix of 27 × 17 stimuli were shown on a white background. In the central position, a fixation dot was shown instead of a line element. Single lines had a length of 0.7° of visual angle; the matrix's dimension was 24.2° × 16.2°. The target was a gray oblique line element tilted 45° either to the left or right (equiprobably). The color singleton distractor was a red horizontal or vertical line. The remaining 456 line elements were gray horizontal or vertical lines. In the *homogeneous condition*, all of the remaining 456 line elements (and the color singleton) were either horizontal or vertical (changing randomly from trial to trial, cf. Figure 1A). In the *heterogeneous condition*, 228 of the remaining lines were horizontal and 228 were vertical, randomly assigned to the matrix positions (cf. Figure 1B). In each trial, the target and the color singleton appeared at two out of six equiangular positions on an imaginary circle (cf. Figure 1). Two of the positions were 3.4° above or below fixation on the vertical midline. The other four positions were 2.9° left or right of the vertical midline and 1.7° above or below the horizontal midline. In one third of the trials, the target was presented in one of the vertical midline positions and the singleton was presented in a lateral position. In another third of the trials, location of target and singleton were reversed and in the remaining third of the trials, both were presented in a lateral position, namely in opposite hemifields.

Procedure

A trial started with the presentation of a gray central fixation dot that remained on the screen throughout the entire trial. After 500 ms, the search display was presented for 200 ms and then replaced with a blank display. Participants were asked to press one of the response buttons (labeled "/" or "\") in order to indicate the orientation of the target in the search display, i.e., whether the target was pointing right upwards or right downwards. Button assignment was balanced across participants. Response speed was emphasized, but there was no time limit for the response. After participants' response, the fixation dot disappeared for 1000 ms until a new fixation dot announced the start of a new trial. Participants were told that both the context (the 456 horizontal and vertical lines) and the color singleton were irrelevant to the task and could be ignored.



Homogeneous Contexts



Heterogeneous Contexts

Figure 1. Exemplary search displays. In the upper panel, target (gray oblique line) and singleton distractor (red vertical line) are embedded in a homogeneous context of gray vertical (or horizontal) lines. In the lower panel, target and singleton are embedded in a heterogeneous context of randomly arranged vertical and horizontal lines. Participants were to indicate the orientation of the target (leftward vs. rightward) while ignoring the distractor and the context. Black-dashed circles illustrate the possible target, and singleton locations and were not visible to participants. The target could be presented in a lateral position and the distractor on the vertical midline (lower panel), vice versa (upper panel), or both could be presented in a lateral position (not shown here).

All three position conditions (target lateral, distractor vertical vs. target lateral, distractor lateral vs. target vertical, distractor lateral) were combined with the two context conditions (homogeneous vs. heterogeneous), leading to six experimental conditions. There were 192 trials per condition (1152 in total), randomly mixed across 24 blocks of 48 trials each. Two additional blocks in the beginning of the experiment served as training. After each block, performance feedback (response times and accuracy) was given to participants.

EEG recording

EEG was recorded with Ag–AgCl electrodes from 64 electrodes (according to the International 10–10 System). Horizontal and vertical EOGs were recorded bipolarly 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 off-line to the average of all electrodes. Electrode impedances were kept below 5 kΩ. Sampling rate was 1000 Hz with a high cutoff filter of 250 Hz and a low cutoff filter of 0.1 Hz.

Data analysis

Behavioral data

Mean response times (RT) and accuracy were calculated for each participant, separately for each context type (homogeneous vs. heterogeneous) and each position condition (target lateral, distractor vertical vs. target lateral, distractor lateral vs. target vertical, distractor lateral) and submitted to a 2 × 3 ANOVA. Trials with false responses were removed from the RT analysis. Trials with exceedingly long RT (±2 *SD* from mean RT calculated separately for each participant) were removed from accuracy and RT analyses.

EEG data

EEG was averaged off-line over a 700-ms epoch including a 200-ms prestimulus baseline with epochs time-locked to the search display onset. Only trials with correct responses were analyzed. Furthermore, trials in which EOG electrodes revealed eye movements or blinks (indicated by any absolute voltage difference in a segment exceeding 80 μV or voltage steps between two sampling points exceeding 50 μV) or signal loss (voltage lower than 0.10 μV for a 100-ms interval) were excluded from analysis. Across all participants, 95.2 % of the correct trials showed no contamination with eye movements or blinks ($SD = 5.8$ %). Additionally, segments were excluded from further analysis on an individual-channel basis with the same criteria. One participant was excluded from further data analysis because only 50% of the trials were left after artifact rejection.

For the N2pc analyses, the EEG was averaged for each participant separately for electrode sites contralateral and ipsilateral to the target (or to the distractor in trials with a target on the vertical midline). EEG was further averaged separately for each context type (homogeneous vs. heterogeneous), each position condition (target lateral, distractor vertical vs. target lateral, distractor lateral vs. target vertical, distractor lateral) and three epochs (150–200 ms; 200–250 ms; 250–300 ms). For statistical analyses, the difference of contralateral and ipsilateral ERPs (contra minus ipsi) was calculated for electrodes PO7 and PO8 and forwarded to a two-way repeated measures ANOVA with the factors Context (homogeneous vs. heterogeneous) and Position (target lateral, distractor vertical vs. target lateral, distractor lateral vs. target vertical, distractor lateral). ANOVAs were calculated separately for each of the three epochs.

Results

Behavioral data

Response times (cf. Figure 2A). Response times were generally faster for homogeneous ($M = 470$ ms) than for heterogeneous ($M = 497$ ms) contexts, $F(1, 19) = 39.5$, $p < 0.001$, $\eta^2 = 0.675$. Response times were also modulated by target and distractor location, being shortest for lateral targets and vertical distractors ($M = 479$ ms), followed by lateral targets and lateral distractors ($M = 483$ ms) and vertical targets and lateral distractors ($M = 488$ ms), $F(2, 38) = 12.5$, $p < 0.001$, $\eta^2 = 0.396$. An interaction of context and location showed that the shorter response times for homogenous than for heterogeneous contexts were more pronounced for vertical targets and lateral distractors ($\Delta M = 35$ ms) than for lateral targets and lateral distractors ($\Delta M = 27$ ms) and lateral targets and vertical distractors ($\Delta M = 22$ ms), $F(2, 38) = 9.8$, $p < 0.001$, $\eta^2 = 0.340$.

Accuracy (cf. Figure 2B). A two-way ANOVA with the factors context (homogeneous vs. heterogeneous) and location (target lateral/distractor vertical vs. target lateral/distractor lateral vs. target vertical/distractor lateral) revealed a trend for Location $F(2, 38) = 3.2$, $p = 0.056$, $\eta^2 = 0.141$. Accuracy was highest in trials with a vertical target and lateral distractor (M = 93.5%, followed by trials with a lateral target and vertical distractor (M = 92.3%) and trials with a lateral target and distractor (M = 92.1%). No other effects were significant (all $p > 0.130$).

ERP Data

Event-related brain potential results are shown in Figure 3.

First epoch (150–200 ms)

The lateralized ERP was more positive for distractors with a vertical target ($M = 0.08$ μV; green lines in Figure 3) than for targets both with a lateral distractor

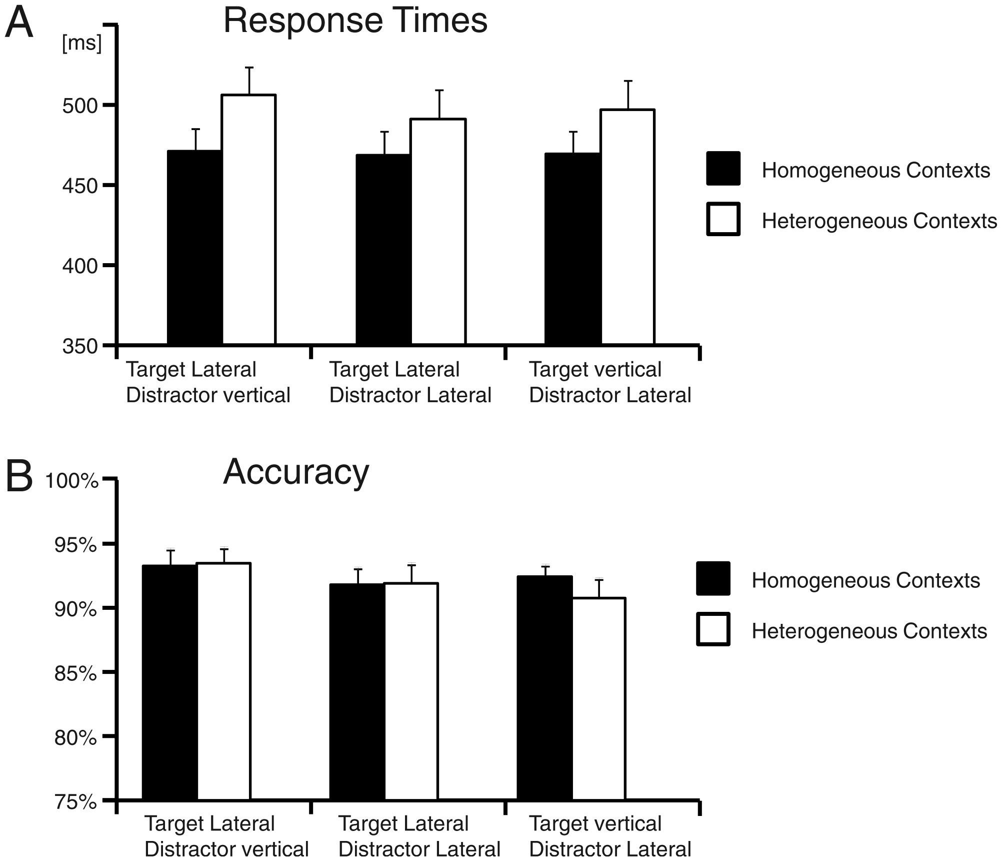


Figure 2. Response times (A) and accuracy (B) for targets in homogeneous contexts (filled bars) and heterogeneous contexts (empty bars). Results are shown separately for trials with lateral target and vertical distractor (left side), trials with lateral target and lateral distractor (middle), and vertical target and lateral distractor (right side). Error bars denote the standard error of the mean.

