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Stimulus homogeneity enhances implicit learning: Evidence from contextual cueing

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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 (color) 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.

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. color or orientation) or a combination of such features. In their *attentional engagement theory*, Duncan and Humphreys (1989, 1992) emphasize the crucial role of distractor homogeneity 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 group which is subsequently processed as one single structural unit. Increasing the homogeneity of distractors increases search efficiency, because homogeneous elements are being grouped more easily, and grouping reduces the number of perceptual units that have to be searched subsequently in order to find the target. 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 homogeneous 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 et al., 2011).

In addition to stimulus homogeneity, prior knowledge was demonstrated to be a mechanism that is capable of guiding attention. In a seminal study by Chun and Jiang (1998) participants had to search for a T letter in a context of distracting L letters of

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different orientation. While in one half of the trials, context configurations were randomly generated and thus novel to observers, in the other half of the trials, context configurations were 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 & Nakayama, 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 homogeneity

While the role of stimulus homogeneity for visual search has been demonstrated numerous times (Donk & Soesman, 2011; Duncan & Humphreys, 1989, 1992; Feldmann-Wüstefeld & Schubö, 2013; Schubö, Wykowska, & Müller, 2007), its role for contextual cueing has received far less interest (e.g., Rausei, Makovski, & Jiang, 2007). The present study investigates whether stimulus homogeneity can influence contextual cueing as well as visual search. Since changing the homogeneity of stimuli a context configuration comprises does not affect the spatial layout, a prerequisite of stimulus homogeneity 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 Chun and 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 homogeneity plays a role *during acquisition* of the internal representation of a context configuration.

In particular, distractor homogeneity 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 because it belongs to one objects (Luck & Vogel, 1997; Woodman, Vecera, & Luck, 2003), or because expert knowledge in chess allows coding of several stimuli as integrated chunks (Gobet & Simon, 1996). For example, Luck and Vogel (1997) presented observers with arrays of bars with different colors, orientations and with or without discontinuities and observers had to perform a change detection task, i.e., they had to indicate whether one of the items changed from display to display. When observers were required to store one feature in visual working memory (e.g., color), performance was basically identical to when observers had to store a conjunction of all three features (e.g., color, orientation, and gap/no gap). This suggests that the features are grouped to one object that is then efficiently kept in visual working memory. These examples from change detection tasks show that processing of integrated information can enhance short-term memory processes such as visual-working memory. Also long-term memory enhancement was found due to grouping of stimuli: the presence of statistical regularities and associations among stimuli that were unknown to the observers were found to increase the memory capacity for features to be remembered when stimuli were in close proximity: when throughout the experiment some color pairs were more likely to appear than other color pairs, observers remembered more items from these displays than from displays where the colors were paired randomly (Brady, Konkle, & Alvarez, 2009). We speculate that increased stimulus homogeneity increases contextual cueing due to a related mechanism: context configurations of more homogeneous 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 homogeneous stimuli that serve as a more efficient spatial cue to deploy attention to the associated target location. In contextual cueing paradigms, the beneficial search performance due to previous implicit learning is related to long-term-memory. Thus enhanced contextual cueing for homogeneous contexts would indicate that grouping does not only affect visual working memory, but also more sustained memory processes.

1.2. Rationale of the present study

In the present series of experiments we varied the homogeneity of distractors in various ways which allows investigating the impact of stimulus homogeneity on contextual cueing. To our knowledge, this has not been investigated so far which may appear surprising since the stimuli used by Duncan and Humphreys (1989) are particularly similar to the ones usually used in contextual cueing experiments (Chun & Nakayama, 2000; Kunar & Flusberg, 2006; Schankin & Schubö, 2009; Zellin et al., 2011).

In Experiment 1 we varied the distractor homogeneity by using Ls of one, two or four orientations. This is similar to Duncan and 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 homogeneity. The low-homogeneity condition (four L orientations) was similar to classical contextual cueing experiments in which distractors were usually of four orientations (Chun & Jiang, 1998; Kunar & Flusberg, 2006). 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 that the classical contextual cueing effect (reduced RTs for repeated context configurations) would be replicated in all conditions. Further, since distractor homogeneity allows grouping and hence processing of fewer perceptual units, we predicted to replicate the classical homogeneity effect, i.e. reduced RTs for more homogeneous distractors. Most importantly, we hypothesized that internal representations of context configurations with more homogeneous 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 homogeneity enhances contextual cueing, i.e. the accelerated search for a target in repeatedly presented context configurations is more pronounced if the context comprises more homogeneous 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° × 1.2°). Distractors and target were white (HSV: 0, 0, 100) presented on a gray (0, 0, 50) background. Search displays always consisted of 13 distractors and 1 target, distributed on an imaginary matrix of 10 × 7 cells (21° × 14.5°). 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. Homogeneity 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. 1 (upper row) shows sample displays.

