VISUAL COGNITION, 2011, 19 (2), 203–233

Psychology Press
Taylor & Francis Group

Limitations of perceptual segmentation on contextual cueing in visual search

Markus Conci[1] and Adrian von Mühlenen[2]

[1]Department Psychologie, Ludwig-Maximilians Universität München, München, Germany
[2]Department of Psychology, University of Warwick, Warwick, UK

In visual search, detection of a target in a repeated layout is faster than search within a novel arrangement, demonstrating that contextual invariances can implicitly guide attention to the target location ("contextual cueing"; Chun & Jiang, 1998). Here, we investigated how display segmentation processes influence contextual cueing. Seven experiments showed that grouping by colour and by size can considerably reduce contextual cueing. However, selectively attending to a relevant subgroup of items (that contains the target) preserved context-based learning effects. Finally, the reduction of contextual cueing by means of grouping affected both the latent learning and the recall of display layouts. In sum, all experiments show an influence of grouping on contextual cueing. This influence is larger for variations of spatial (as compared to surface) features and is consistent with the view that learning of contextual relations critically interferes with processes that segment a display into segregated groups of items.

Keywords: Contextual cueing; Implicit learning; Perceptual grouping; Visual search.

Complex, natural environments require the visual system to focus only on goal-relevant aspects of a scene while suppressing irrelevant information. Therefore, attention is concerned with selecting only a subset of significant

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Please address all correspondence to Markus Conci, Allgemeine und Experimentelle Psychologie, Department Psychologie, Ludwig-Maximilians Universität, Leopoldstr. 13, D-80802 München, Germany. E-mail: conci@psy.uni-muenchen.de

This work was supported by Deutsche Forschungsgemeinschaft (DFG) Research Group (FOR 480) and CoTeSys Excellence Cluster (142) grants. We thank Barbara Neumayer, Philipp Schiebler, Luning Sun, and Sonja Riegert for their help with data collection, and Jay Pratt, Thomas Geyer, and two anonymous reviewers for valuable comments on an earlier draft of the manuscript.

http://www.psypress.com/viscog DOI: 10.1080/13506285.2010.518574

objects from the multiple, available input. However, the detailed and rich mosaic of objects in natural environments is not simply information that requires to be filtered and segregated from prioritized subsets. Rather, seemingly irrelevant details can substantially support selection, given that objects are typically perceived within specific scenes and contexts (see Bar, 2004; Henderson & Hollingworth, 1999, for reviews). Thus, invariant relations between objects can offer powerful cues, such that consistent mappings between objects and their respective contexts facilitate performance (i.e., Palmer, 1975).

In fact, visual covariation has been shown to support the recognition of objects in complex displays (see Chun, 2000; Chun & Nakayama, 2000, for reviews). For example, Chun and Jiang (1998) showed that observers can learn the spatial relations between search items and use this in subsequent trials to guide attention more efficiently to the target. In their contextual-cueing experiment, the presented search arrays consisted of one target T and 11 nontarget Ls (see Figure 1A for an example of a comparable display). Displays differed in that targets could either appear in an "old" or "new" configuration: For old configurations, the target was always presented within the same arrangement of nontargets. These were compared to new configurations that always presented novel nontarget arrangements on each trial. Consequently, the difference between old and new configurations indicates whether there is an influence of invariant spatial layouts (i.e., layouts that are repeated over and over again) on the difficulty of target detection. The results showed that the repetition of the spatial arrangement of a given old configuration leads to a benefit in the mean reaction time (RT), as compared to when the spatial layout was new (the contextual-cueing effect) even though observers were not able to explicitly discern repeated displays from novel arrangements. Consequently, Chun and Jiang interpreted their findings as evidence for a mechanism that implicitly encodes the spatial associations between display items. Contextual cueing was interpreted as being the result of associations formed between the spatial locations of the nontarget items and the target location. As a result of these learned associations, search performance was facilitated with repeated presentation.

Although contextual cueing facilitates search on the basis of contextual invariances, it has been shown to be highly susceptible to spatial interference. For instance, contextual cueing was reduced when a learned contextual layout was combined with a set of randomly distributed search items close to the target location (Olson & Chun, 2002; Song & Jiang, 2005). This finding suggests that contextual cueing is primarily driven by a (local) set of about three associative links between the target location and the surrounding nontargets (see also Brady & Chun, 2007, for a computational model). Despite of these local cues, the global configural layout has also shown to be a somewhat smaller source for context-based learning (Brockmole,

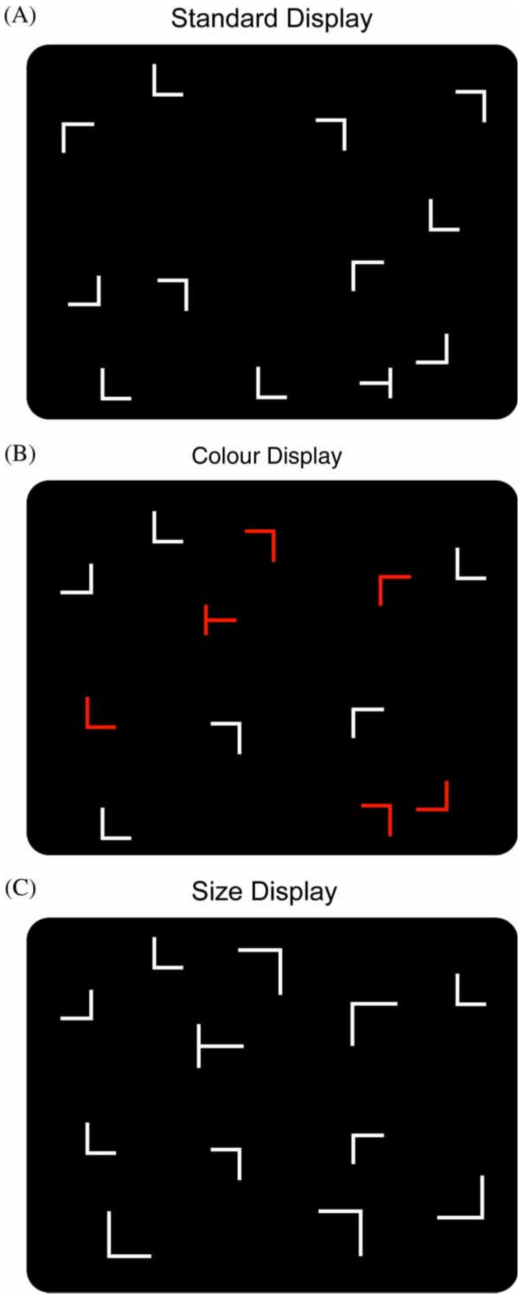

Figure 1. Examples of the standard (A), colour (B), and size (C) search displays. To view this figure in colour, please see the online issue of the Journal.

Castelhano, & Henderson, 2006; Jiang & Wagner, 2004; but see Kunar, Flusberg, & Wolfe, 2006). Thus, both local spatial associations and global configural cues determine contextual cueing.

Interference with contextual cueing not only occurs for displays that contain randomly distributed (i.e., nonpredictive) search items but also when the display contains a salient, segmented region (Conci & von Mühlenen, 2009). For instance, when four nontarget Ls were arranged such that they formed a square grouping, contextual cueing did not show a benefit for old display layouts (even though the square was in a given display always at the same location—and thus predictive of the target location). Subsequent experiments demonstrated that this effect occurred for several types of regular groups (e.g., closed squares, or symmetrically arranged cross-shapes). One potential interpretation to account for such interference in contextual cueing by means of the segmented shapes would be that grouping essentially reduced the number of informative cues that would allow to efficiently predict the target location. Thus, learning the relations between a set of four grouped items is less informative than learning a set of four spatially distributed items, and this, in turn, effectively reduced context-based guidance in search.

The current study aimed at exploring the relation between perceptual grouping and context-based learning in further detail. In our previous study (Conci & von Mühlenen, 2009), grouping was always locally applied to a set of four adjacent nontargets, arranged such that these formed a coherent region. Here, we employed a form of "subset search" (e.g., Friedman-Hill & Wolfe, 1995) in which the entire display was segmented on the basis of similarities between items (defined either by colour, or by size), and the target could be randomly assigned to one or the other of the two groups. For example, in Experiment 1, "colour" displays were presented that contained six grey and six red search items, leading to two segmented groups of items by means of colour (see Figure 1B, for an example). These "grouped" displays were compared to randomly generated displays (of uniform colour, i.e., without a specific grouping principle) similar to the ones used in previous studies (e.g., Chun & Jiang, 1998; Lleras & von Mühlenen, 2004). The randomly generated, "standard" displays served as a baseline measure (see Figure 1A, for an example). On the basis of our previous results (Conci & von Mühlenen, 2009), we hypothesized that grouping would interfere with contextual cueing. Thus, if a display consisted of two segmented clusters, then contextual cueing should be reduced because the potential variability of the contextual cues is reduced by means of the similarity-based segmentation of the two search subsets. Alternatively, no reduction of contextual cueing should be observable if interference arises locally, such that only close, regional clusters interfere with context-based learning.