($M = -1.39$ μV; blue lines) and with a vertical distractor ($M = -1.46$ μV; red lines), main effect of Position, $F(2, 38) = 43.5$, $p < 0.001$, $\eta^2 = 0.696$. Lateralized ERPs were also more negative for targets or distractors in a homogeneous context ($M = -1.23$ μV) than in a heterogeneous context ($M = -0.61$ μV), $F(1, 19) = 18.2$, $p < 0.001$, $\eta^2 = 0.490$. An interaction of Position and Context indicated a differential effect for the two context types, $F(2, 38) = 12.3$, $p = 0.001$, $\eta^2 = 0.392$. Targets in homogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -2.00$ μV; $p < 0.001$; $\varepsilon = 1.86$; red lines) or lateral distractor ($M = -1.89$; μV; $p < 0.001$; $\varepsilon = 1.61$; blue lines). Distractors in homogeneous contexts elicited no reliable lateralized activity ($M = 0.21$ μV; $p = 0.494$; $\varepsilon = 0.60$; green lines). Targets in heterogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -0.92$ μV; $p < 0.001$; $\varepsilon = 1.38$; red lines) or lateral distractor ($M = -0.88$ μV; $p < 0.001$; $\varepsilon = 1.64$; blue lines). Distractors in heterogeneous contexts elicited no reliable lateralized activity ($M = -0.05$ μV; $p = 0.749$; $\varepsilon = 0.10$).

Second epoch (200–250 ms)

The lateralized ERP was more positive for distractors with a vertical target ($M = 0.72$ μV; green lines) than for targets with a lateral distractor ($M = -2.17$ μV; blue lines) or for targets with a vertical distractor ($M = -2.35$ μV; red lines), main effect of Position, $F(2, 38) = 31.7$, $p < 0.001$, $\eta^2 = 0.625$. The lateralized ERP was about the same size in homogeneous ($M = -1.33$ μV) as in heterogeneous contexts ($M = -1.64$ μV), $F(1, 19) = 2.9$, $p = 0.104$, $\eta^2 = 0.133$. An interaction of Position and Context indicated a differential effect for the two context types, $F(2, 38) = 4.4$, $p = 0.019$, $\eta^2 = 0.189$. Targets in homogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -2.22$ μV; $p < 0.001$; $\varepsilon = 1.57$; red lines) or lateral distractor ($M = -2.26$; μV; $p < 0.001$; $\varepsilon = 1.79$; blue lines). Distractors in homogeneous contexts elicited a reliable lateralized positivity ($M = 0.51$ μV; $p = 0.008$; $\varepsilon = 0.95$; green lines). Targets in heterogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -2.49$ μV; $p < 0.001$; $\varepsilon = 2.41$; red lines) or lateral distractor ($M = -2.08$ μV; $p < 0.001$; $\varepsilon =$

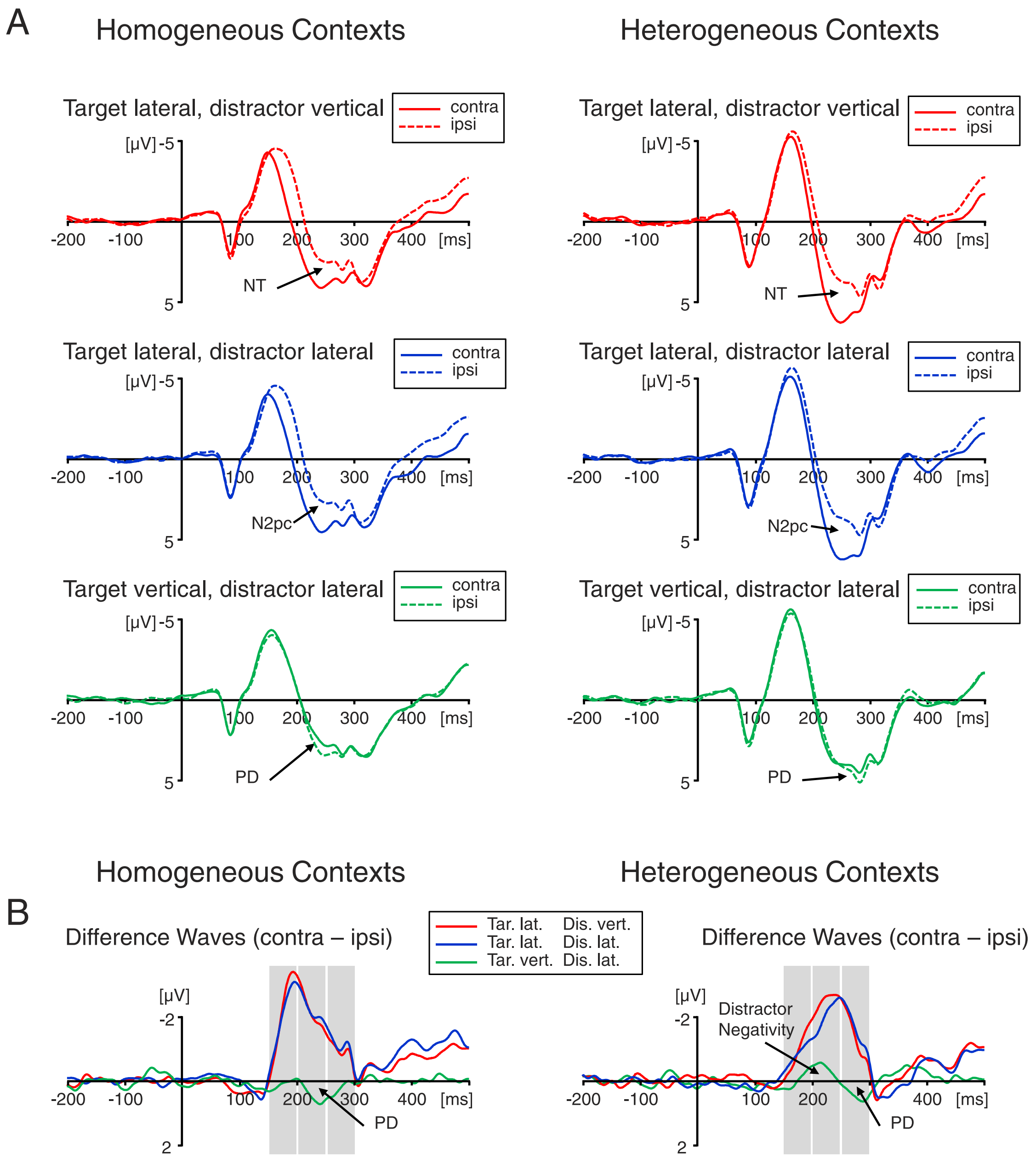


Figure 3. (A) Grand-average ERPs recorded at PO7/PO8, contralateral (solid lines) and ipsilateral (dashed lines) to lateralized stimuli in homogeneous (left panels) and in heterogeneous (right panels) contexts. Results are shown separately for trials with lateral target and vertical distractor (upper row, red lines), for trials with lateral target and lateral distractor (middle row, blue lines; 'contra' denotes contralateral to targets here), and for trials with vertical target and lateral distractor (lower row, green lines; 'contra' denotes contralateral to distractors here). The N2pc is the difference between electrodes contralateral and ipsilateral to target locations when a distractor is presented laterally. The Target-Negativity (NT) denotes this difference when a distractor is presented vertically. The Distractor-Positivity (PD) is the difference between electrodes contralateral and ipsilateral to distractor locations when a target is presented vertically. (B) Shows the same data as (A) but as difference waves (contralateral – ipsilateral). Gray-shaded rectangles depict the time epochs used for statistical analyses. All data are filtered with a 40 Hz low-pass filter for illustration purposes.

1.78; blue lines). Distractors in heterogeneous contexts elicited a reliable lateralized negativity ($M = -0.36$ μV; $p = 0.025$; $\varepsilon = 0.77$; green lines).

Third epoch (250–300 ms)

The lateralized ERP was more positive for distractors with a vertical target ($M = 0.39$ μV; green lines) than for targets with a vertical distractor ($M = -1.19$ μV; red lines) or for targets with a lateral distractor ($M = -1.42$ μV; blue lines), $F(2, 38) = 21.5$, $p < 0.001$, $\eta^2 = 0.530$. The lateralized ERP was more negative for targets or distractors in a heterogeneous ($M = -0.90$ μV) than for targets in a homogeneous context ($M = -0.58$ μV), $F(1, 19) = 6.5$, $p = 0.020$, $\eta^2 = 0.254$. An interaction of Position and Context indicates a differential effect for the two context types, $F(2, 38) = 3.2$, $p = 0.050$, $\eta^2 = 0.146$. Targets in homogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -0.96$ μV; $p = .006$; $\varepsilon = 0.98$; red lines) or lateral distractor ($M = -1.13$; μV; $p = .001$; $\varepsilon = 1.18$; blue lines). Distractors in homogeneous contexts elicited a reliable lateralized positivity ($M = 0.36$ μV; $p = .019$; $\varepsilon = 0.81$; green lines). Targets in heterogeneous contexts elicited a reliable lateralized negativity when presented with a vertical ($M = -1.42$ μV; $p < 0.001$; $\varepsilon = 1.44$; red lines) or lateral distractor ($M = -1.71$ μV; $p < 0.001$; $\varepsilon = 1.41$; blue lines). Distractors in heterogeneous contexts elicited a reliable lateralized positivity ($M = 0.42$ μV; $p = 0.025$; $\varepsilon = 0.78$; green lines).