2.1.3. Trial sequence

A trial began with a fixation dot presented for 500 ms at the center of the screen followed by the search display that was visible for 700 ms (for similar exposure durations see Schankin & Schubö, 2009). The search display was replaced by a blank grey (0, 0, 50) 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.

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 homogeneity 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 × 3 × 18 within-subjects design with the

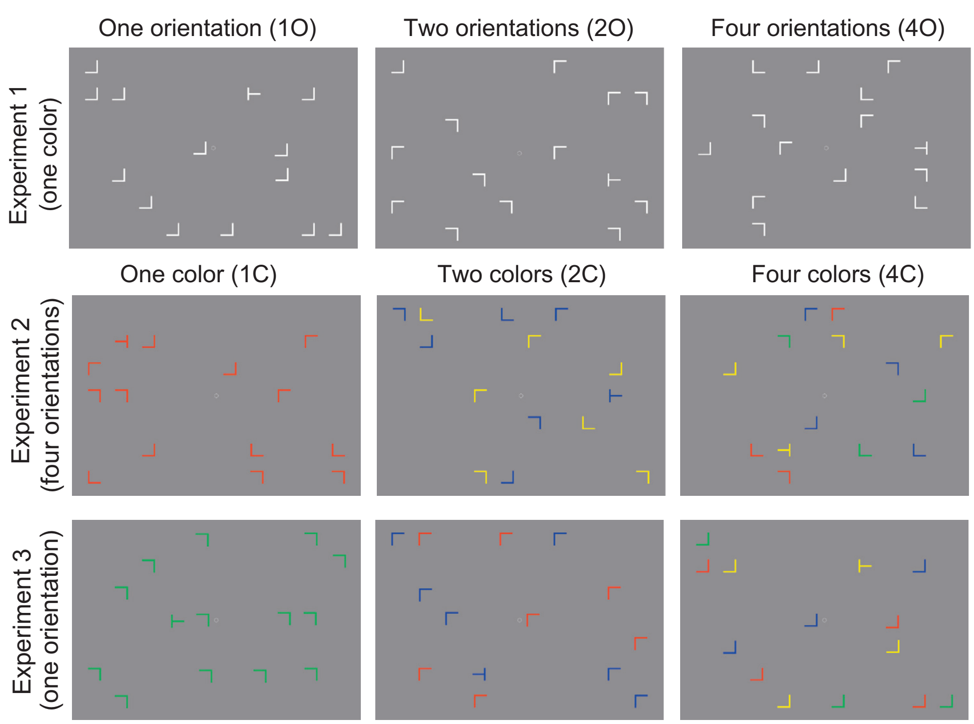

Fig. 1. Example search displays as used in Experiment 1 (upper row), Experiment 2 (middle row) and Experiment 3 (lower row). All contexts consisted of 13 Ls and one T that were distributed on a 10 × 7 matrix. Participants were instructed to indicate the orientation of the target letter T (left vs. right). 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; left column), two (2C; middle column) four (4C; right column) different colors.

factors Context novelty (new vs. old), Distractor homogeneity (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

2.2.1. Response times

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 homogeneity (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 increasing homogeneity (M_{4O} = 657 ms vs. M_{2O} = 638 ms vs. M_{1O} = 613 ms), $F(2,38) = 40.85$, $p < .001$, $\eta^2 = .68$, and with epoch (M_{epoch1} = 695 ms vs. M_{epoch6} = 611 ms), $F(5,95) = 41.71$, $p < .001$, $\eta^2 = .69$. Response times in new contexts was generally slower than in old contexts (M_{new} = 646 ms vs. M_{old} = 626 ms), $F(1,19) = 27.94$, $p < .001$, $\eta^2 = .60$. 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), $F(5,95) = 2.96$, $p = .030$, $\eta^2 = .14$. 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), $F(2,38) = 5.26$, $p = .020$, $\eta^2 = .22$. No other effects were significant (all $p > .696$). Fig. 2 (upper row) visualizes mean RT for old vs. new contexts as a function of epoch with individual plots for each of the homogeneity conditions.