To anticipate, Experiment 1 confirmed our hypothesis that grouping by colour reduces contextual cueing. In addition, Experiment 2 showed that grouping by size interferes even more with contextual cueing. Moreover, Experiment 3 rules out that this reduction is simply reflecting a search bias towards the group that is more likely to contain the target. The subsequent two experiments show that contextual cueing is preserved when participants focus on the target-relevant group, either on the basis of top-down knowledge (Experiment 4) or by means of bottom-up saliency (Experiment 5). Finally, Experiments 6 and 7 show that the interference by size-based groupings affects both learning and its subsequent retrieval in contextual cueing, suggesting that grouping severely disturbs both the acquisition and the expression of contextual cueing.

EXPERIMENT 1

Experiment 1 was performed to investigate the effects of grouping by colour on the encoding of spatial context in visual search. We compared how memory-based attentional guidance varies for standard and colour displays (see Figure 1A and 1B). The standard displays consisted of only grey search items. By contrast, in the colour displays, half of the items were grey and the other half red, thus allowing colour-based grouping processes to segment the display into subsets of items.

Methods

Participants. Fourteen observers (one male; mean age = 34.9 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credits or payment of 8 Euros.

Apparatus and stimuli. The experiment was conducted with an IBM PC-compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli subtended $0.7^\circ \times 0.7^\circ$ and were presented in grey (8.5 cd/m^2) or red (6.9 cd/m^2) against a black (0.02 cd/m^2) background on a 17-inch monitor screen. Stimulus colours were subjectively matched in terms of luminance by the experimenter. Search displays always consisted of 12 items, one target, and 11 nontargets. The target was a T shape rotated 90° either to the left or to the right. Nontargets were L shapes rotated randomly in one of four orthogonal orientations. Search displays were generated by placing one T and 11 L's randomly within the cells of an 8×6 Matrix (cell size 2.5°). Within each cell, the stimuli were randomly jittered horizontally and vertically in steps of 0.1° within a range of $\pm 0.6^\circ$. Two types of displays were generated: In *standard* displays, all stimuli were presented in grey, and in *colour* displays, six of the 12 display items were randomly chosen and presented in red, and the remaining six items were presented in grey. This means, the target could be either red or grey. Example displays are shown in Figure 1A and 1B.

Trial sequence. Each trial started with the presentation of a central fixation cross for 500 ms. The fixation cross was followed by the search display, to which observers responded with a speeded response via mouse keys. The task was to search for an oriented T among Ls and to decide as quickly and accurately as possible whether the T was oriented to the left or to the right. Displays remained on-screen until a response was recorded. In case of an erroneous response, feedback was provided by an alerting sign ("–") presented for 1000 ms at the centre of the screen. Each trial was separated from the next by an interval of 1000 ms.

Design and procedure. A three-factor within-subjects design was used. The independent variables were context, display type, and epoch. Context had two levels, old and new. For the old context condition, the arrangement of nontarget items was the same on every presentation. In the new context condition, a new, random arrangement of nontarget items was generated on every presentation. To rule out location probability effects, the target appeared equally often in each of 24 possible locations throughout the experiment. The orientation of the target was determined randomly for each trial, whereas the orientations of the nontarget items were preserved for the old context condition. The second variable, display type, also had two levels, standard and colour. Standard displays presented stimuli in grey while colour displays were presented with six red stimuli and six grey stimuli chosen randomly. Note that the assignment of the colours was preserved for old context conditions. Finally, the third variable, epoch, simply divided the experiment into six subsequent bins, allowing the assessment of possible learning effects over the course of the experiment.

At the beginning of the experiment, participants completed one block of 24 practice trials generated randomly to familiarize them with the task. All subsequent experimental blocks contained the same 12 old displays and a set of 12 newly generated displays in randomized order. For each block, half (i.e., six) of the old displays were standard displays and the other half (i.e., the other six) were colour displays. Similarly, half of the new displays were standard displays and the other half were colour displays. The experiment had 720 experimental trials in total, divided into 30 blocks of 24 trials each.

Recognition test. After completion of the final block in the search task, observers completed a recognition test. They were informed that certain display configurations were repeated in the experiment they just completed and instructed to decide whether a given display had been shown previously or not. One block of 24 recognition trials was presented to observers. Half of the trials were old displays that were previously presented to them, the other half were newly generated random displays. No feedback was given. Observers were instructed to give a nonspeeded response via mouse keys and to decide whether they had seen the display before or not.

Results

Search task. Mean errors for each observer and variable combination were calculated. Overall, erroneous responses were quite rare (1.3%). A repeated-measures $2 \times 2 \times 6$ analysis of variance (ANOVA) on the error rates with the factors context (old/new), display type (standard/colour), and epoch (1–6) revealed no significant effects.

Mean RTs for each observer were calculated excluding erroneous responses and RTs departing more than 2.5 standard deviations (*SD*s) from the mean. Overall, less than 1% of all trials were excluded by this outlier criterion in this and all subsequent experiments. The mean correct RTs as a function of epoch are presented in Figure 2, separately for standard and colour displays (left and right panels, respectively). Individual RTs were subjected to a repeated-measures $2 \times 2 \times 6$ ANOVA similar to the error analysis. The analysis revealed all three main effects to be significant: Context, $F(1, 13) = 66.48$, $p < .001$; display type, $F(1, 13) = 51.18$, $p < .01$; and epoch, $F(5, 65) = 12.24$, $p < .001$. Old context trials were faster than new context trials (averaged contextual-cueing effect: 158 ms), responses to standard displays were, on average, 102 ms faster than responses to colour displays, and RTs got faster over time (RTs were 113 ms faster in Epoch 6 than in Epoch 1). Furthermore, the two-way Display type $\times$ Context interaction, $F(1, 13) = 9.98$, $p < .01$, was highly significant, and the three-way Context $\times$ Display type $\times$ Epoch interaction, $F(5, 65) = 2.23$, $p = .06$,

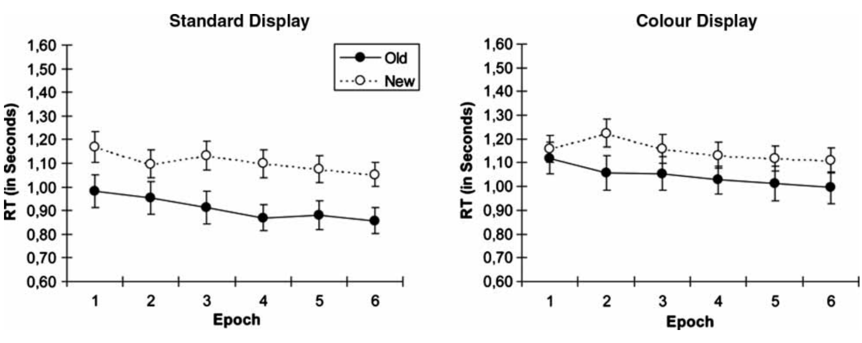

Figure 2. Mean reaction times (with standard error bars) as a function of epoch in the standard (left) and colour (right) conditions of Experiment 1. Filled and unfilled circles correspond to old and new context conditions, respectively.

was marginally significant. The two-way interaction indicated that contextual cueing was more pronounced with standard than with colour displays (192 ms vs. 124 ms, respectively). The marginally significant three-way interaction indicated that, for standard display types, the contextual-cueing effect remained at a stable level across epochs (all $ps <$ .001), whereas for colour display types contextual cueing was only observable from Epoch 2 onwards (Epoch 1: $p = .21$; all other $ps < .05$).

As can be seen from Figure 2, a substantial contextual-cueing effect was already evident in the first epoch. To further explore the onset of contextual learning, mean RTs were calculated separately for each block (rather than combining blocks into epochs). This blockwise analysis showed that contextual cueing emerged very early and was already evident in the third block, showing an effect of 155 ms. A series of t-tests comparing old and new contexts confirmed this observation. The effect of contextual repetition was only significant from Block 3 onwards (all $ps <$ .05, except for Blocks 8, 17, and 29), suggesting that contextual learning had a quick onset after the beginning of the experiment. A similar rapid contextual learning effect was also observed in the subsequent experiments (see also Conci & von Mühlenen, 2009, for a similar fast onset of contextual cueing).

Recognition test. The overall accuracy in the recognition test was 53%. Participants correctly identified old patterns on 56.5% of all trials (hit rate) but this did not differ from their false alarm rate of 51.7%, $t(13) = 0.77$, $p =$ .45, suggesting that participants had no or very little explicit awareness in recalling the display repetitions.