Latency analyses

In order to assess onset latency differences between homogeneous and heterogeneous contexts for the P_D and the N_T, a jackknife-based procedure was applied (Miller, Patterson, & Ulrich, 1998). The points in time were determined at which the ERP components of 20 grand averages, each excluding one of the 20 participants, reached 50% of the peak amplitude. Subsequently, the jackknife estimate of the standard error of the differences S_D and t values were calculated. The difference in onset latencies between waveforms of different experimental conditions was tested by dividing the latency difference with the estimated S_D. The resulting statistics follow the sampling distribution of Student's t statistic (for a detailed description of the entire method, see Miller et al., 1998). Results showed that the P_D appeared significantly earlier for homogeneous than for random contexts ($D = 42$ ms, $t(19) = -3.57$, $p = .002$). Also N_T appeared significantly earlier for homogeneous than for random contexts ($D = 12$ ms, $t(19) = -4.69$, $p < 0.001$).

General discussion

The present experiment investigated whether background homogeneity affects the extent to which an irrelevant salient distractor captured the observer's attention when presented together with a target. Observers had to search for an oblique line embedded in a homogeneous or heterogeneous context and to ignore a color distractor. We adapted an ERP technique developed by Hickey et al. (2009) which allows separating neural processes underlying prioritized target processing and distractor inhibition. The Distractor-Positivity (P_D) is a positive deflection in the ERP contralateral to a distractor when a target is simultaneously presented unlateralized and reflects suppression of irrelevant information (Hickey et al., 2009). The Target-Negativity (N_T) is a negative deflection in the ERP contralateral to a target when a distractor is simultaneously presented unlateralized and reflects enhancement of relevant information (Hickey et al., 2009). Both components may sum up to the traditional N2pc component which reflects attention deployment in the visual field (e.g., Eimer, 1996; Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004; Luck & Hillyard, 1994).

By using neural correlates of target and distractor processing, we wanted to investigate whether the previously found more efficient target processing in homogeneous contexts (Duncan & Humphreys, 1989; Meinecke & Donk, 2002; Schubö et al., 2007) is accompanied by a more efficient inhibition of salient distractors. If so, we expect a pronounced P_D. Conversely, it may be that salient distractors are processed with priority in homogeneous contexts as well, leading to larger filtering costs. In that case, distractors should elicit a less pronounced or even inverted P_D in homogeneous contexts. Finally, it may also be possible that homogeneity does not affect distractor inhibition but only target enhancement. In that case, we would expect a more pronounced N_T in homogeneous contexts but no modulation of the P_D.

As expected, our results showed evidence for efficient target processing in homogeneous contexts: A large negative deflection was observed already in the first epoch (150–200 ms) for targets with distractors in the opposite hemifield (i.e., a classical N2pc) and for targets with distractors on the vertical midline (i.e., an N_T). This suggests that already at an early point, attention was deployed to the target. This was done in a similar way for both targets irrespective of the additional distractor's location. Also in the second (200–250 ms) and third (250–300 ms) epoch, a pronounced N2pc and N_T were found, suggesting persistent attention deployment at target locations. In addition, the lateralized ERP showed a positive deflection for distractors (i.e., a P_D), in the second and third epoch. This suggests active suppression of the distractor in homogeneous contexts from 200 ms onward.

Also in heterogeneous contexts target processing seemed efficient, as both an N2pc and N_T were observed throughout all epochs. Similarly to what was found for homogeneous contexts, these components did not differ with respect to the additional distractor's location. This suggests that also in heterogeneous contexts, attention was deployed to the target rather early in time. Concerning distractor processing, results showed a different picture. A "classical" P_D, i.e., a distractor-related positivity, could only be observed in the third epoch, suggesting relatively late suppression of the distractor. In the second epoch, however, the lateralized ERP elicited by distractors was *negative* (i.e., an N_D). Thus it seemed that rather than showing suppression of the distractor, the distractor seemed to have captured attention in this case. When presented in a heterogeneous context, the distractor seemed to have attracted the observer's attention at least to some degree before it could be inhibited.

The divergent P_D pattern and time course for homogeneous and heterogeneous contexts was well in line with behavioral findings: Response times were faster for targets in homogeneous contexts than for targets in heterogeneous contexts. This result replicates previous studies which have found facilitated search performance in homogeneous compared to heterogeneous contexts (e.g., Akyürek et al., 2010; Duncan & Humphreys, 1989; Schubö et al., 2007). The present findings extend these results by demonstrating that contexts of varying homogeneity do also result in differential attention deployment towards salient distractors. Accordingly, the shorter response times for targets in homogenous contexts may have resulted from both more efficient target processing and less distractor-induced filtering costs.

Time course of target enhancement and distractor suppression in contexts of varying homogeneity

When comparing the attention-related ERP components observed for contexts of varying homogeneity, one may state that the pattern of components reflecting target processing (the N_T and N2pc) seems to be far less divergent than the pattern of the distractor-related P_D. Both N_T and N2pc were slightly more pronounced for homogeneous contexts, a result replicating findings of earlier studies (e.g., Schubö et al., 2007). Besides, attention deployment to targets in homogeneous contexts seemed to happen slightly faster than to targets in heterogeneous contexts: In the first epoch, N_T and N2pc reached a maximum peak for homogenous contexts while they were still ascending in heterogeneous contexts (cf. Figure 3B). This finding suggests that at this early point in time, attention deployment was at its maximum at target locations in homogeneous contexts while attention deployment in heterogeneous contexts was still evolving. This is well in line with the notion that attention deployment towards a target in heterogeneous contexts takes more time to develop (Akyürek et al., 2010; Duncan & Humphreys, 1989; Schubö et al., 2007). More pronounced activation of cortical regions representing attended stimuli has also been found in single cell recordings in animal brains (Roelfsema, Lamme & Spekreijse, 1998; Spitzer, Desimone, & Moran, 1988; Treue & Maunsell, 1999). The present results suggest that such enhanced cortical representation of a target, that may be reflected in the N_T (Hickey et al., 2009), happens at an earlier point in time when the target is presented in a homogeneous context. This enhanced cortical representation may have resulted in faster identification of the target, leading to shorter response times for targets in homogenous than in heterogeneous contexts.

Faster identification of targets in homogeneous contexts may also have been a consequence of more efficient distractor inhibition. The P_D results strongly support this notion: In the first epoch, a P_D could be observed for neither homogeneous nor heterogeneous contexts, suggesting that at this early point in time the salient distractor was not yet suppressed. In the second and third epoch, a reliable P_D for distractors was observed in homogeneous contexts. This observation is in line with earlier findings that P_D is most pronounced between 200 and 300 ms (Hickey et al., 2009) and suggests strong and efficient suppression of salient distractors. The P_D elicited by heterogeneous contexts showed a different picture: A reliable P_D was observed only after 250 ms, suggesting delayed distractor suppression. The distractor-elicited negativity observed between 200 and 250 ms showed that attentional capture preceded distractor suppression. Attentional capture by a salient irrelevant distractor has been reported before (e.g., Hickey et al., 2006; Schubö, 2009). The authors argued that attention is first captured by the irrelevant color singleton before attention can be deployed towards the relevant target in a second step. This effect may have been similar in the present experiment: Attention may have been captured by the salient color distractor before the target could be attended.

In addition to previous findings, our results revealed differential effects of distractor processing as a function of context homogeneity. Distractor-induced attention capture was only found when target and distractor were presented in heterogeneous contexts. In homogeneous contexts, attention deployment seemed more efficient, allowing distractor suppression at an earlier point in time. Apparently, the visual system needed more time to "get rid of" the salient distractor in heterogeneous than in homogenous contexts. Duncan and Humphreys (1989) argued that reducing the heterogeneity of nontarget elements increases search efficiency because similar (or homogeneous) elements are being grouped, and grouping reduces the number of perceptual units that have to be searched in order to find the target (see also Bacon & Egeth, 1991; Schubö, Schröger, & Meinecke, 2004; Schubö et al., 2007). In addition to more efficient grouping, enhanced attention deployment towards targets in homogeneous contexts may be caused by the higher salience of the target in homogeneous contexts. For example, it has been found that a higher local feature contrast causes an increase of salience as revealed by a higher proportion of correct saccadic eye movements (Van Zoest & Donk, 2008) especially for short latency responses (Van Zoest & Donk, 2004; see also Donk & Soesman, 2010). Since in the present experiment, the local feature contrast of target versus surrounding was higher in homogeneous than in heterogeneous contexts (cf. Li, 2002; Schubö, Akyürek, Lin, & Vallines, 2011), the resulting higher salience of the target may have contributed to the larger and earlier N_T component in homogeneous contexts. As the distractor was defined by color, not orientation, its salience was presumably equal in homogenous and heterogeneous contexts.[1] Hence the distractor-elicited N_T and then later P_D in heterogeneous contexts, reflecting less efficient distractor inhibition, maybe due to impaired processing of the less salient target.