2.2.2. Accuracy

Overall accuracy was 90.3%. A repeated ANOVA with the factors Homogeneity, Novelty, and Epochs revealed that Accuracy increased with distractor homogeneity (M_{1O} = 92.8% vs. M_{2O} = 89.8% ms vs. M_{4O} = 88.2% ms), $F(2,38) = 47.95$, $p < .001$, $\eta^2 = .72$ and with epoch (M_{epoch1} = 85.6% vs. M_{epoch6} = 92.6%), $F(5,95) = 22.08$, $p < .001$, $\eta^2 = .54$. Accuracy in new contexts was generally worse than in old contexts (M_{new} = 87.8% vs. M_{old} = 92.7%), $F(1,19) = 29.06$, $p < .001$, $\eta^2 = .61$. There were no other significant effects, all $p > .243$.

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 & Flusberg, 2006; Schankin & Schubö, 2009). Further, Experiment 1 showed that more homogeneous context configurations accelerate visual search for an embedded target, a replication of the distractor homogeneity effect (Duncan & Humphreys, 1989). Importantly, the present results showed that contextual cueing was more pronounced when contexts were homogeneous: 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 homogeneity previously found in visual search tasks were argued to be based on efficient pre-attentive grouping that allowed subjects to process larger structural units (Bacon & Egeth,

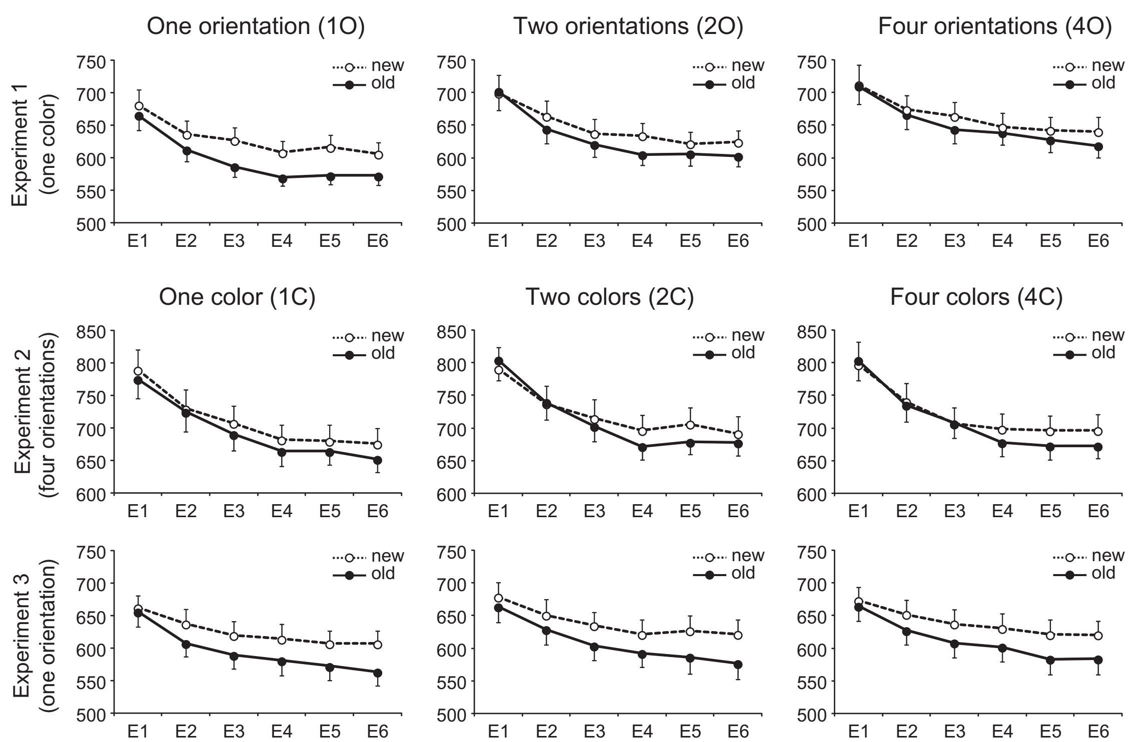

Fig. 2. Mean (±SEM) reaction times as a function of Epoch (1–6, each pooled across three successive blocks) and Novelty (new vs. old). The upper row shows results for Exp. 1 where all Ls were white and distractor homogeneity varied on orientation and the middle row shows results for Exp. 2 where Ls had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