Discussion

The results of Experiment 1 replicated previous findings, showing that invariant contextual layouts can guide selection (Chun & Jiang, 1998). When contextual information was preserved across trials, RTs were faster than when displays presented newly generated spatial arrangements.

Moreover, grouping by colour had a general effect of slowing the RTs: When new displays were presented with items in a single colour, search was 68 ms faster than when new displays were presented in two colours, $t(13) = 2.49$, $p < .05$. In general, this RT cost in search suggests that the heterogeneity of the colour displays reduced search efficiency (cf. Duncan & Humphreys, 1989). However, the colour groupings also affected the contextual-cueing effect: When observers were presented with colour displays, learning of preserved context led to a significantly smaller benefit in performance than when there were standard displays (124 ms vs. 192 ms, respectively; even though slower RTs in the colour as compared to the standard display condition would leave more "space" for an effect to evolve). Consequently, this pattern indicates that grouping by colour interferes with the encoding of contextual information. This confirms our hypothesis that perceptual grouping interferes with contextual cueing (see also Conci & von Mühlenen, 2009). To investigate the generality of this finding, in Experiment 2, contextual cueing was tested for displays that grouped by size.

EXPERIMENT 2

Experiment 1 showed that colour displays constrain contextual cueing in search. This suggests that learning of contextual layouts is somewhat restricted by the organizational principles that segment a display into segregated subsets. Conversely to Experiment 1, studies that investigate the effects of subset formation on visual search have typically used colour as a means to group display items (e.g., Friedman-Hill & Wolfe, 1995). However, studies on contextual cueing show that context-based learning is primarily defined by the spatial relations between search items, whereas the respective surface attributes of an object (such as its colour) generally do not affect contextual cueing (Chun & Jiang, 1998; Olson & Chun, 2002). Thus, grouping on the basis of spatial information (size) might even interfere more with contextual cueing than surface-based (colour) segmentation. To test this prediction, in Experiment 2, we compared standard (i.e., ungrouped) search arrangements with displays that group by size (see Figure 1C for an example display).

Methods

Experiment 2 was very similar to the previous experiment, except that colour displays were replaced by "size" displays, where six of the 12 display items were randomly chosen to be 60% larger than the other display items, that is, they were $1.1^\circ \times 1.1^\circ$, whereas the others were $0.7^\circ \times 0.7^\circ$. Again, the target could be either large or small. As for the previous experiment, the size displays were compared to standard displays (see Figure 1C and 1A for example displays, respectively). Fourteen observers (four male; mean age = 27.1 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credits or payment of 8 Euros per hour. All other details of the experiment were identical to the procedure described for Experiment 1.

Results

Search task. Error rates were again rare (0.7%). A $2 \times 2 \times 6$ repeated-measures ANOVA conducted with the factors context (old/new), display type (standard/size), and epoch (1–6) revealed no significant effects.

Mean RTs for all trials were calculated excluding erroneous responses and RTs that were greater than 2.5 *SD* from the mean. Figure 3 presents the mean correct RTs as a function of epoch for standard and size displays (left and right panels, respectively). The corresponding RT ANOVA revealed two significant main effects, context, $F(1\ 13) = 37.28$, $p < .001$, and epoch, $F(5, 65) = 5.83$, $p < .001$. Old contexts led to faster responses than new displays (mean contextual-cueing effect: 141 ms), and response latencies became faster with increasing epoch (mean RTs were 90 ms faster in Epoch 6 than in Epoch 1). In addition, the two-way interaction Context × Display type, $F(1, 13) = 30.54$, $p < .001$, and the three-way interaction Context × Display type × Epoch, $F(5, 65) = 9.69$, $p < .001$, were significant. The Context × Display type interaction confirms that contextual cueing was much stronger for standard displays than for size displays (contextual-cueing effects were 241 ms and 41 ms, respectively). In addition, the significant three-way interaction indicated that for standard display types, contextual cueing was stable across epochs (all *p*s < .001). By contrast, for size displays the contextual facilitation was almost zero across epochs (all *p*s > .12), except for Epoch 2 ($p < .03$).

Next, to compare both the influence of grouping by colour (Experiment 1) and grouping by size (Experiment 2) on contextual cueing, a mixed-design ANOVA was performed adding the between-subjects factor experiment (1/2) to the within-subjects factors context (old/new), display type (standard/grouped), and epoch (1–6). This analysis revealed significant within-subject effects that mirrored the results described above. Importantly,

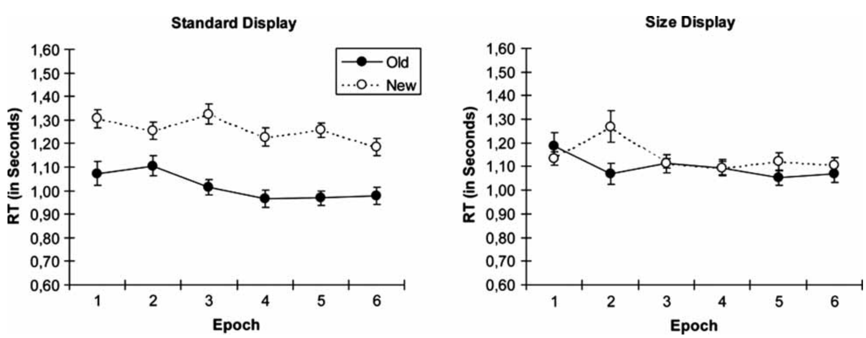

Figure 3. Mean reaction times (with standard error bars) as a function of epoch in the standard (left) and size (right) conditions of Experiment 2. Filled and unfilled circles correspond to old and new context conditions, respectively.

the between-subjects factor experiment also depicted significant main effects and interactions, in particular, a significant three-way interaction of Experiment × Context × Display type, $F(1, 312) = 4.58$, $p < .05$, which indicates that grouping by size deteriorated the contextual-cueing effect more than grouping by colour (41 ms vs. 124 ms, respectively).

Recognition test. Mean accuracy in the recognition test was 56%. Participants correctly identified old patterns on 61.9% of all trials (hit rate). The hit rate differed significantly from the false alarm rate of 49.5%, $t(13) = 2.98$, $p < .05$. This difference between hits and false alarms was mainly due to three participants that could recognize the old displays to some extent (hit rates for these three participants were approximately 25% above their corresponding false alarm rates). Follow-up analyses did, however, reveal that the recognition of a given display was not correlated with the size of the contextual-cueing effect, $r = .14$, $p = .62$. Also, mean RTs for the recognized old display configurations did not differ from old display configurations that were not recognized, $t(13) = 1.11$, $p = .28$. Thus, the explicit encoding of certain aspects of a scene did clearly not dictate the strength of contextual cueing.

Discussion

In Experiment 2, a reliable contextual-cueing effect was again found with the standard displays. Varying the stimulus size within displays led to a drastic reduction of contextual cueing (from 241 ms for standard to 41 ms for size displays). Importantly, this large reduction (83%) in the contextual-cueing effect also differed from the relatively smaller reduction (35%) observed for grouping by colour displays in Experiment 1 (from 192 ms for standard to 124 ms for colour displays; see Experiment 1), indicating that interference in contextual cueing is even stronger with size groupings than with colour groupings.

As for colour displays, the overall search performance for size displays was slowed by 119 ms relative to baseline, i.e., when comparing new size with new standard display types, $t(13) = 3.93$, $p < .001$. Search for a colour display did, however, not differ from search for a size display in the new context condition, $t(26) = 0.651$, $p = .52$. This indicates that although both types of heterogeneous displays lead to a comparable reduction in search efficiency, contextual cueing was more affected by size than by colour. Consequently, these results suggest that grouping per se reduces the effectiveness of contextual cueing. However, given that primarily, the spatial relations are important for contextual cueing (see Chun & Jiang, 1998; Olson & Chun, 2002), grouping by means of spatial characteristics (i.e., size) exhibits a greater detrimental effect on cueing than grouping by surface characteristics (i.e., colour), although this effect is not manifest in the overall search performance.

EXPERIMENT 3

The reduction of contextual cueing in both size and colour displays indicates that grouping interferes with contextual cues. Thus, when the display layouts were segmented into distinct groups of items, contextual cueing was less, or, not always effective in guiding attention to the target. However, an alternative explanation to this grouping interference account could be based on a general search bias towards one of the two groups. For instance, in Experiment 1, the target was grey in 75% of all cases (i.e., in all the standard displays and in half of the colour displays). The same holds for Experiment 2, where the target was small in 75% of all cases. Consequently, this could have led to an overall bias to search all grey or small items first, disrupting the contextual-cueing effect in displays that contain a red or large target. Such a bias could then account for the overall reduction of contextual cueing for grouped displays. This issue was addressed in Experiment 3, which replicated Experiment 2 without any search bias: Now, all displays were ambiguous in terms of the target size (i.e., both display types could be presented with large or small items; see Figure 4). Thus, if the disrupting effect on contextual cueing in Experiment 2 was due to an overall search bias, then the reduction in contextual cueing should not occur in Experiment 3. However, if the disrupting effect is due to grouping interference, then contextual cueing should be as strongly reduced in Experiment 3 as in Experiment 2.