The role of homogeneity in top-down and bottom-up processes

There is an ongoing debate to what extent irrelevant salient information attracts an observer's attention and is processed without the observer intending to do so. There has been some support for the view that physical salience can barely be overruled by volitional control (Theeuwes, 1992, 2004; Theeuwes et al., 2000), and a large proportion of studies has shown that volitional control can be very efficient already at an early point in visual processing (Bacon & Egeth, 1991; Folk et al., 1992; Folk, Leber, & Egeth, 2002; Folk & Remington, 2006; Kim & Cave, 1999; Leblanc, Prime, & Jolicoeur, 2008; Wykowska & Schubö, 2011). More recent research has shown that top-down and bottom-up processes may not be a dichotomy but may rather both contribute to visual selection (e.g., Awh et al., 2012; Wykowska & Schubö, 2011) which in turn may depend on several factors such as the attentional demands (Kiss et al., 2012), the value of a stimulus (Anderson, Laurent, & Yantis, 2011; Hickey, Chelazzi, & Theeuwes, 2010), or the complexity of the search process (Töllner, Rangelov, & Müller, 2012).

The present experiment provides evidence that an additional factor may determine the relative contribution of top-down and bottom-up processes, namely the homogeneity of the context in which stimuli are embedded. When contexts were homogeneous, no attentional capture by irrelevant salient distractors was observed. In heterogeneous contexts, however, active suppression of the distractor was delayed, supposedly a consequence of attentional capture by the distractor. This distinction does not necessarily mean that distractor inhibition is not grounded on low-level features, but it suggests that at least top-down processing is less vulnerable to interferences from potentially distracting low-level features in homogeneous contexts whereas attention deployment in heterogeneous contexts is more vulnerable to distraction by salient stimuli.

Keywords: visual search, bottom-up, top-down, homogeneity, N2pc, distractor-positivity, target-negativity

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Footnote

[1] The alignment of the color singleton distractors to the respective background suggests identical salience in homogeneous and heterogeneous contexts. Although the iso-orientation surround suppression (e.g., Bair, Cavanaugh, & Movshon, 2003) may be reduced for any given line element in heterogeneous contexts (compared to homogeneous contexts), this supression should be the same for all line elements in heterogeneous contexts (except for the target). Hence there should be no increase in salience for distractors in both context types on the orientation feature map (e.g., Itti & Koch, 2001). However, there should be an identical increase in salience on the color feature map for distractors in both contexts since the color difference for distractor (red) versus context line (black) was identical in both contexts. As a result, distractors should receive more activation than their surroundings on the priority map (see Wolfe, 1994), but this activation should be identical in homogeneous and heterogeneous contexts.

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TITLE:

Stimulus homogeneity enhances implicit learning: Evidence from contextual cueing

Running Head:

Contextual Cueing and stimulus homogeneity

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Abstract

Visual search for a target object is faster if the target is embedded in a repeatedly presented invariant configuration of distractors (‘*contextual cueing’*). It has also been shown that the homogeneity of a context affects the efficiency of visual search: targets receive prioritized processing when presented in a homogeneous context compared to a heterogeneous context, presumably due to grouping processes at early stages of visual processing. The present study investigated in three Experiments whether context homogeneity also affects contextual cueing. In Experiment 1, context homogeneity varied on three levels of the task-relevant dimension (orientation) and contextual cueing was most pronounced for context configurations with high orientation homogeneity. When context homogeneity varied on three levels of the task-irrelevant dimension (colour) and orientation homogeneity was fixed, no modulation of contextual cueing was observed: high orientation homogeneity led to large contextual cueing effects (Experiment 2) and low orientation homogeneity led to low contextual cueing effects (Experiment 3), irrespective of color homogeneity. Enhanced contextual cueing for homogeneous context configurations suggest that grouping processes do not only affect visual search but also implicit learning. We conclude that memory representation of context configurations are more easily acquired when context configurations can be processed as larger, grouped perceptual units. However, this form of implicit perceptual learning is only improved by stimulus homogeneity when stimulus homogeneity facilitates grouping processes on a dimension that is currently relevant in the task.

Keywords: Visual search, contextual cueing, implicit learning, homogeneity

1. Introduction

In everyday life, humans are confronted with a huge amount of incoming visual information. Due to limited capacity the visual system needs to select some information while disregarding other, a mechanism called *visual selective attention*. Visual search tasks have often been used to examine how attention is deployed across the visual field (Duncan & Humphreys, 1992; Eimer, Kiss, & Cheung, 2010; Found & Müller, 1996; Schubö, Wykowska, & Müller, 2007; Wolfe, 1994). In a typical visual search task, participants are requested to indicate whether a pre-defined target is presented within a set of distractors that differ from the target in a particular feature (e.g. colour or orientation) or a combination of such features. In their *attentional engagement theory*, Duncan & Humphreys (1989, 1992) emphasize the crucial role of distractor similarity in the deployment of visual attention in such tasks. They proposed that at an early 'parallel' stage of visual coding, incoming visual information is segmented into structural units based on the operation of elementary segmentation and on grouping principles. These structural units form the input for subsequent processing stages on which attention is being deployed to potential targets. On this early stage, elements that are similar are linked together to form a larger perceptual unit which is subsequently processed as one single structural unit. Increasing the similarity of distractors increases search efficiency, because similar elements are being grouped, and grouping reduces the number of perceptual units that have to be searched subsequently in order to find the target. Similarity grouping also accelerates subsequent rejection of distractors as it facilitates singling out the target element that does not belong to the uniform structure. The more similar distractors are, the more efficient grouping mechanisms are at work and the more easily identification of an embedded target is achieved (Duncan & Humphreys, 1989; Nothdurft, 1992; Schubö, Akyürek, Lin, & Vallines, 2011).

In addition to stimulus similarity, prior knowledge was demonstrated to be a mechanism that is capable of guiding attention. In a seminal study by Chun & Jiang (1998) participants had to search for a T letter in a context of distracting L letters of different orientation. While one half of the context configurations was randomly generated in each trial and thus novel to observers, the other half of the context configurations was repeated throughout the experiment. The time to find a target and report its orientation depended on prior exposure to a search display (Chun & Jiang, 1998). Reaction times for targets progressively decreased when the target was being repeatedly presented in an invariant configuration of distractors compared to a new configuration of distractors. Observers were not aware that some of the context configurations had been repeated throughout the experiment, suggesting that context configurations are implicitly learned (Chun & Jiang, 1998). Such shorter reaction times for repeated than for new context configurations was described as 'contextual cuing' since the visual *context*, i.e. the configuration of distractors, served as a spatial cue indicating a specific target location. The association between context configuration and target location is acquired when contexts are repeatedly presented throughout the experiment by mere exposure (Chun & Jiang, 1998; Chun, 2000).

This association accelerates the search process as a result of improved prioritization of the target location: The more established such an implicit memory representation of a repeated context configuration is, the more efficiently is attention guided to the associated target location (Chun & Jiang, 1998; Ogawa, Takeda, & Kumada, 2007; Schankin & Schubö, 2009; Zhao et al., 2012). In sum, regularities such as the structure or gist of the visual field can be acquired and on a later occasion help the observer to find relevant information.

1.1 Contextual cueing and stimulus similarity

While the role of stimulus similarity for visual search has been demonstrated numerous times (Donk & Soesman, 2011; Duncan & Humphreys, 1989, 1992; Feldmann-Wüstefeld & Schubö, 2013; Schubö et al., 2007), its role for contextual cueing has received far less interest (e.g., Rausei, Makovski, & Jiang, 2007). The present study investigates whether stimulus similarity can, similarly to visual search, also enhance contextual cueing. Since changing the similarity of stimuli a context configuration comprises does not affect the spatial layout, a prerequisite of stimulus similarity affecting contextual cueing is that in addition to the spatial layout, the stimulus identity is internally represented. The role of distractor identity and spatial layout was tested by Chung & Jiang (1998). In their Experiment 2, the spatial configuration of distractors, i.e. the location of the individual distractors in repeated context configurations was kept constant. However, the distractor identity, i.e. the particular distractor type at a given location, was altered. Repeated contexts still showed shorter reaction times than novel contexts, i.e. contextual cueing was still observed. These results demonstrate that once representations of context configurations were acquired, the spatial structure suffices to guide attention to the presumed target location (Jiang & Chun, 2001; see also Jiang & Wagner, 2004). However, this does not rule out the possibility that stimulus identity and thus stimulus similarity plays a role *during acquisition* of the internal representation of a context configuration.

A study by Rausei and colleagues (2007) investigated the role of stimulus similarity in acquisition of contextual cueing. The authors varied the target-distractor similarity in a contextual cueing experiment to compare how efficiently context configurations are learned. They used ordinary Ls or altered Ls whose horizontal line was shifted to the vertical center thus making the distractor L more similar to the target T. When Ls were more similar to the T, search was more difficult (a replication of earlier results in visual search, Duncan & Humphreys, 1989), but importantly, contextual cueing was unaffected (Rausei et al., 2007). This may not be surprising given the fact that in contextual cueing paradigms, a distractor arrangement is associated with a target *location*, not a target identity. In other words, regularities in the *context configuration* are learned and then associated with a target location. As a consequence, the identity of the target and thus the similarity of the target with distractors is not important (Chun & Jiang, 1998) and may therefore not modulate contextual cueing in Rausei et al’s (2007) study. The identity of the distractors and hence the similarity among distractors, however, may play a more important role because the similarity among distractors defines a property of the context configuration that is learned. In particular, similarity among distractors may be relevant for contextual cueing due to grouping processes enhancing memory representations. Indeed, grouping was found to efficiently boost memory processes: visual representations in memory were found to be more efficient in change detection tasks when visual spatial information could be grouped according to Gestalt principles (Luck & Vogel, 1997a; Woodman, Vecera, & Luck, 2003), expert knowledge in chess (Gobet & Simon, 1996a) or due to the presence of statistical regularities and associations among stimuli that were prior unknown to the observers (Brady, Konkle, & Alvarez, 2009a). We speculate that increased stimulus similarity increases contextual cueing due to a related mechanism: context configurations of more similar stimuli may be learned more easily because representations of grouped stimuli rather than single stimuli can be stored in memory. As a result more established memory representations are achieved for highly similar stimuli that serve as a more efficient spatial cue to deploy attention to the associated target location.

