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Predictive visual search: role of environmental regularities in the learning of context cues

Artyom Zinchenko¹, Markus Conci¹, Hermann J. Müller^{1,2} & Thomas Geyer¹

1 Department Psychologie, Ludwig-Maximilians-Universität München, Munich, Germany

2 Department of Psychological Science, Birkbeck College, University of London, London, United Kingdom

Correspondence to:

Artyom Zinchenko

Department Psychologie

Lehrstuhl für Allgemeine und Experimentelle Psychologie

Ludwig-Maximilians-Universität München

Leopoldstraße 13 80802 München, Germany

Tel: +49-(0)89/2180-2336

Fax: +49(0)89/2180-5211

E-Mail: Artyom.Zinchenko@psy.lmu.de

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1 Abstract

2 Repeatedly searching through invariant spatial arrangements in visual search displays
3 leads to the build-up of memory about these displays (contextual-cueing effect). In the present
4 study, we investigate (1) whether contextual cueing is influenced by global statistical
5 properties of the task; and if so (2) whether these properties increase the overall strength
6 (asymptotic level) or the temporal development (speed) of learning. Experiment 1a served as
7 baseline against which we tested the effects of increased or decreased proportions of repeated
8 relative to non-repeated displays (Experiments 1b and 1c, respectively), thus manipulating the
9 global statistical properties of search environments. Importantly, probability variations were
10 achieved by manipulating the number of non-repeated (baseline) displays so as to equate the
11 total number of repeated displays across experiments. In Experiment 1d, repeated and non-
12 repeated displays were presented in longer streaks of trials, thus establishing a stable
13 environment of sequences of repeated displays. Our results showed that the build-up of
14 contextual cueing was expedited in the ‘statistically-rich’ Experiments 1b and 1d, relative to
15 the baseline Experiment 1a. Further, contextual cueing was entirely absent when repeated
16 displays occurred in the minority of trials (Experiment 1c). Together, these findings suggest
17 that contextual cueing is modulated by observers’ assumptions about the reliability of search
18 environments.

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20 Word count: 204/250

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22 Keywords: environmental statistics, contextual cueing, predictive coding, visual search

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1 Introduction

2 Natural images contain various statistical regularities (Kersten, Mamassian, & Yuille,
3 2004). For instance, objects in real life are often positioned at invariant locations (e.g., icons
4 on the desktop of an office computer, a mailbox in a front yard; Palmer, 1975), and the human
5 visual system is able to acquire these regularities from past experience to prioritize where to
6 look and to attend for efficient visual processing of the sensory environment. One such
7 mechanism, which supports the efficient guidance of attention, is contextual cueing (Chun,
8 2000). Contextual cueing refers to the expedited visual search for targets presented in
9 invariant ('repeated') distractor configurations. Typically, participants perform a relatively
10 difficult search for a target letter "T" embedded in a set of distractor letters "L". Unbeknownst
11 to them, half of the trials contain repeated ('old') displays, while the spatial arrangement of
12 the distractors surrounding the target is compiled anew on each trial in the other half of trials
13 ('new' displays). The typical finding is that reaction times (RTs) are faster to old as compared
14 to new displays. This RT benefit for repeated layouts is referred to as the contextual-cueing
15 effect, which has been shown to remain effective for up to 10 days (van Asselen & Castelo-
16 Branco, 2009; Zellin, von Mühlennen, Müller, & Conci, 2014). Moreover, participants' ability
17 to discriminate repeated from non-repeated displays is typically only at chance level. Chun
18 and Jiang (1998) took these findings to suggest that learned spatial target-distractor
19 associations, stored in implicit long-term memory, come to guide search, by "cueing"
20 attention to the target location (Schankin & Schubö, 2009).

21 The ability to learn and to predict future environmental states is also a central element of
22 current theories of human information processing. At the heart of the so-called predictive-
23 coding models (Friston, 2010; Gold & Shadlen, 2007; Huang & Rao, 2011) is the idea that the
24 brain is essentially an inference machine that actively tries to explain its sensations by
25 reducing surprise, or prediction errors, on the basis of learned information from prior
26 environmental interactions. Thus, in order to behave optimally in a multi-faceted and multi-
27 sensory world, it is important to build-up memory representations about the current sensory
28 environment and to use this memory for predicting important objects (events) on future
29 occasions. Applying this idea to the context-based guidance of visual search, statistical
30 knowledge in the form of target-distractor associations stored in memory would correspond to
31 some model of the world (Hohwy, 2015) that the brain can use for predicting important
32 aspects of the scene (such as the location or identity of the critical target object). Critically,