Methods

Experiment 3 was identical to Experiment 2 except that the stimulus sizes were systematically varied for all types of display. Uniform (standard) displays now consisted of search arrays with either all small items ($0.7^\circ \times 0.7^\circ$) or large items ($1.3^\circ \times 1.3^\circ$), whereas variable (size) displays were the same as in Experiment 2, presenting both item sizes in a single display (see Figure 4). Thus, in both uniform and variable displays, the target could be large or small with equal probability. Fourteen observers (5 male; mean age = 25.9 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credits or payment of 8 Euros per hour. All other details of the experiment were identical to Experiment 2.

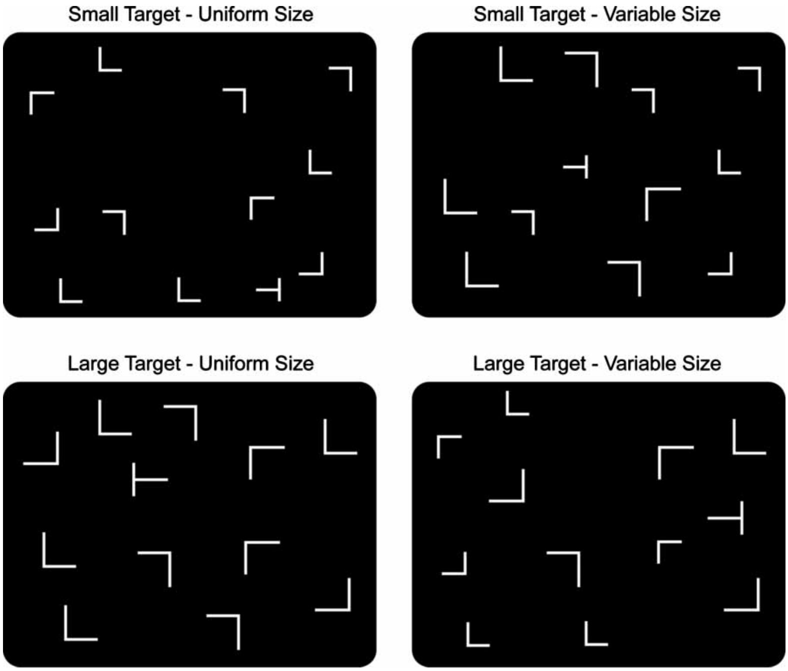

Figure 4. Examples of uniform (left) or variable (right) search displays containing small (upper panels) or large (lower panels) targets in Experiments 3 and 4.

Results

Search task. Error rates were again relatively rare (1.2%) and a $2 \times 2 \times 6$ repeated-measures ANOVA conducted with the factors context (old/new), display type (uniform/variable), and epoch (1–6) showed no significant effects.

Mean RTs were collapsed for all trials excluding error responses and RTs that were greater than 2.5 *SD* from the mean. Figure 5 presents the mean correct RTs as a function of epoch for uniform and variable displays (left and right panels, respectively). In addition, RTs were compared by means of a corresponding $2 \times 2 \times 6$ repeated-measures ANOVA, which showed significant main effects of context, $F(1, 13) = 6.38$, $p < .03$, and epoch, $F(5, 65) = 15.06$, $p < .001$. As in the previous experiments, old contexts led to faster responses than new contextual layouts (mean contextual-cueing effect: 60 ms) and responses got faster in the course of the experiment (from 1153 ms in Epoch 1 to 973 ms in Epoch 6). Importantly, the Context $\times$ Display type interaction was also significant, $F(1, 13) = 4.98$, $p < .05$, showing a much larger contextual-cueing effect in uniform (100 ms) as compared to variable (20 ms) displays. In addition, pairwise comparisons showed that for uniform displays, cueing effects were found in Epochs 2–6 (all ps $< .03$),

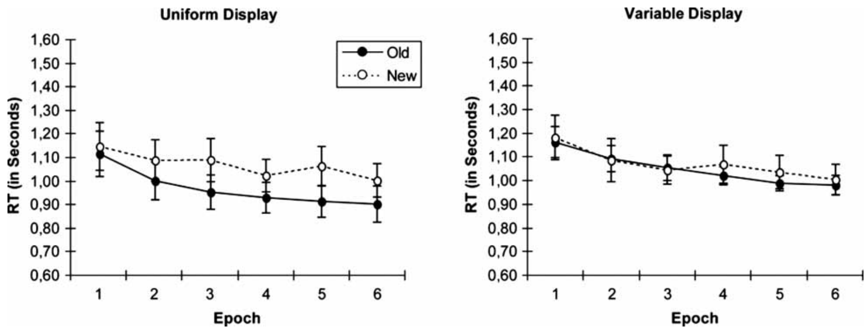

Figure 5. Mean reaction times (with standard error bars) as a function of epoch for uniform (left) and variable (right) displays in Experiment 3. Filled and unfilled circles correspond to old and new context conditions, respectively.

whereas no contextual cueing was evident for all epochs in variable displays (all $ps > .3$). Finally, the Context × Epoch interaction was marginally significant, $F(5, 65) = 2.28$, $p = .056$, demonstrating that contextual cueing was only evident from Epoch 2 onwards.

In summary, as in the previous experiments, displays that presented (size) groupings showed a reduction in the contextual-cueing effect of about 80%. Importantly, this reduction in contextual cueing is very similar to the 83% reduction in Experiment 2, suggesting that a potential search bias towards a subset of (small) items cannot account for the reduction in contextual cueing. Instead this finding supports the grouping interference account.

Nevertheless, we further explored a potential influence of target-size ambiguity on search, by exploring intertrial contingencies (see also Geyer, Shi, & Müller, 2010). For instance, it could be that (despite of no apparent search bias) contextual cueing was particularly vulnerable whenever two successive trials presented different target sizes (i.e., target switches), relative to target size repetitions. Thus, a reduction in contextual cueing could potentially be explained with switch costs due to changes in the target features across successive trials. To this end, RTs were entered into a 2 × 2 × 2 repeated-measures ANOVA with the factors target size (switch/repetition), context (old/new), and display type (uniform/variable). This analysis revealed, as earlier, a significant main effect of context, $F(1, 13) = 5.81$, $p < .04$, and a significant Context × Display type interaction, $F(1, 13) = 5.88$, $p < .04$. As can be seen from Figure 6, there was overall a reliable (60 ms) contextual-cueing effect and a reduction of contextual cueing for variable (relative to uniform) displays (16 ms and 104 ms, respectively), comparable to the results obtained previously. However, this effect was independent of the between-trial target switches or repetitions, as there was no significant effect of the factor target size (e.g., compare left and right panels in Figure 6).

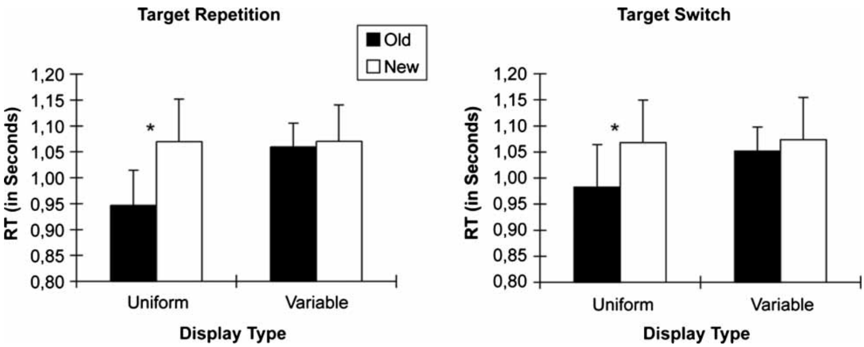

Figure 6. Intertrial effects in Experiment 3: Mean RTs are plotted as a function of display type for repetition trials (left; target size was the same in the previous trial) and switch trials (right; target size was different in the previous trial). Filled and unfilled bars correspond to old and new context conditions, respectively. An asterisk indicates significant differences between pairwise comparisons ($p < .001$).

Recognition test. Mean accuracy in the recognition test was 45%. Participants correctly identified old patterns on 51.1% of all trials (hit rate). This did, however, not differ from their false alarm rate of 41.7%, $t(13) = 1.77$, $p = .1$, showing no (or only little) awareness for repeated layouts in old displays.