1.2 Rationale of the present study

In the present series of experiments we varied the similarity among distractors in various ways which allows investigating the impact of stimulus similarity on contextual cueing. To our knowledge, this has not been investigated so far which may appear surprising since the stimuli used by Duncan & Humphreys (1989) are particularly similar to the ones usually used in contextual cueing experiments (Chun & Nakayama, 2000; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Schankin & Schubö, 2009; Zellin, Conci, von Mühlenen, & Müller, 2011).

In Experiment 1 we varied the distractor similarity by using Ls of one, two or four orientations. This is similar to Duncan & Humphreys (1989; Experiment 3) with the difference that half the context configurations used in the present experiment were invariant, i.e. they were repeatedly presented throughout the experiment (to yield contextual cueing). This was done for three levels of distractor similarity. The low-similarity condition (four L orientations) was similar to classical contextual cueing experiments in which distractors were usually of four orientations (Chun & Jiang, 1998; Kunar et al., 2007). Since prior knowledge about a context configuration reduces the number of potentially interesting locations in the visual field and thereby restricts selection to the most likely target locations, we predicted to replicate the classical contextual cueing effect (reduced RTs for repeated context configurations) in all conditions. Further, since distractor similarity allows grouping and hence processing of fewer perceptual units, we predicted to replicate the classical similarity effect, i.e. reduced RTs for more similar distractors. Most importantly, we hypothesized that internal representations of context configurations with more similar distractors are acquired more efficiently, because in this case groups of stimuli rather than single stimuli have to be learned. Accordingly, we predicted that higher distractor similarity enhances contextual cueing, i.e. the accelerated search for a target in repeatedly presented context configurations is more pronounced if the context comprises more similar distractors.

2. Experiment 1

2.1 Material and methods

2.1.1 Participants

20 participants (4 male), mean age 23.1 years (*SD* = 3.0), completed Experiment 1. All had normal or corrected-to-normal visual acuity and were naive to both the paradigm and the objective of the experiment.

2.1.2 Apparatus and Stimuli

Participants were seated in a comfortable chair in a dimly lit, sound attenuated chamber, with a gamepad *(Microsoft Sidewinder USB)* in their hands. Participants had to use their left and right index finger to press two buttons on the back of the gamepad. Stimulus presentation and response collection were controlled by a *Windows* PC using *E-Prime* routines. All stimuli were presented on a LCD-TN screen (*Samsung Syncmaster 2233*) that was placed 100 cm away from participants.

Distractors were L-shaped items rotated 0°, 90°, 180° or 270° and embedded targets were left- or right-tilted T-shaped items (each 1.2°x1.2°). Distractors and target were white (RGB: 255, 255, 255) presented on a gray (128,128,128) background. Search displays always consisted of 13 distractors and 1 target, distributed on an imaginary matrix of 10 x 7 cells (21°x14.5°). The target appeared on one of 12 possible target locations (3.5° or 8° left or right to fixation), distractor Ls were placed randomly on the remaining cells so that 7 items were presented on the left and 7 on the right side of the display. Similarity of distractors varied on three levels: One (1O), two (2O) or four orientations (4O) of Ls were used within one context. Which orientation or combinations of orientations were actually used in the display was counterbalanced across contexts. If two or four orientations were used, they were (as closely as possible) equally distributed to the right and left visual field. Fig. 1A shows an exemplary display.

2.1.3 Trial Sequence

A trial began with a fixation dot presented for 500 ms at the centre of the screen followed by the search display that was visible for 700 ms. This short exposure duration was used to curb eye movements and to discourage search strategies that may interfere with implicit learning (for similar exposure durations see Schankin & Schubö, 2009). The search display was replaced by a blank grey (128,128,128) screen for 1300 ms before the next fixation dot indicated the start of a new trial. Participants were instructed to report the orientation of the target as quickly as possible (within 2000 ms after onset of the search display) by pressing the corresponding button (i.e. left button for left-pointing T) while avoiding false responses. Participants were told that distractors were not important and could be ignored.

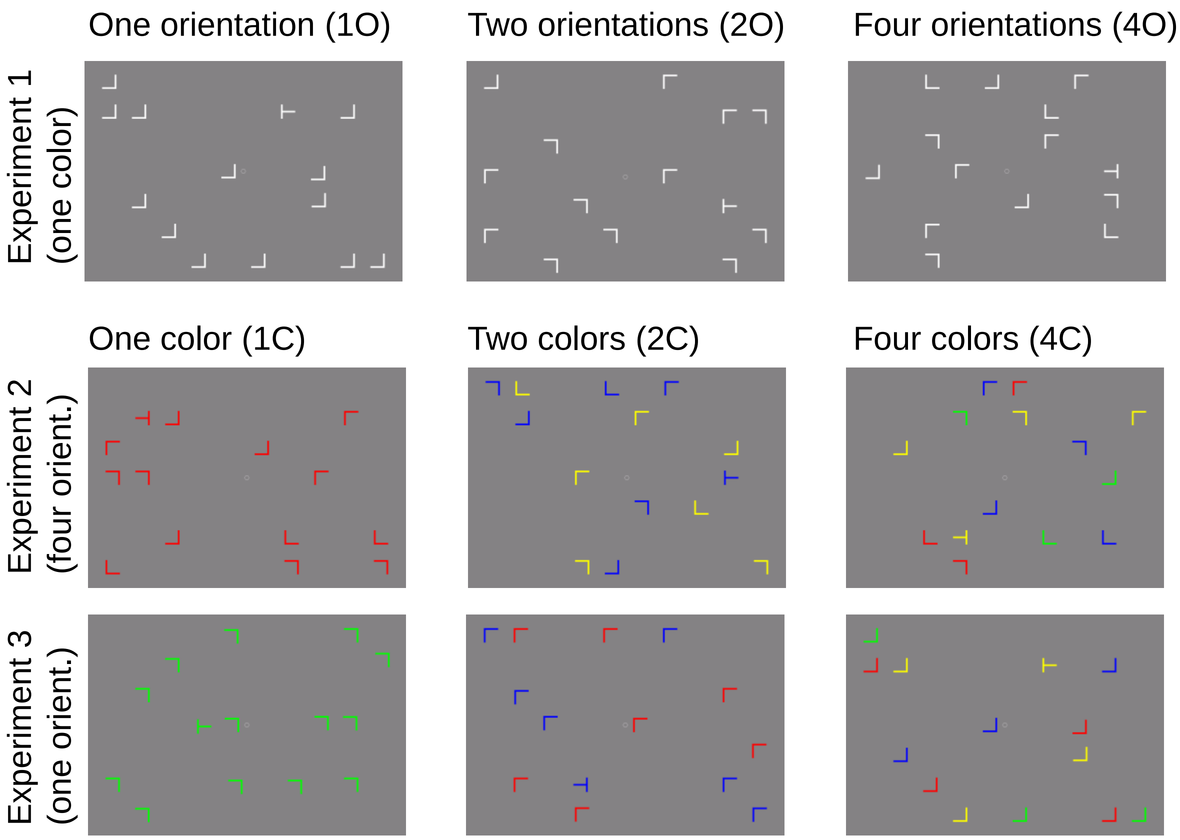

Fig. 1: Example search displays as used in Experiment 1 (upper row), Experiment 2 (middle row) and Experiment 3 (lower row). All contexts consisted of 13 Ls and one T that were distributed on a 10x7 matrix. Participants were instructed to indicate the orientation of the target letter T (left vs. right). In Experiment 1, contexts were always white and distractor Ls were of one (1O; left column), two (2O; middle column) or four (4O; right column) orientations. In Experiment 2, Ls were always of four orientations and in Experiment 3, Ls were always of one orientation. In Experiment 2 and 3, contexts were colored in one (1C; upper row), two (2C; middle row) four (4C; lower row) different colors.

2.1.4 Design and Procedure

The experiment started with one practice block of 72 trials with 24 randomly generated contexts of each of the three homogeneity conditions, randomly intermingled. The subsequent experiment consisted of 18 blocks of 72 trials. For each participant, 36 contexts (three for each distractor similarity condition, one for each of the twelve target locations) were generated that were repeated throughout the experiment, once per block (‘old contexts’). For these contexts, distractor orientation and location as well as target location were fixed. Target identity (left or right) was not fixed for old contexts to avoid a direct association of a response with a specific context. In addition, 36 new (randomly generated) contexts were presented in each block, 12 for each homogeneity condition. This resulted in a 2 x 3 x 18 within-subjects design with the factors Context novelty (new vs. old), Distractor similarity (1O, 2O, 4O) and Block (1-18). Within each block, all trial types were randomly intermingled, target locations and target orientations were counterbalanced and used equally often in each block.

In a final recognition phase, observers were informed that some of the contexts were repeated throughout the experiment. They were shown 72 contexts, 36 of which were new and 36 were old contexts, presented in random order, and were asked to indicate whether a context had previously been shown in the experiment (unspeeded response).