1991; Duncan & Humphreys, 1989, 1992; Nothdurft, 1992; Schubö, Wykowska, & Müller, 2007). The present results suggest that homogeneity 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, Konkle, & Alvarez, 2009; Gobet & Simon, 1996; Luck & Vogel, 1997; Woodman, Vecera, & Luck, 2003). For example, Gobet and Simon (1996) presented observers with pictures of chess boards with several chess pieces in it and observers had to keep the configuration in memory for short intervals. The authors showed that chess experts can store chunks of chess pieces in memory, increasing the memory capacity compared to novices that store single chess pieces in memory. Brady, Konkle, and Alvarez (2009) used simple geometric shapes (colored circles) which were grouped by proximity. If nearby circles showed statistical regularities, e.g., two colors were more often presented next to each other than others, observers were more likely to remember items than when two colors were randomly paired. Luck and Vogel (1997) also used simple geometric shapes (e.g., arrays of bars with different colors and orientations) in a change detection task. They showed that conjunctions of features from different dimensions (e.g., color and orientation) can be stored in visual working memory as efficiently as single features, suggesting chunks of features rather than individual features were stored in memory. While these examples show that grouping due to expertise in a visual domain, statistical regularities and proximity/integration to one object can improve memory organization, the present results extend these findings and show that stimulus homogeneity can enhance memory representations, presumably due to grouping processes. Since contextual cueing is related to long-term memory processes, the present results further show that, besides visual working-memory, more sustained aspects of memory processes can be affected by stimulus homogeneity.

In Experiment 1, the homogeneity 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 . The relation of sequence or shape and target location was unknown to the observers. Nevertheless, observers implicitly learned the association which helped them to more efficiently perform the search task: while the sequence itself was always increasing response speed, shape cues only helped to further accelerate search when shape was made explicitly 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 homogeneous 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 homogeneity 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 homogeneity 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 homogeneity 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 homogeneity. Conversely, if Experiment 2 and Experiment 3 yielded similar variations in contextual cueing as were observed in Experiment 1, this would suggest that implicit learning is much broader and contexts are more thoroughly processed; as a result homogeneity 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 homogeneity were realized by coloring distractors in one (1C), two (2C) or four (4C) colors within a context. In the 4C conditions, distractor colors were equally distributed in both hemifields (e.g., one quarter red, blue, green and yellow distractors for both the left and right hemifield). In the 2C condition, each of the six combinations of distractor colors was used equally often and within one context, distractor colors were equally distributed in both hemifields. In the 1C condition, each of the four colors was used equally often to color the distractors. Target color was chosen randomly from one of the 1, 2 or 4 colors used in a specific context and, for repeatedly presented contexts, then fixed throughout the experiment. In the 4C (2C) color condition, the four (two) possible target colors were equally often used in each homogeneity condition, both for old and new contexts (i.e., three (six) old contexts for each color and each homogeneity condition). Also distractor color and distractor orientation were fixed throughout the experiment. Colors were red (HSV: 0, 100, 100), yellow (60, 100, 100), green (120, 100, 0) and blue (240, 100, 100). For a sample search display, see Fig. 2 (middle and lower row).

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

3.2.1.1. Response times. RTs were analyzed analogously to Experiment 1. RT decreased with increasing distractor homogeneity

(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 $p > .782$).

3.2.1.2. Accuracy. Overall accuracy was 86.9%. A repeated ANOVA with the factors homogeneity, Novelty, and Epochs revealed that Accuracy increased with epoch (M_{epoch1} = 80.2% vs. M_{epoch6} = 89.8%), $F(5,95) = 18.31$, $p < .001$, $\eta^2 = .49$. Accuracy in new contexts was generally worse than in old contexts (M_{new} = 86.2% vs. M_{old} = 87.5%), $F(1,19) = 8.70$, $p = .008$, $\eta^2 = .31$. Accuracy was not modulated by distractor homogeneity (M_{4C} = 87.6% vs. M_{2C} = 86.2% vs. M_{1C} = 86.7%), $p = .178$. There were no other significant effects, all $p > .278$.

3.2.2. Experiment 3

3.2.2.1. Response times. RTs were analyzed analogously to Experiment 1 and 2. RT decreased with increasing distractor homogeneity (M_{4C} = 623 ms vs. M_{2C} = 622 ms vs. M_{1C} = 608 ms), $F(2,38) = 12.14$, $p < .001$, $\eta^2 = .39$, and with epoch (M_{epoch1} = 662 ms vs. M_{epoch6} = 595 ms), $F(5,95) = 34.00$, $p < .001$, $\eta^2 = .64$. Responses in new contexts were generally slower than in old contexts (M_{new} = 632 vs. M_{old} = 603), $F(1,19) = 64.23$, $p < .001$, $\eta^2 = .77$. 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), $F(8,152) = 5.91$, $p < .001$, $\eta^2 = .24$. No other effects were significant (all $p > .709$).