Discussion

Experiment 3 replicated Experiment 2 in showing a stable (but numerically somewhat reduced) contextual-cueing effect (of 100 ms) for uniform displays together with a large and significant reduction in contextual cueing (remaining at 20 ms) whenever displays were presented with segmented groups of items. Thus, this pattern of effects confirms that grouping interferes with contextual cueing. By contrast, a search bias towards a given target size cannot account for this difference. In addition, an analysis of the intertrial contingencies showed that contextual cueing was not affected by whether a target switched in size or not across successive trials. Rather, the presence or absence of distinct groupings alone determined the size of contextual cueing.

EXPERIMENT 4

The first three experiments have shown that grouping by colour or by size interferes with contextual cueing. Contrary to this overall interference by grouping, Jiang and Chun (2001) showed that directing attention towards a subset of items preserved contextual cueing within the attended set but eliminated contextual cueing within the nonattended group. Consequently, it appears that directing attention towards a consistent set of items can overcome (or modulate) the limitations of grouping on contextual cueing. In Experiment 4, we further tested if it would be possible to override this interference by directing attention (comparable to the approach taken by Jiang & Chun, 2001): Would a reduction of contextual cueing still occur if observers were biased to *always* select the target-relevant subgroup of items (i.e., the group that contains the target)? To this end, the same variations of size-based groupings were presented as in Experiment 3. The only difference in Experiment 4 was that the size of the target was held constant across the whole experiment. That is, for half of the participants the target was always large, whereas for the other half it was always small; thus, all participants could focus attention only on the subset containing the target.

Methods

Experiment 4 was very similar to Experiment 3, except that the size of the target was consistent across the whole experiment. Note that observers were not informed that the target size was constant throughout the experiment. To control for possible effects of target size, half of the participants were presented with a large target; the other half were presented with a small target (see Figure 4, bottom and top panels, respectively). As for previous display type variations, in the current experiment uniform (i.e., standard) displays were compared to variable-size displays. In uniform displays all items had equal size (see Figure 4, left), whereas in variable displays half of the search items were large and the other half were small (see Figure 4, right). Fourteen observers (three male; mean age = 26.6 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credits or payment of 8 Euros per hour. All other details of the experiment were identical to Experiment 3.

Results

Search task. Error rates were, as for previous experiments, relatively rare (1.6%). A comparison between subjects presented with large and small targets revealed no significant differences, $t(12) = 0.51$, $p = .96$ (in a mixed-design ANOVA, target size also showed no significant interactions with all other experimental factors). Both groups were collapsed for the subsequent $2 \times 2 \times 6$ repeated-measures ANOVA conducted with the factors context (old/new), display type (uniform/variable), and epoch (1–6). This analysis revealed no significant effects.

Mean RTs for all trials were calculated excluding erroneous responses and RTs that were greater than 2.5 *SD* from the mean. Figure 7 presents the mean correct RTs as a function of epoch for uniform and variable displays

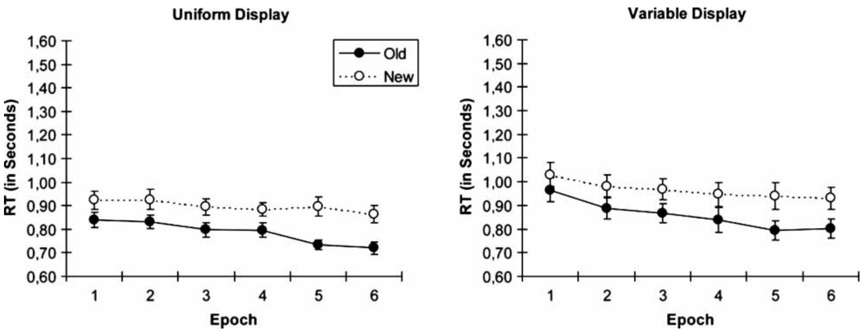

Figure 7. Mean reaction times (with standard error bars) as a function of epoch in the uniform (left) and variable (right) conditions of Experiment 4. Filled and unfilled circles correspond to old and new context conditions, respectively.

(left and right panels, respectively). As for the analysis of error rates, the mean RTs were collapsed for different target sizes as a comparison of the mean RTs did not reveal a significant difference, $t(12) = 0.52$, $p = .95$ (again, a mixed-design ANOVA also showed no significant interactions of target size with all other experimental factors). In a subsequent step, RTs were compared by means of a corresponding $2 \times 2 \times 6$ repeated-measures ANOVA, which revealed significant main effects of context, $F(1, 13) = 17.08$, $p < .01$, display type, $F(1, 13) = 4.93$, $p < .05$, and epoch, $F(5, 65) = 14.17$, $p < .001$. Old contexts led to faster responses than new contextual layouts (mean contextual-cueing effect: 109 ms), and responses to uniform displays were 69 ms faster than responses to variable displays. With increasing epoch, RTs became 109 ms faster from the first to the sixth epoch. In addition, significant interactions were obtained for Context $\times$ Epoch, $F(5, 65) = 4.41$, $p < .01$, and for Display type $\times$ Epoch, $F(5, 65) = 2.81$, $p < .05$. The Context $\times$ Epoch interaction indicated that contextual learning increased as the experiment progressed (contextual-cueing effects were 74 ms in Epoch 1 and 134 ms in Epoch 6). In addition, the Display type $\times$ Epoch interaction showed RTs decreased by 130 ms from Epoch 1 to Epoch 6 for variable displays, as compared to a smaller decrease (by 89 ms) for uniform displays. Note, that the Display type $\times$ Context and the three-way interactions were nonsignificant (both ps $> .87$).

Recognition test. Mean accuracy in the recognition test was 51%. Participants correctly identified old patterns on 50.5% of all trials (hit rate). This did, however, not differ from their false alarm rate of 47.1%, $t(13) = 0.38$, $p = .71$, indicating that no explicit awareness of the display repetitions could be formed.

Discussion

As in all previous experiments, Experiment 4 showed a robust contextual-cueing effect for uniform displays: Search in repeated contextual layouts was faster than search within random displays. Contrary to the previous experiment(s), the displays that contained a segmented group did not, however, lead to a reduction in contextual cueing (contextual-cueing effects were 112 ms and 106 ms for uniform and variable displays, respectively). Nevertheless, as for previous experiments, search in variable new displays was again (73 ms) slower than search in uniform displays, $t(13) = 2.22$, $p < .05$. This suggests that while, in general, search was affected by the display segmentation, contextual learning was unaffected. Therefore, the introduction of a valid attentional bias towards the target-relevant subgroup was enough for the occurrence of contextual cueing. In general agreement with Jiang and Chun (2001), search was facilitated for old contexts, with reliable learning on the basis of contextual invariances even for displays that contain a segmented group of items. This suggests that contextual cueing is robust when predictive information is selectively and consistently attended. However, when there is no attentional bias for a certain group of items, then contextual cueing is much more vulnerable (see Experiments 1 and 2), suggesting that attention is only effective in maintaining contextual cueing as long as selection is predictive.

EXPERIMENT 5

Experiment 4 demonstrated strong contextual cueing despite of the size variations within the displays if observers were biased to select the target-relevant subgroup of search items. Note, however, that with this approach, the target was constant across the whole experiment (either always large or always small). In Experiment 5, we investigated if bottom-up saliency could also have a comparable influence on contextual cueing when the target was not constant across trials. To this end, colour displays were presented to observers as in Experiment 1. However, in order to manipulate the bottom-up saliency, the colour of the group of items that contained the target was systematically varied in brightness. In the *salient target colour* condition, the subgroup of (six) items that contained the target were presented in bright colour (red or grey), and the other subgroup was presented in dim colours (grey or red, respectively). Similarly, for the *nonsalient target colour* condition, the target subgroup was presented in dim colours and the subgroup that did not contain the target was presented in bright colours. Consequently, if contextual cueing depends on the (dynamic) selection of the target-relevant subgroup of items, then contextual guidance should be stronger for displays that present the target within the salient subgroup of items.

Methods

Experiment 5 presented colour displays that were identical to the colour displays in Experiment 1 (see Figure 1B), except that the brightness of the two colour groups was either bright or dim. Salient target colour displays presented the six items in the colour of the target in bright grey (23.3 cd/m^2) or bright red (15.2 cd/m^2), and the other six items in dim grey (8.5 cd/m^2), or dim red (6.9 cd/m^2), respectively. By contrast, for the nonsalient target colour condition, bright and dim colours were switched for the two subgroups of items such that the target would be presented within the dim subgroup of items. As for Experiment 1, bright and dim stimulus colours were subjectively matched in luminance by the experimenter. Fourteen observers (six male; mean age = 29.7 years) with normal or corrected-to-normal visual acuity participated in the experiment, receiving course credits or payment of 8 Euros per hour. All other details of the experiment were identical to Experiment 1.