2.2 Results

Trials with false responses and RTs exceeding the individual's mean RT by ± 2 SD were excluded from the analysis. A repeated measures ANOVA with the within-subject factors Distractor similarity (1O vs. 2O vs. 4O), Novelty (old, new) and Epochs (6 epochs each pooled from three successive blocks to have more robust measures) revealed that RT decreased with distractor similarity (M_{4O} = 657 ms vs. M_{2O} = 638 ms vs. M_{1O} = 613 ms), F(2,38) = 40.85, p < .001, η^2 = .68, and with epoch (M_{epoch1}= 695 ms vs. M_{epoch6}= 611 ms), F(5,95) = 41.71, p < .001, η^2 = .69. Performance in new contexts was generally worse than in old contexts (M_{new} = 646 ms vs. M_{old} = 626 ms), F(1,19) = 27.94, p < .001, η^2 = .60. An interaction of Epoch and Novelty showed that the RT advantage for old contexts was more pronounced in later than in earlier epochs, indicating contextual cueing (ΔM_{epoch1}= 5 ms vs. ΔM_{epoch6}= 26 ms), F(5,95) = 2.96, p = .030, η^2 = .14. Furthermore, an interaction of Homogeneity and Novelty showed that the RT advantage for old contexts increased with homogeneity (ΔM_{4O} = 13 vs. ΔM_{2O} = 17 ms vs. ΔM_{1O} = 33 ms), F(2,38) = 5.26, p = .020, η^2 = .22. No other effects were significant (all p > .696). Fig. 2A visualizes mean RT for old vs. new contexts as a function of epoch with individual plots for each of the homogeneity conditions.

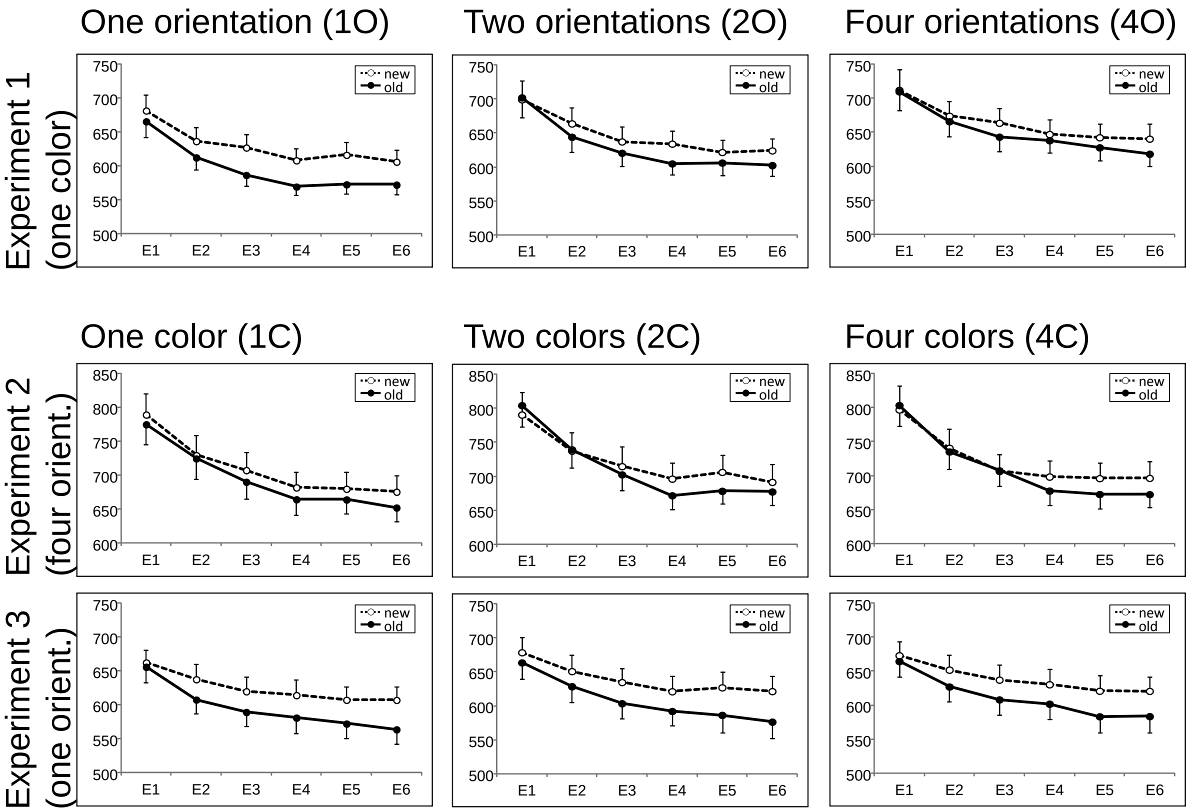

Fig. 2: Mean (±SEM) reaction times as a function of Epoch (1 – 6, each pooled across three successive blocks) and Novelty (new vs. old). The upper row shows results for Exp. 1 where all Ls were white and distractor similarity varied on orientation and the middle row shows results for Exp. 2 where Ls had four orientations and distractor similarity varied on color. The lower row shows results for Exp. 3 where all Ls had the same orientation and distractor similarity varied on colour. Each column shows a different level of distractor similarity: the left column shows results for contexts with highest distractor similarity (1O in Exp. 1 and 1C in Exp. 2 and 3). The middle column shows results for medium distractor similarity (2O in Exp. 1 and 2C in Exp. 2 and 3). The right column shows results for the lowest distractor similarity (4L in Exp. 1 and 4C in Exp. 2 and 3).

2.3 Discussion

Experiment 1 showed that repeatedly presented (old) context configurations accelerate the search for an embedded target compared to previously unexposed (new) context configurations. This is a replication of implicit learning effects in visual search earlier described as 'contextual cueing' (Chun & Jiang, 1998; Kunar et al., 2007; Schankin & Schubö, 2009). Further, Experiment 1 showed that more homogeneous context configurations accelerate visual search for an embedded target, a replication of the distractor similarity effect (Duncan & Humphreys, 1989). Importantly, the present results showed that contextual cueing was more pronounced when similarity among distractors was high: when all distractors had the same orientation (1O), targets benefited most from being presented in an old context, followed by distractors with two orientations (2O) and four orientations (4O). Beneficial effects of distractor similarity previously found in visual search tasks were argued to be based on efficient pre-attentive grouping that allowed to more efficiently process larger structural units (Bacon & Egeth, 1991; Duncan & Humphreys, 1989, 1992; Nothdurft, 1992; Schubö et al., 2007). The present results suggest that similarity does also play a crucial role in implicit learning as reflected in contextual cueing. It may be that in the 1O condition, groups of stimuli rather than single stimuli were transferred into memory due to grouping processes. This is in line with previous research showing that grouped stimuli can be more easily encoded (Brady et al., 2009a; Gobet & Simon, 1996a; Luck & Vogel, 1997a; Woodman et al., 2003) and shows that contextual cueing may also benefit from enhanced memory representations of grouped stimuli.

In Experiment 1, the similarity among distractors was varied on the dimension *orientation*. Since observers had to report the orientation of the target T, orientation was a task-relevant dimension. Other, task-irrelevant dimensions (e.g., color or size) were not varied. Interestingly, it was found in previous studies that implicit learning of visual stimuli was only enhanced if the stimuli were defined on a currently task-relevant dimension (Jimenez & Mendez, 1999). Jimenez and Mendez used a sequence learning task in which both the sequence and the shape were predictive of the target location in a particular trial. For example, after a target was presented at location A, the next target would most likely appear at location B. Similarly, after presentation of a particular shape, the next target would most likely appear at location C. While the sequence itself was always accelerating response times, shape cues only helped to further accelerate search when shape was made task-relevant in a secondary task (e.g., observers had to count the number of particular shapes). In other words: "…learning about the relationships between shapes and locations is acquired when participants are told to perform a secondary task that requires them to consider these shapes and to respond to them." (Jimenez & Mendez, 1999, p. 256). Regarding contextual cueing, it was argued that contexts were implicitly learned because they have to be processed to some extent before they can be discarded and attention can be guided to the target (Chun & Jiang, 1998; Chun & Nakayama, 2000). Since more similar distractors are processed more easily (Duncan & Humphreys, 1989), this could have resulted in more established memory representations and thus more efficient attention guidance. This raises the question whether similarity among distractors has to be on a task-relevant dimension in order to result in enhanced contextual cueing. If only information on the task-relevant dimension is implicitly processed thus subsequently helping to guide attention (Jimenez & Mendez, 1999), differential contextual cueing as observed in Experiment 1 should disappear when distractor similarity is solely varied on a task-irrelevant dimension because this dimension is not considered by observers. Experiment 2 and 3 were designated to answer this question and to examine to what extent distractor properties are processed when observers are repeatedly searching for embedded targets. In the following experiments, distractor similarity regarding orientation was kept constantly low (4O; Experiment 2) or constantly high (1O; Experiment 3) while it was varied regarding color, a dimension completely irrelevant in the task. If only information congruent to the task, i.e. orientation information, is implicitly learned, contextual cueing should stay on low level (Experiment 2) or on a high level (Experiment 3) regardless variation in color similarity. Conversely, if Experiment 2 and Experiment 3 yielded similar variations in contextual cueing as were observed in in Experiment 1, this would suggest that implicit learning is much broader and contexts are more thoroughly processed; as a result similarity on task-irrelevant dimensions may boost implicit learning quite as well as task-relevant dimensions do.

3. Experiment 2 and 3

3.1 Material and methods

Experiment 2 and 3 were identical to Experiment 1 except for the following exceptions. In Experiment 2, contexts always contained distractors of four orientations (as in condition 4O in Exp. 1). In Experiment 3, contexts always contained distractors of one orientation (as in condition 1O in Exp. 1). In both Experiment 2 and 3, three levels of distractor similarity were realized by coloring distractors in one (1C), two (2C) or four (4C) colors within a context. Target color was chosen randomly from one of the 1, 2 or 4 colors used in a specific context. For repeatedly presented contexts, target color as well as distractor color and distractor orientation were fixed throughout the experiment. Colors were blue (0,0,255), green (0,255,0), red (255,0,0) and yellow (255,255,0). For an exemplary search display, see Fig. 2B.