3.2.2.2. Accuracy. Overall accuracy was 89.7%. A repeated ANOVA with the factors Homogeneity, Novelty, and Epochs revealed that Accuracy increased with distractor homogeneity (M_{4O} = 89.8% ms vs. M_{2O} = 88.9% ms vs. M_{1O} = 90.5%), $F(2,38) = 3.23$, $p = .05$, $\eta^2 = .15$ and with epoch (M_{epoch1} = 87.1% vs. M_{epoch6} = 89.8%), $F(5,95) = 5.05$, $p < .001$, $\eta^2 = .21$. Accuracy in new contexts was generally worse than in old contexts (M_{new} = 89.0% vs. M_{old} = 90.4%), $F(1,19) = 14.09$, $p = .001$, $\eta^2 = .43$. There were no other significant effects, all $p > .125$.

3.2.3. 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 toward new or old contexts (*C*; Macmillan & Creelman, 1991). In Experiment 1, *d*-prime values (M_{1O} = 0.08 vs. M_{2O} = 0.06 vs. M_{4O} = 0.05), $F(2,38) = 0.01$, $p = 0.994$, $\eta^2 < .01$ and *C* values (M_{1O} = 0.04 vs. M_{2O} = 0.09 vs. M_{4O} = 0.06), $F(2,38) = 0.04$, $p = 0.962$, $\eta^2 < .01$, were comparable for all homogeneity conditions. Neither mean accuracy nor *d*-prime nor *C* depended on context homogeneity (all $p > .393$). Further, no *d*-prime or *C* value was significantly different from 0 as revealed by repeated *t*-tests for one sample (all $p > .430$). In Experiment 2, *d*-primes values (M_{1O} = 0.04 vs. M_{2O} = 0.12 vs. M_{4O} = 0.07), $F(2,38) = 0.10$, $p = 0.909$, $\eta^2 = .01$ and *C* values (M_{1O} = 0.21 vs. M_{2O} = 0.12 vs. M_{4O} = −0.06), $F(2,38) = 2.05$, $p = 0.143$, $\eta^2 = .10$, were comparable for all homogeneity conditions. The *C* value for contexts with one orientation distractor (1O) was significantly different from 0 ($p = .030$), indicating a tendency to label contexts as new in this condition. All other *C* values and *d*-prime values were not significantly different from 0 (all $p > .166$). In Experiment 3, *d*-primes values (M_{1O} = 0.07 vs. M_{2O} = 0.01 vs. M_{4O} = 0.004), $F(2,38) = 0.33$, $p = 0.719$, $\eta^2 = .02$ and *C* values (M_{1O} = 0.03 vs. M_{2O} = −0.09 vs. M_{4O} = −0.08), $F(2,38) = 0.05$, $p = 0.950$, $\eta^2 < .01$, were comparable for all homogeneity conditions. Further, no *d*-prime or *C* value was significantly different from 0 as revealed by repeated *t*-tests for one sample (all $p > .409$).

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 homogeneities 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 Fig. 3 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), $p = .541$, $\varepsilon = 0.77$, the 2C condition (M = 29 ms), $p = .613$, $\varepsilon = 0.63$ and the 4C condition (27 ms), $p = .335$, $\varepsilon = 1.21$, 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), $p = .740$, $\varepsilon = 0.42$, the 2C condition (M = 10 ms), $p = .811$, $\varepsilon = 0.30$ and the 4C condition (11 ms), $p = .820$, $\varepsilon = 0.29$, of Experiment 2. Thus Experiment 2 and 3 showed that homogeneity 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

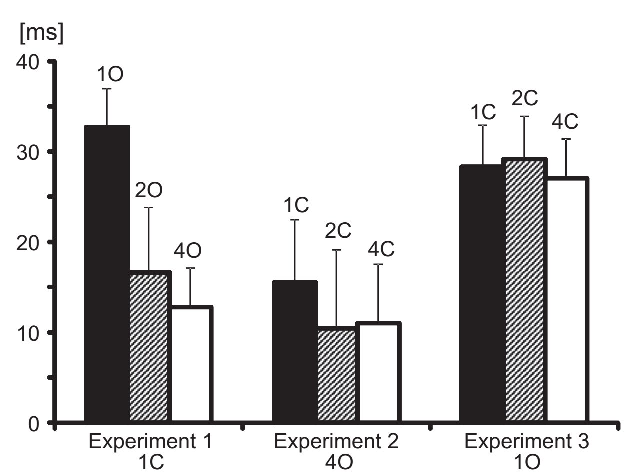

Fig. 3. Mean contextual cueing (RT new contexts minus RT old contexts) across all epochs, separately for each experiment and each distractor homogeneity. Blacks bars represent data from trials with highest distractor homogeneity (one orientation in Exp. 1 and one color in Exp. 2 and 3), black-striped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

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.