Results

Search task. Error rates were, as for previous experiments, relatively rare (2.0%). A comparison between red and grey target colours revealed no significant differences, $t(13) = 1.21$, $p = .25$. Both target colours were subsequently collapsed for a $2 \times 2 \times 6$ repeated-measures ANOVA conducted with the factors context (old/new), target group (salient/nonsalient), and epoch (1–6). This analysis revealed no significant effects.

Mean RTs for all trials were calculated excluding erroneous responses and RTs that were greater than 2.5 *SD* from the mean. Figure 8 presents the mean correct RTs as a function of epoch for salient and nonsalient target groups (left and right panels, respectively). Similar to the analysis of error rates, the mean RTs were collapsed for different target colours as a comparison of the mean RTs did again not reveal a significant difference between grey and red, $t(13) = 0.83$, $p = .42$. In a subsequent step, responses were compared by means of a corresponding $2 \times 2 \times 6$ RT ANOVA. This analysis revealed significant main effects of context, $F(1, 13) = 106.33$, $p < .001$, target group, $F(1, 13) = 12.65$, $p < .01$, and epoch, $F(5, 65) = 5.02$, $p < .001$. Targets in old contexts were detected 109 ms faster than targets in new contexts, and the salient target group led to faster response latencies than the nonsalient target group (mean difference: 70 ms). Finally, the main effect of epoch indicated that RTs decreased as the experiment progressed (from 919 ms in Epoch 1 to 886 ms in Epoch 6). In addition, significant interactions

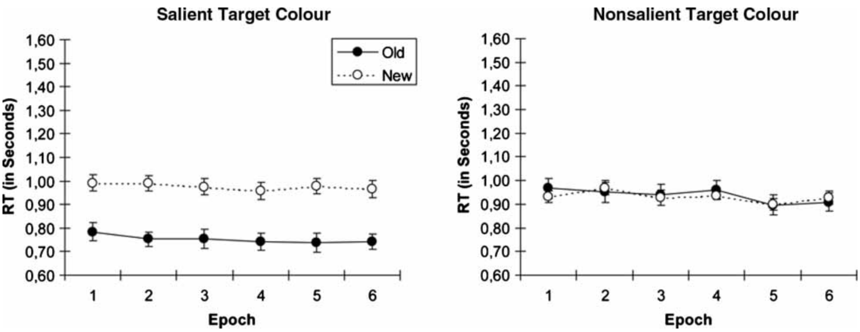

Figure 8. Mean reaction times (with standard error bars) as a function of epoch in the salient (left) and nonsalient (right) target conditions of Experiment 5. Filled and unfilled circles correspond to old and new context conditions, respectively.

were obtained for Context × Target group, $F(1, 13) = 43.12$, $p < .001$, and for Target group × Epoch, $F(5, 65) = 3.24$, $p < .05$. The Context × Target group interaction showed that a reliable contextual-cueing effect was only obtained for the salient target group (224 ms), but not for the nonsalient target group (−7 ms). In addition, the Target group × Epoch interaction demonstrated a linear decrease (by 38 ms) for the salient target group until Epoch 3 (and constant RTs thereafter) but no corresponding decrease for the nonsalient target group (RTs were more variable across epochs with a maximal difference of 51 ms between Epochs 4 and 5; see Figure 6). Finally, the Context × Epoch interaction was marginally significant, $F(5, 65) = 1.04$, $p = .09$, showing a trend for an increase of the contextual-cueing effect with epoch (from 86 ms in Epoch 1 to 122 ms in Epoch 6). No other significant effects were obtained.

Recognition test. Mean accuracy in the recognition test was 45%. Participants correctly identified old patterns on 41.1% of all trials (hit rate). This did, however, not differ from their false alarm rate of 48.2%, $t(13) = 1.32$, $p = .21$, indicating that there was no or only little awareness of the display repetitions.

Discussion

Experiment 5 demonstrated that contextual cueing can be dynamically modulated by bottom-up saliency: When the target was presented within a salient (i.e., bright) group of items, contextual cueing facilitated search. However, when the target was part of the nonsalient (i.e., dim) group of items, no influence of contextual information was observable. Consequently, this difference between target groups indicates that not only a consistent bias towards a relevant subgroup preserves contextual cueing (see Experiment 4), but also bottom-up saliency can bias selection and enable contextual cueing in a variable manner across trials. Thus, guidance can help to overcome the reduction in contextual cueing observed previously in Experiments 1 to 3.

Taken together, this pattern of results suggests that selection by means of salience can modulate contextual cueing: If the target is within the less-salient set of items, then contextual cueing is abolished or drastically reduced. However, when predictive top-down (Experiment 4) or bottom-up (Experiment 5) information is available to guide search, then this will determine whether contextual cueing can support search or not.

EXPERIMENT 6

Experiments 2 and 3 indicated that groupings based on spatial characteristics of a display may be particularly efficient in reducing the contextual-cueing effect (at least if selection is not based on predictive information; see Experiment 4). In Experiment 6, we investigated the level at which grouping interferes with contextual cueing. For instance, in previous studies (Jiang & Leung, 2005; see also Jiang & Chun, 2001) it has been shown that selectively attending to a subgroup of items primarily affects the *expression* of learning while demonstrating preserved latent *learning* of the display layouts as a whole. Here, we adopted Jiang and Leung's (2005) procedure to test whether learning itself or the expression of the learned information is influenced by grouping. We presented size and standard displays in the first five epochs (identical to Experiment 2). Subsequently, in Epoch 6, the size displays were presented with preserved spatial layout but *without* grouping information to investigate whether learning of the context has actually occurred in the size displays, but it could not be expressed.

Methods

Epochs 1 to 5 consisted of a *learning session*, identical to the procedure described for Experiment 2. Following learning, in Epoch 6 (Blocks 26–30) a *transfer session* started immediately after Block 25 without any further instruction. This transfer session was identical to the previous learning session, except that stimuli in size displays were now presented at one size only ($0.7^\circ \times 0.7^\circ$), similar to standard displays (which served as a baseline measure). Despite of these size differences between learning and testing, for both display types, the layout was preserved for old context trials. Finally, as for previous experiments, a recognition test was presented to observers (using the displays from the learning session) in Block 31. Fourteen observers (three male; mean age = 30.3 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credit or payment of 8 Euros per hour. All other details of the experiment were identical to Experiment 2.

Results

Search task. Error rates were again quite rare (1.7%). For the learning session, a $2 \times 2 \times 5$ repeated-measures ANOVA was conducted with the factors context (old/new), display type (standard/size), and epoch (1–5). This analysis revealed, as for all previous experiments, no significant effects. Similarly, for the transfer session, a 2×2 repeated-measures ANOVA was performed with the factors context (old/new) and display type (standard/size). This analysis again did not show any significant effects.

Mean RTs for all trials were calculated excluding erroneous responses and RTs that were greater than 2.5 *SD* from the mean. Figure 9 presents the mean correct RTs in the learning and transfer session as a function of epoch for standard and size displays (left and right panels, respectively). Responses during learning were subjected to a corresponding $2 \times 2 \times 5$ ANOVA. This analysis revealed all main effects to be significant: Context, $F(1, 13) = 70.33$, $p < .001$, display type, $F(1, 13) = 8.59$, $p < .05$, and epoch, $F(4, 52) = 7.99$, $p < .001$. Repeated (old) contexts led to faster responses than novel layouts (mean contextual-cueing effect: 140 ms), and responses to standard displays were 41 ms faster than responses to size displays. Also, response latencies increased with epoch (mean RTs were 71 ms faster in Epoch 5 than in Epoch 1). In addition, significant two-way interactions of Context × Epoch, $F(4, 52) = 5.06$, $p < .01$, and Context × Display type, $F(1, 13) = 76.99$, $p < .001$, were obtained. Finally, the three-way interaction was significant, $F(4, 52) = 2.82$, $p < .05$. The Context × Epoch interaction

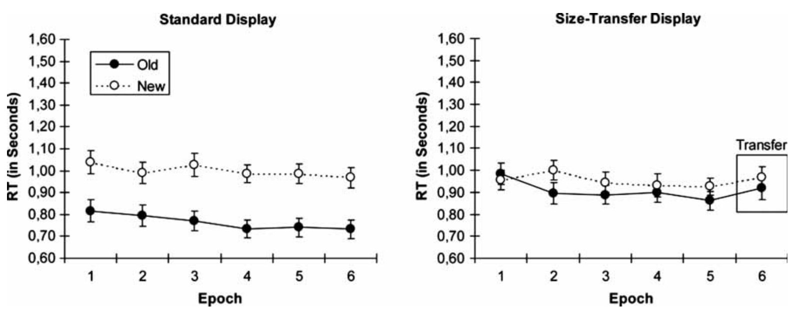

Figure 9. Mean reaction times (with standard error bars) as a function of epoch in the standard (left) and size transfer (right) conditions of Experiment 6. The size transfer condition presented size-grouped displays in Epochs 1–5 as in Experiment 2. In Epoch 6 (transfer), the (previous) size displays were now presented as standard displays. Filled and unfilled circles correspond to old and new context conditions, respectively.

indicated that the contextual-cueing effect increased as the experiment progressed (from 98 ms in Epoch 1 to 155 ms in Epoch 5). In addition, the Context $\times$ Display type interaction showed that contextual cueing was much stronger for standard than for size displays (234 ms and 46 ms, respectively) mirroring the results from Experiment 2. In addition, the three-way interaction indicated that contextual cueing was reliable across epochs for standard displays (all $ps < .001$), as opposed to a more variable pattern of contextual-cueing effects for size displays (no significant effects in Epochs 1 and 4, all $ps > .12$; as opposed to small but significant effects for Epochs 2, 3, and 5, all $ps < .05$; see Figure 9).