20 participants (8 male), mean age 22.7 years (*SD* = 4.4) completed Experiment 2 and 20 new participants (6 male), mean age 23.5 (*SD* = 3.0), took part in Experiment 3 for payment or course credit. All had normal or corrected-to-normal visual acuity and were naive to both the paradigm and the objective of the experiment. None of the participants had participated in Experiment 1.

3.2 Results

3.2.1 Experiment 2

RTs were analyzed analogously to Experiment 1. RT decreased with distractor similarity (M_{4C} = 623 ms vs. M_{2C} = 622 ms vs. M_{1C} = 608 ms), $F(2,38) = 12.18$, $p < .001$, $\eta^2 = .39$, and with epoch (M_{epoch1}= 662 ms vs. M_{epoch6}= 595 ms), $F(5,95) = 33.81$, $p < .001$, $\eta^2 = .64$. Responses in new contexts were generally slower than in old contexts (M_{new} = 632 vs. M_{old} = 603), $F(1,19) = 63.90$, $p < .001$, $\eta^2 = .77$. An interaction of Epoch and Novelty showed that the RT advantage for old contexts was more pronounced in later than in earlier epochs (ΔM_{epoch1}= 10 ms vs. ΔM_{epoch6}= 40 ms), $F(8,152) = 5.96$, $p < .001$, $\eta^2 = .24$. No other effects were significant (all $p > .683$).

3.2.2 Experiment 3

RTs were analyzed analogously to Experiment 1 & 2. RT decreased with distractor similarity (M_{4C} = 717 ms vs. M_{2C} = 717 ms vs. M_{1C} = 703 ms), $F(2,38) = 6.56$, $p = .004$, $\eta^2 = .28$, and with epoch (M_{epoch1}= 793 ms vs. M_{epoch6}= 678 ms), $F(5,95) = 19.50$, $p < .001$, $\eta^2 = .50$. Responses in new contexts were generally slower than in old contexts (M_{new} = 719 vs. M_{old} = 706), $F(1,19) = 5.62$, $p = .029$, $\eta^2 = .23$. An interaction of Epoch and Novelty showed that the RT advantage for old contexts was more pronounced in later than in earlier epochs (ΔM_{epoch1}= -2 ms vs. ΔM_{epoch6}= 20 ms), $F(5,95) = 3.21$, $p = .010$, $\eta^2 = .14$. No other effects were significant (all $p > .782$).

Recognition Test

For all three Experiments, one-way ANOVAs with the within-subject factor Homogeneity were conducted to compare recognizability of old and new contexts with respect to accuracy in the recognition test, sensitivity to detect an old context (d-prime), and response bias towards new or old contexts (C; Macmillan & Creelman, 1991). Neither mean accuracy nor d-prime nor C depended on context homogeneity (all $p > .393$). In addition, hit rate and false alarm rate for detection of old contexts did not differ for any of the homogeneity conditions (all $p > .07$).

3.3 Discussion

Similarly to Experiment 1, Experiment 2 and 3 found evidence for contextual cueing, i.e., accelerated search for a target in repeatedly presented (old) contexts compared to previously unexposed (new) contexts. Besides, the generally faster responses for targets in homogeneous context configurations compared to heterogeneous context configurations from Experiment 1 was replicated in both Experiment 2 and 3. In contrast to Experiment 1, contextual cueing was equally pronounced for all distractor color similarities in Experiment 2 and 3. In Experiment 2, when always four distractor orientations were used, contextual cueing was on a relatively low level and not modulated by variations in distractor color. Similarly in Experiment 3, when all distractors always had the same orientation, contextual cueing was on a relatively high level but again not modulated by variations in distractor color. Apparently in Experiment 2 implicit learning was on the same level as in the 4O condition of Experiment 1, while in Experiment 3 implicit learning was on the same level as in the 1O condition of Experiment 1 (see Figure 4 for a direct comparison). This observation was confirmed by pairwise t-tests across experiments: the mean RT advantage (new minus old contexts) across all epochs (1-6) was of equal size in the 1O condition of Experiment 1 (M = 33 ms) as in the 1C condition (M = 29 ms), p = .541, ε = 0.77, the 2C condition (M = 29 ms), p = .613, ε = 0.63 and the 4C condition (27 ms), p = .335, ε = 1.21, of Experiment 3. Similarly, the mean RT advantage was equally pronounced in the 4O condition of Experiment 1 (13 ms) as in the 1C condition (M = 15 ms), p = .740, ε = 0.42, the 2C condition (M = 10 ms), p = .811, ε = 0.30 and the 4C condition (11 ms), p = .820, ε = 0.29, of Experiment 2. Thus Experiment 2 and 3 showed that similarity among distractors has to be on a task-relevant dimension in order to result in enhanced contextual cueing. This is in accordance with the finding that implicit learning is limited to information on a task-relevant dimension (Jimenez & Mendez, 1999) and suggests that grouping principles that generally enhance search processes (Duncan & Humphreys, 1989) come only into play for memory encoding when they help structuring the visual field on a dimension that is currently relevant to identify the target.

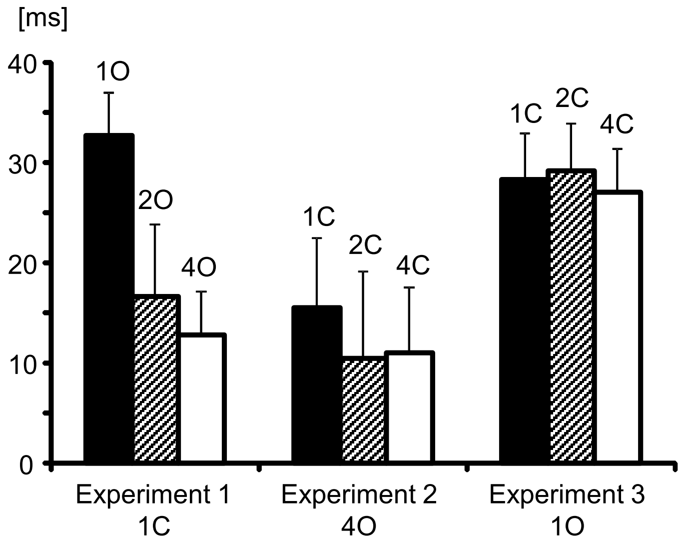

Fig. 3: Mean contextual cueing (RT new contexts minus RT old contexts) across all epochs, separately for each experiment and each distractor similarity. Blacks bars represent data from trials with highest distractor similarity (one orientation in Exp. 1 and one color in Exp. 2 & 3), black-striped bars represent data from trials with medium distractor similarity (two orientations in Exp. 1 and two colors in Exp. 2 & 3) and white bars represent data from trials with lowest distractor similarity (four orientations in Exp. 1 and four colors in Exp. 2 & 3). Error bars represent standard errors of the mean.

4. General Discussion

The present series of Experiments investigated how contextual cueing is affected by the similarity of distractors in a context configuration. The key finding was that contextual cueing is enhanced when stimuli are more similar, but only if similarity relates to the currently relevant dimension.

In three Experiments, participants had to find and report *orientation* of a target T. In Experiment 1, the target was embedded in a context configuration of distractors that varied on the same dimension as the target – distractor Ls had one, two or four *orientations*. Repeatedly presented context configurations accelerated search compared to novel context configurations, a manifestation of ‘contextual cueing’ (Chun & Jiang, 1998). Contextual cueing was most pronounced when distractors were highly similar, i.e. of one orientation only, and least pronounced when distractors were highly dissimilar, i.e. of four orientations. This cannot be due to more *explicit* learning since contexts could not be recognized as new or old in a recognition test after the experiment. [footnote 1]

In Experiment 2 and 3, distractor similarity did not vary on orientation; there were always all four orientations (Exp. 2) or only one orientation (Exp. 3) used. Instead, in Experiment 2 and 3 distractor similarity varied on a different dimension that was not task-relevant – distractor Ls had one, two or four *colors*. Both in Experiment 2 and 3 contextual cueing was evident but found to not be modulated by distractor similarity. In Experiment 2, contextual cueing was on a relatively low level comparable to the condition with four orientations in Experiment 1. In Experiment 3, contextual cueing was on a relatively high level comparable to the condition with one orientation in Experiment 1. The results thus indicate that not distractor similarity as such can improve implicit learning but the boost of contextual cueing may rather depend on the dimension on which distractors are similar to one another. Variations in distractor similarity only affect contextual cueing when similarity varies on the same dimension that is relevant for the task, i.e. orientation in a contextual cueing task.

4.1 Implicit learning of homogeneous contexts

Contextual cueing, was argued to be based on more efficient attention guidance as it was suggested that repeated exposure to invariant repeated contexts established implicitly learned associations of context configurations and target locations (Chun & Jiang, 1998; Ogawa, Takeda, & Kumada, 2007; Schankin & Schubö, 2009; Zhao et al., 2012). Regularities such as the spatial configuration or the structure in the visual field can be memorized, and on a later occasion it can be used to guide attention to a formerly relevant location.