4. General discussion

The present series of Experiments investigated how contextual cueing is affected by the distractor homogeneity in a context configuration. The key finding was that contextual cueing is enhanced when stimuli are more homogeneous, but only if homogeneity 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 homogeneous, i.e. of one orientation only, and least pronounced when distractors were highly heterogeneous, 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.

In Experiment 2 and 3, distractor homogeneity 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 homogeneity 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 homogeneity. 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 do not indicate that distractor homogeneity as such can improve implicit learning but that the boost of contextual cueing may rather depend on the dimension on which distractors are homogeneous. Variations in distractor homogeneity only affect contextual cueing when homogeneity 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. For example, it was suggested that repeated exposure to invariant repeated contexts establishes 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 homogeneous 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 homogeneous distractors as revealed by a main effect of homogeneity. This is a replication of earlier studies showing that that stimulus homogeneity is a crucial determinant of *visual search* (Desimone & Duncan, 1995; Schubö, Schröger, & Meinecke, 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 homogeneity 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 homogeneous distractors in Experiment 1? Results from Experiment 1 suggest that contexts of more homogeneous 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, Wykowska, & Müller, 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, 2009; Gobet & Simon, 1996; Luck & Vogel, 1997; Woodman & Luck, 2003). Accordingly, in Experiment 1 the configuration of more homogeneous 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 homogeneity 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 homogeneity). This constitutes a specific advantage for implicit learning of context configurations with high homogeneity on a task-relevant dimension.

One may object that the more pronounced contextual cueing in homogeneous contexts was partially due to a higher overall accuracy: in fact search accuracy was 4.6% higher in the high-homogeneity (1O) condition than in the low-homogeneity (4O) condition (4.1% in old contexts). In some of the incorrect trials the target may have been missed, e.g. the target was not found during the limited exposure duration of 700 ms. Target misses may have resulted in fewer opportunities for acquiring contextual cueing because in trials in which a target was missed, the association of target and context was not further strengthened. Thus, differences in contextual cueing between high- and low-homogeneity displays may have been a consequence of differences in search difficulty. However, it should be noted that in some of the incorrect response trials, the target may have well been found and the erroneous answer may have been due to response errors or misperception of the target orientation. These trials should also have contributed to acquirement of contextual cueing. Besides, it seems unlikely that 4.1% more successful searches for the T made acquiring contextual cueing more efficient. Moreover, in Experiment 2, where a similar difference in accuracy had been observed, no difference in contextual cueing was found. This argues against an explanation in terms of search difficulty as a potential confound, although this possibility cannot be entirely rejected.

Since grouping was not directly manipulated in the present series of experiments, other accounts why contextual cueing in homogeneous contexts was enhanced may apply. For example, it may be possible that homogeneous contexts are less ambiguous than heterogeneous contexts and thus target locations can be derived from contexts more validly. Besides it may be possible that homogeneous contexts are processed faster and an (implicit) match with previous contexts, allowing conclusions about the likely target location, is possible earlier in time. Future research could directly manipulate whether grouping is necessary or not, for example with simple line arrangements similar to those used in texture segmentation tasks (e.g., Nothdurft, 1991) and then compare the extent of contextual cueing.

The limitation of homogeneity-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 processing homogeneous stimuli depends on the task-relevant dimension. In our experiments, distractor processing benefitted primarily from distractors being homogeneous 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 processed as one perceptual unit that may have resulted in the observed enhanced memory representation of such 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 more efficient processing of distractors has also occurred in these cases (main effect of homogeneity in Experiment 2 and 3), at least this homogeneity advantage did not contribute to enhanced memory representations since contextual cueing remained on a low level (no interaction of homogeneity 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 receive a higher pre-activation thus increasing the probability of attention allocation toward 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 representations 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 et al., 2011). Since scene properties can be processed very fast and pre-attentively (Wolfe et al., 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 homogeneity. Since grouping according to gestalt principles such as homogeneity 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.

5. Conclusions

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

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