Epoch 6 (transfer) revealed that there was no sudden benefit for contextual cueing when size-based grouping was removed (see Figure 9). This observation was confirmed by a comparisons of learning and transfer, which showed near-identical contextual-cueing effects in Epoch 6 (transfer) as compared to learning (contextual-cueing effects were 234 [236] ms and 46 [49] ms for standard and size displays in Epochs 1–5 [Epoch 6], respectively), without significant differences in the contextual-cueing effect between Epochs 5 and 6 for both standard and size displays (all $ps > .6$).

Recognition test. The analysis of results in the recognition test indicated that contextual learning was implicit. Mean accuracy in the recognition test was 53%. Participants correctly identified old patterns on 47.1% of all trials (hit rate). This did not, however, differ from their false alarm rate of 52.3%, $t(13) = 1.39$, $p = .18$. Consequently, this nonsignificant difference between hits and false alarm rates indicates that no explicit awareness of the display repetitions was evident.

Discussion

Experiment 6 replicated the basic pattern of results obtained for Experiments 2 and 3: Standard displays exhibited a robust contextual-cueing effect, whereas for size displays contextual cueing was reduced by approximately 80%.

In addition, contextual cueing during learning and transfer showed no differences, indicating that grouping interfered with learning itself (rather than during recall of learned information): In the transfer session, no recovery of contextual cueing could be observed even though the grouping cues were removed from the displays. This outcome contrasts with Jiang and Leung (2005), who found an instantaneous recovery of contextual cueing when a repeatedly ignored display subset had suddenly to be attended. One potential explanation for the different outcome in the current study could be that contextual cueing was blocked because during learning and transfer the displays underwent a slight change (i.e., the large items change into small items). However, Jiang and Wagner (2004) demonstrated that rescaled search displays are capable of maintaining contextual cueing as long as the spatial relations are preserved. Thus, on the basis of this result, the small spatial changes between search items during learning and transfer should not have influenced contextual cueing. Instead, we speculate that the crucial difference between the current experiment and the experiment by Jiang and Leung was that they engaged in different mechanisms: For instance, in size displays, bottom-up perceptual grouping was manipulated and caused interference. By contrast, Jiang and Leung manipulated the search-relevant attentional set in a top-down manner, leaving contextual learning unaffected (see also Experiment 4, for a similar finding). Thus, latent learning may occur for top-down attentional selection (as in Jiang & Leung, 2005). However, no learning of contextual information is observable when bottom-up perceptual segmentation constrains search.

EXPERIMENT 7

Experiment 7 tested whether contextual learning across successive presentations could generalize to a display that maintains the context but suddenly presents spatial grouping information. To this end, in Experiment 7, observers learned a set of standard displays in a five-epoch learning session. In Epoch 6 (transfer), a subset of these displays was now presented with preserved contexts together with size-based grouping cues that segmented the display into two subsets of items.

Methods

The first five epochs (Blocks 1–25) in Experiment 7 consisted of a *learning session* that presented standard displays only. In each block, 12 old displays were presented together with 12 newly generated displays. Following learning, in Epoch 6 (Blocks 26–30) a *transfer session* started immediately after Block 25. This transfer session was identical to the previous learning session, except that half of the displays in old and new contexts were now presented as size displays (see Experiment 2). Thus, in Epoch 6 we intended to test how spatial groupings would influence an already-learned context. Again, in Block 31, a recognition test was presented to observers (presenting the displays from the learning session). Fourteen observers (eight male; mean age = 27.2 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving course credit or payment of 8 Euros per hour. All other details of the experiment were identical to Experiment 2.

Results

Search task. Error rates were rare (1.6%). For the learning session, a 2 × 5 repeated-measures ANOVA was conducted with the factors context (old/new) and epoch (1–5). This analysis revealed a significant main effect for context, $F(1, 13) = 5.39$, $p < .05$, indicating that fewer errors were made in old (1.2%) as compared to new (1.9%) trials. No other significant effects were obtained. For the transfer session, a 2 × 2 repeated-measures ANOVA was performed with the factors context (old/new) and display type (standard/size). This analysis did not show significant effects.

Mean RTs for all trials were calculated excluding erroneous responses and RTs that were greater than 2.5 *SD* from the mean. Figure 10 presents the mean correct RTs in the learning and transfer session as a function of epoch. Responses during learning were compared by means of a corresponding 2 × 5 ANOVA. This analysis revealed significant main effects of context, $F(1, 13) = 62.47$, $p < .001$, and epoch, $F(4, 52) = 8.48$, $p < .001$, depicting a robust contextual cueing effect of 149 ms together with a decrease in response latencies with epoch (from 921 ms in Epoch 1 to 860 ms in Epoch 5).

In Epoch 6 (transfer), the sudden presentation of grouped displays had the effect that contextual cueing was reduced by 70% (see Figure 10, circles and squares correspond to standard and size display types, respectively). Comparisons of contextual cueing in Epoch 5 (learning) and Epoch 6 (transfer), indicated that the contextual cueing effect increased for standard displays from 148 ms (Epoch 5) to 200 ms (Epoch 6), $t(13) = 2.45$, $p < .03$. By contrast, for size displays, contextual cueing in Epoch 6 was significantly reduced to 45 ms relative to Epoch 5, $t(13) = 4.37$, $p < .001$.

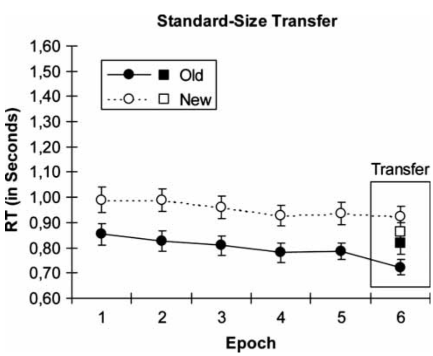

Figure 10. Mean reaction times (with standard error bars) as a function of epoch in Experiment 7. Epochs 1–5 presented standard displays. In Epoch 6 (transfer), half of the displays were presented as standard displays as before (circles), and the other half was now presented as size displays (squares). Filled and unfilled markers correspond to old and new context conditions, respectively.

Recognition test. The analysis of results in the recognition test indicated that contextual learning was implicit. Mean accuracy in the recognition test was 51%. Participants correctly identified old patterns on 51.8% of all trials (hit rate). This did, however, not differ from their false alarm rate of 50.6%, $t(13) = 0.21$, $p = .83$. Consequently, this nonsignificant difference between hits and false alarm rates indicates that no explicit awareness of the display repetitions was evident.

Discussion

Experiment 7 demonstrated that size-based grouping information can have a strong impact on learned contextual layouts: Across five epochs, observers learned a set of repeated displays. When these learned displays were suddenly presented at varying sizes (transfer), the contextual facilitation was greatly reduced by ~70% (relative to Epoch 5). Consequently, grouping information not only hinders learning of contextual information (as suggested by Experiment 6) but it also distorts previously learned contextual layouts during transfer (i.e., when a learned layout is suddenly presented with features that support the segmentation of items into distinct subsets).

GENERAL DISCUSSION

The present study investigated the influence of grouping on contextual cueing. For all reported experiments, a strong contextual-cueing effect was reliably obtained for baseline (i.e., standard) displays, replicating previous studies (e.g., Chun & Jiang, 1998). By contrast, contextual cueing was greatly reduced when displays contained features that support the segmentation of the search display into two distinct subsets: In Experiment 1, displays that were grouped by colour showed a significant reduction of contextual cueing (by ~35%) relative to the baseline condition. Moreover, in Experiment 2, grouping by size information had an even-greater detrimental effect (by ~80%) on contextual cueing. Subsequently, Experiment 3 replicated Experiment 2 while showing that the reduction of contextual cueing for grouped displays cannot be explained by a search bias that might have resulted in Experiments 1 and 2 from the unequal distribution of target features. These results show that grouping interferes with contextual cueing, and the constraints for groupings are larger when based on spatial features (i.e., size) than on surface features (i.e., colour; see also Olson & Chun, 2002).