In the present study more similar distractors did not only enhance implicit learning as evident in contextual cueing but also visual search as such. In all three Experiments, targets were found faster in context configurations with more similar distractors as revealed by a main effect of Similarity. This is a replication of earlier studies showing that that stimulus similarity is a crucial determinant of *visual search* (Desimone & Duncan, 1995; Schubö et al., 2004; Wolfe, 1994). According to the attentional engagement theory (Duncan & Humphreys, 1989, 1992; for neural evidence see Desimone and Duncan, 1995; Chelazzi, 1999) search efficiency increases with increasing similarity among distractors due to grouping processes that reduce the number of perceptual units that have to be searched and discarded until the target is found (Duncan & Humphreys, 1989; Schubö, Wykowska, & Müller, 2007; Wolfe, 1994). Perceptual grouping of elements into larger units happens at early stages of visual perception and does not require focal attention (Humphreys, 1998). As it is assumed to happen prior to deployment of attention it may determine what is attended (Li, 2002; Nothdurft, 1992; Schubö et al., 2011). How can the attentional engagement theory account for the findings of enhanced contextual cueing for more similar distractors in Experiment 1? Results from Experiment 1 suggest that contexts of more similar distractors are not only more efficiently processed during search but also more efficiently represented in memory thus resulting in enhanced contextual cueing when repeatedly presented. Thus one may speculate that pre-attentive grouping based on texture segmentation and Gestalt principles (Bacon & Egeth, 1991; Duncan & Humphreys, 1989, 1992; Nothdurft, 1992; Schubö et al., 2007) may also enhance transfer of representations of grouped stimuli into memory. This is in line with findings showing that learning is more efficient when visual spatial information could be grouped (Brady, Konkle, & Alvarez, 2009b; Gobet & Simon, 1996b; Luck & Vogel, 1997b; Woodman & Luck, 2003). Accordingly, in Experiment 1 the configuration of more similar distractors may have led to a more efficient memory representation because groups of distractors rather than single distractors could be stored, resulting in less required storage capacity. This seems to have been different in Experiment 2 and 3 when distractor similarity varied on the task-irrelevant dimension ‘color’. Here, the data suggest that more established memory representations of context configurations that accelerate visual search could not be obtained for more homogeneous context configurations (high color similarity). This constitutes a specific advantage for implicit learning of context configurations with high similarity on a task-relevant dimension. The limitation of similarity-induced enhanced contextual cueing to task-relevant dimensions is in accordance with previous findings from implicit learning observed in sequence learning tasks: implicit learning of associations between shape cues and upcoming responses was found to depend on the extent to which processing of the shape dimension was made task-relevant; shape cues only helped to accelerate search when shape was made task-relevant in a secondary task (Jimenez & Mendez, 1999). The present results extend these previous findings and suggest that efficiency of grouping processes depends on the task-relevant dimension. In our experiments, distractors were primarily grouped on the dimension that was currently relevant to observers. For instance distractors were identical on the task-relevant dimension *orientation* in the 1O condition in Experiment 1 and in all conditions of Experiment 3. According to the attentional engagement theory (Duncan & Humphreys, 1989), in these conditions orientation-identical distractors could be grouped to form one perceptual unit what may have resulted in the observed enhanced memory representation of such grouped elements. Contrarily in the 1C condition in Experiment 2 and 3 and in all conditions of Experiment 1, distractors were also identical on the task-irrelevant dimension *color*. Although the present results suggest that grouping has also occurred in these cases (main effect of similarity in Experiment 2 and 3), at least grouping did not contribute to enhanced memory representations since contextual cueing remained on a low level (no interaction of similarity and Novelty in Experiment 2 and 3). Presumably implicit learning is limited to visual information congruent to the task, i.e. orientation information in contextual cueing tasks.

4.2 Attention guidance by learned contexts through activations on a salience map

Visual attention theories often assume that deployment of focal attention is based upon a salience map that codes the visual field in a topographical manner by representing all stimuli in the visual field with a particular activation according to their physical distinctiveness from other stimuli (Itti & Koch, 2000; Li, 2002; Wolfe, 1994). This salience map receives input from different feature maps each representing a specific physical quality of the visual environment and sums up these values to determine the distinctiveness of the represented stimulus in a featureless manner (Itti & Koch, 2001). Contextual cueing was explained in terms of higher activation for the target location associated with a given context configuration (Geyer, Zehetleitner & Müller, 2010). Accordingly, during visual processing activation on a salience map is compared with (implicitly) stored representations of context configurations in terms of previous activation patterns. If the current activation pattern matches a prior activation pattern, the target location associated with that activation pattern will received a higher pre-activation thus increasing the probability of attention allocation towards the cued location (Geyer et al., 2010). This seems a plausible assumption since it has been shown with a connectionist model that repetitive activation of a given pattern will increase activation for a target location constantly associated with that pattern (Brady & Chun, 2007). The present Experiment 1 found more pronounced contextual cueing for homogeneous than for heterogeneous contexts, suggesting that amplification of salience signals was more pronounced for representation of targets on the salience map for homogeneous than for heterogeneous context configurations. One may speculate that this was due to faster processing of homogeneous stimulus arrangements (Duncan & Humphreys, 1989) and hence faster computation of salience signals which resulted in earlier comparison of the current salience map activation with prior activation patterns as suggested by Geyer et al. (2010). However, the present Experiments 2 and 3 showed that more homogeneous contexts only resulted in enhanced contextual cueing when the context was homogeneous on a task-specific dimension. Since the salience map was conceptualized to receive prioritized input from feature maps representing currently relevant dimensions (Itti & Koch, 2001), one may argue that a match of the current activation pattern with a previous activation pattern is detected earlier in time due to prioritized access of relevant feature maps to representations of prior activation patterns. On the other hand it may be that that representations of homogeneous contexts in the 'contextual memory' (Geyer et al., 2010) are represented more efficiently thus allowing more reliable comparisons with current activations patterns. This is in line with the finding that contexts with larger set sizes that make the contexts less distinguishable and therefore more ambiguous yield smaller contextual cueing effects (Hodsoll & Humphreys, 2005) presumably because the comparison of prior and current contexts is hampered.

4.3 The benefits of implicit learning

Implicit learning, i.e. the unintentional and unconscious learning, may be beneficial because limited attentional resources can be efficiently deployed (Shanks, 2005). The type of implicit memory evident in contextual cueing is well-tuned to every-day life situations since the visual organization of our environment is often such that objects can be found on typical positions (e.g., a pot on a stove) within a complex scene (van Asselen, Sampaio, Pina, & Castelo-Branco, 2011). Since scene properties can be processed very fast and pre-attentively (Wolfe, Võ, Evans, & Greene, 2011), a memorized association of a given scene with relevant locations may result in an efficient way to guide attention. The fact that one does not have to be aware of the association may render the association even more powerful since retrieval from implicitly learned memory content is usually accelerated (Shanks, 2005) and it allows more information to be acquired compared to explicit learning (Lewicki, Hill, & Bizot, 1988).

The present findings suggest that implicit learning mechanisms can be boosted by very basic physical properties such as stimulus similarity. Since grouping according to gestalt principles such as similarity was found to happen pre-attentively (Humphreys, 1998) it may determine what is attended (Li, 2002; Nothdurft, 1992; Schubö et al., 2011), but also what is represented in memory. As such, pre-attentive processes may be generally more likely to affect implicit learning.

4.4 Conclusions

The present study investigated the impact of distractor similarity and repetition of distractor configurations on visual search for an embedded target. Faster search for a target in repeatedly presented contexts compared to novel context configurations was found throughout all experiments without observers being aware of the repetition. This indicates implicit learning of contexts that serve as a spatial cue for the target location and is a replication of an effect referred to as contextual cueing (Chun & Jiang, 1998). Further, in all experiments more homogeneous context configurations yielded shorter RTs than less homogeneous context configurations, for both orientation (Experiment 1) and color (Experiment 2 and 3), a replication of earlier findings (e.g., Duncan & Humphreys, 1989).

The novel and central finding of the present study was that contextual cueing depended on the similarity among distractors. Context configurations of more similar distractors boosted contextual cueing compared to context configurations of less similar distractors. However, this was only true when distractor similarity varied on the task-relevant dimension orientation (Experiment 1), but not when distractor similarity varied on the task-irrelevant color dimension (Experiment 2 and 3). The present study thus extends previous research showing that distractor similarity enhances visual search by the finding that distractor similarity also enhances implicit learning as evident in contextual cueing.

Footnote 1

As there was no three-way interaction of Distractor similarity, Novelty and Epoch, one may argue that contextual cueing was not affected by distractor similarity. The two-way interaction of Distractor similarity and Novelty indicates a boost of the RT advantage of old over new contexts by more similar distractors. The lacking three-way interaction may in turn be interpreted as a constant boost throughout the experiment rather than an increasing boost over time. That is, although contextual cueing becomes more pronounced towards the end of the experiment, distractor similarity modulates contextual cueing from the very beginning and may be an additive, stable effect on top of contextual cueing.

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Affidavit (Eidesstattliche Versicherung)

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation „The role of context homogeneity in the deployment of visual attention“ selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

I hereby confirm that this dissertation is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

Marburg/ Munich, 14th Nov 2013

(Dipl.-Psych. Tobias Feldmann-Wüstefeld)

Authors contributions to each publication

“Textures shape the attentional focus: Evidence from exogenous and endogenous cueing.” (Study I)
TFW and AS conceived and designed the research. TFW performed research and conducted data analyses. TFW and AS discussed results and wrote the manuscript.

“Context heterogeneity has a sustained impact on attention deployment: Behavioral and electrophysiological evidence.” (Study II)
TFW, AW and AS conceived and designed the research. TFW performed research. TFW and AW conducted data analyses. TFW, AW and AS discussed the results. TFW and AS wrote the manuscript.

“Context homogeneity facilitates both distractor inhibition and target enhancement.” (Study III)
TFW and AS conceived and designed the research. TFW performed research and conducted data analyses. TFW and AS discussed results and wrote the manuscript.

“Stimulus homogeneity enhances implicit learning: Evidence from contextual cueing” (Study IV)
TFW and AS conceived and designed the research. TFW performed research and conducted data analyses. TFW and AS discussed results and wrote the manuscript.

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(Dipl.-Psych. Tobias Feldmann-Wüstefeld) (Prof. Dr. Anna Schubö)