Could a bias towards selecting the target-relevant subset of search items help to overcome interference by grouping? Experiment 4 suggests that, indeed, preselection of a subset of items can preserve contextual cueing: When observers were presented with a constant size of the target throughout the experiment (such that observers could prioritize this target-relevant subset), grouping did not affect contextual learning. Similarly, in Experiment 5, contextual cueing was preserved when the target was presented within a salient (i.e., a bright) colour group, whereas no contextual RT facilitation was evident when the target was presented within a nonsalient (i.e., dim) colour group. Thus, these results suggest that a bias towards selection can remedy the interference by grouping on contextual cueing. The attentional bias is effective for both consistent and dynamic changes of the relevant context (compare Experiments 4 and 5) and shows that prioritizing relevant aspects of a display layout can reduce the amount of interference introduced by grouping. Thus, contextual cueing can be modulated both by top-down task-relevant information and by salience based on bottom-up selection.

In a final set of experiments, we investigated which processes are affected by grouping in contextual cueing (either *learning* or the *recall* of learned information; see Jiang & Leung, 2005). Experiment 6 indicated that grouping by size prevented the learning of contextual layouts. In addition, in Experiment 7, a previously learned context could not be recalled when grouping cues were added for the transfer epoch. This finding shows that grouping and contextual cueing both interfere at a relatively early stage, already hindering the (implicit) learning of contextual information and its subsequent recall during transfer.

Taken together, all experiments reported here show that perceptual grouping interferes with contextual cueing. Grouping has been shown to provide basic units for attentional selection (e.g., Conci, Müller, & Elliott, 2007; Wang, Kristjánsson, & Nakayama, 2005); contextual learning is, at the same time, disturbed by the segmentation of search items into distinct clusters. This contextual-interference effect is consistent with our previous study, which demonstrated a reduction in contextual cueing when salient objects (composed from nontarget items) were present in the displays (Conci & von Mühlenen, 2009). Thus, both sets of experiments show that grouping can reduce the amount of informative context: When the context is combined to form a square, the contextual variance is reduced, and in a comparable manner the clustering of search items on the basis of similarity leads to a reduction of contextual learning. In line with such a dependency of contextual cueing on the spatial segmentation of a display, an investigation of contextual cueing in three-dimensional search layouts has shown contextual-cueing effects to evolve primarily for repetitions of invariant context within but not between segregated depth planes (Kawahara, 2003). Similarly, contextual cueing has shown to be limited by the temporal segmentation of subsets in (preview) search (Hodsoll & Humphreys, 2005). Thus, the segmentation of a display into segregated clusters may interfere with the formation of contextual "associations" (between the target and the context). If the display consists of randomly distributed items, contextual associations are formed such that they support search. However, if a display is prestructured, these global structures interfere with memory-based learning of contextual information and reduce (or even remove) the RT benefit for old displays (see also Olson & Chun, 2002). Only when a bias in selection can help to identify the relevant parts of a scene, can contextual cueing overcome the perceptual interference from grouping.

At what stage in processing does interference with contextual cueing occur? Jiang and Leung (2005; see also Jiang & Chun, 2001; Rausei, Makovski, & Jiang, 2007) demonstrated that contextual cueing occurs for an attended set of items but not for the other "ignored" context. Nevertheless, the ignored context could facilitate search once it was attended. This pattern of results suggests that learning of context is independent of attention whereas the expression of learning (i.e., the recall of display layouts) depends on attending to the context. Thus, selectively attending to only a subset of items does not hinder learning of the display context at unattended locations. Contrary to this outcome, Experiments 6 and 7 indicate that grouping can have severe restrictions on learning contextual relations. For instance, in Experiment 6, the removal of size information in the transfer session did not lead to a recovery of contextual cueing. Thus, this outcome indicates that the grouped displays already constrain the (latent) learning of context, limiting the extent to which the display as a whole is (implicitly) memorized. As such, bottom-up groups interfere with exploiting the statistical covariation given within the context of a scene during search. This suggests that contextual cueing influences search at a relatively early stage of processing (for instance prior to the allocation of attention).

A plausible account for this pattern of (early) interference effects of grouping on contextual cueing is given in the schematic illustration displayed in Figure 11. It is assumed that contextual cueing is primarily driven by the local context in a given display layout (e.g., Brady & Chun, 2007). Thus, the repeated presentation of a given (standard) display will elicit a set of contextual associations, which link the target within the surrounding context of (about three) nontarget items (red, dotted lines in Figure 11A). Note that, in order to encode these contextual associations attention is not required (Leung & Jiang, 2005)—attention is therefore initially distributed across the entire display such that the context can guide search (note that contextual learning is particularly effective during an initial search phase, see Hodsoll & Humphreys, 2005; Jungé, Scholl, & Chun, 2007). By contrast, a different picture emerges when a given display consists of segregated groups of items that are equally salient and are equally likely to contain the target (Figure 11B). In this case, grouping will promote the segmentation of the display layout (grey, dashed lines in Figure 11B). However, at the same time, grouping will interfere (at least to some extent) with contextual learning, and, as a result, contextual guidance is much weaker and search benefits to a lesser

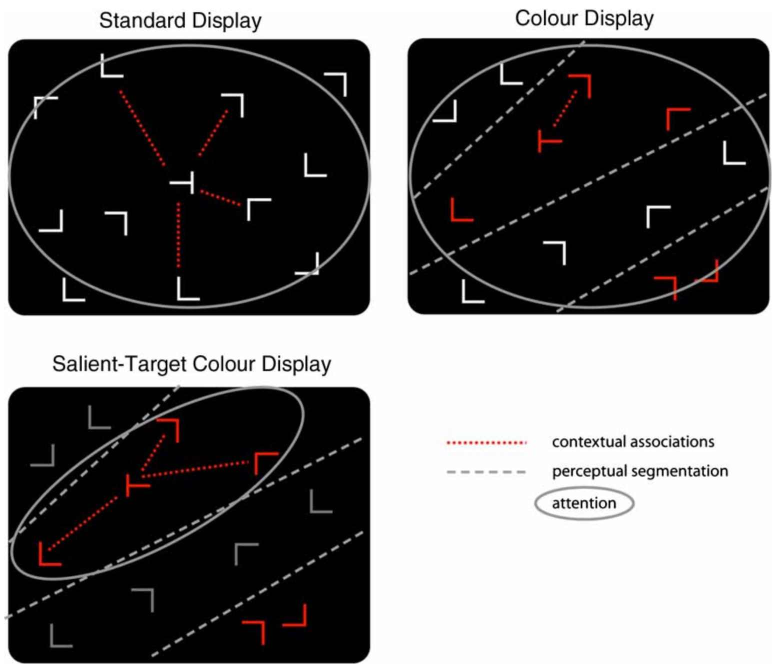

Figure 11. Example display layouts with schematic illustrations of the interactions between contextual learning, grouping, and attention: For a given standard display (A), attention is initially distributed broadly across the entire display, and stable contextual associations (red, dotted lines) are established between the target and the local context. By contrast, the same contextual associations would be distorted by perceptual segmentation processes (grey, dashed lines) in a display that is grouped (colour display, B) due to the interference between contextual and grouping cues. For grouped displays, effective contextual cueing arises when a subset of items is preselected (i.e., prioritized), for example on the basis of stimulus salience (salient target-group display, C). See text for further details. To view this figure in colour, please see the online issue of the Journal.

extent from repetitions of a given display layout. One way to overcome these limitations would be that attention is consistently biased towards one group. For example, when the subgroup that contains the target is relatively more salient (Figure 11C), then focal attention will primarily select that group and contextual associations can be formed within the group, without suffering from “cross-border” interference given by the segmented display. Thus, in sum, within this framework, grouping interacts with contextual learning, with attention serving as a “mediator” in selecting relevant parts of the display.

In conclusion, we have found psychophysical evidence to suggest that context-based learning occurs at a relatively early (i.e., perceptual) stage of processing. The segmentation of a display into distinct groups on the basis of item similarity caused relatively strong interferences with contextual cueing, a process that presumably operates on the association of a local context with a given target location. Only when attention could bias target selection was the interference between context-based learning and grouping overcome, suggesting that statistical learning of contextual invariances is dependent upon the perceptual constraints in a given scene layout.

In general, the current results provide a challenge to the view that contextual cueing is simply a mechanism in support of attentional guidance. Instead, one could assume that context-based learning reflects a relatively general property of the visual system to register regularities given by the environment. However, this ability to incorporate the scene regularities can be rather fragile. For instance, if there are other means to guide attention (e.g., by using grouping information in order to segment a scene), then the ability to use the statistical covariance between objects is clearly reduced or even nonexistent.

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Manuscript received March 2010
Manuscript accepted August 2010