1 predictive-coding models also make assumptions about the relation between sensation and
2 prediction in perceptual experience (i.e., bottom-up and top-down processing, respectively).
3 Specifically, it has been assumed that bottom-up influences vary as a function of the
4 reliability of the sensory environment (Friston, 2010; Hohwy, 2015). A prediction error is
5 likely to act as a learning signal and eventually lead to the build-up (or update) of long-term
6 memory when the environment is itself predictive and contains statistical regularities on many
7 trials. By contrast, prediction errors may be resolved (suppressed) at early stages of the
8 perceptual hierarchy in a ‘noisy’ environment, in which statistical regularities occur only on
9 few trials. Under these conditions, a sensory event, be it a reliable occurrence or unwanted
10 noise, is likely not to affect further (higher-order) processing. Note that predictive coding
11 models equate bottom-up sensation with perceptual prediction errors, so that effectively only
12 the prediction error (defined as the mismatch between sensation and expectation) is made
13 available to higher cognitive processes, including learning about repeated search displays.
14 One prediction that follows from this scheme is that the context-based guidance of visual
15 search is modulated by the relative occurrence of repeated – *signal* – relative to non-repeated
16 – *noise* – trials. The present study was designed to examine this idea.

17 Specifically, we examined whether and how learning of repeated target-distractor
18 arrangements would vary for variable proportions of repeated relative to non-repeated
19 displays. For instance, according to predictive-coding accounts, one would expect that a large
20 proportion of repeated trials would lead to particularly strong context memory about the
21 repeated displays. In line with this, several studies show that the frequency structure of the
22 visual input can modulate learning in a visual-search task. For instance, Geyer, Müller, and
23 Krummenacher (2008; see also Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Töllner,
24 Müller, & Zehetleitner, 2012) found that the latency of the first eye movement (saccade) on a
25 given search trial was reduced when task-irrelevant distractors were frequent and thus
26 expected (i.e., they were effectively excluded from visual selection). Müller et al. (2009)
27 adopted a paradigm in which the most (bottom-up) salient item was not the target, but rather a
28 distracting non-target that had to be ignored (see Theeuwes, 1991). In this task variant,
29 behavioral and oculomotor response latencies to the target are typically slower in the presence
30 compared to the absence of the distractor (an effect referred to as *distractor interference*).
31 Müller and collaborators demonstrated that this effect is sensitive to variation in the
32 proportions of distractor to no-distractor trials. By varying the presentation frequency of
33 distractors occurring in 20%, 50%, or 80% of the trials, they observed a monotonic reduction

1 of distractor interference.

2 The latter finding is in general agreement with recent neuroscientific studies showing that
3 manipulations of the repetition probability lead to a substantial modulation in the neural
4 processing signatures of incoming sensory stimulation. For instance, Summerfield, Trittschuh,
5 Monti, Mesulam, and Egnér (2008; see also Larsson & Smith, 2012; Kovács, Kaiser,
6 Kaliukhovich, Vidnyánszky, & Vogels, 2013) reported a reduction of blood oxygen level-
7 dependent (BOLD) activity in the fusiform face area in response to repeated as compared to
8 non-repeated (face) stimuli, which was particularly pronounced when repetitions were
9 frequent and thus expected. More recently, Summerfield et al. (2011) replicated their original
10 finding using temporally precise electroencephalographic (EEG) measures: they observed
11 enhanced event-related potentials, approximately 300 milliseconds (ms) after stimulus onset
12 at central electrodes, for repeated relative to non-repeated stimuli when repetitions occurred in
13 the majority of trials (and were thus expected).

14 Taken together, these findings indicate that (bottom-up driven) visual exploration can be
15 modulated by expectations generated based on the recently experienced frequency distribution
16 patterns in the task environment; that is, recent experiences, including both short- and long-
17 term memory influences, can act as ‘primes’ to subsequent visual search behavior given
18 sufficient evidence of stimulus repetitions (see Conci, Zellin, & Müller, 2012, for such a
19 view).

20 **Rationale of the present study**

21 The present experiments investigated whether predictive-coding models provide an
22 appropriate account for contextual cueing of visual search, that is, stimulus repetition effects
23 that manifest on a relatively long timescale (of several days; van Asselen & Castelo-Branco,
24 2009). Although contextual cueing is usually considered to reflect effortless and cognitively
25 impenetrable learning (Chun, 2000), the idea developed above on predictive coding suggests
26 that configural learning is influenced by the reliability of sensory signals, corresponding to
27 observers’ implicit assumptions about the presence versus absence of statistical regularities of
28 the current sensory environment (Friston, 2010). In this view, only highly regular
29 environments will lead to a processing focus on bottom-up perceptual input, thus increasing
30 the detection of a statistical regularity in this display and boosting the learning of associations
31 between the target position and the constant distractor context. In the present study, we tested
32 two such environmental regularities: repetition probability, defined as the proportion of

1 repeated relative to non-repeated displays (cf. Larsson & Smith, 2012); and repetition
2 volatility, defined as the rate of change of repeated and non-repeated displays (cf.
3 Summerfield et al., 2011).

4 A related question concerns the specific way in which environmental regularities
5 influence contextual cueing. For example, if contextual cueing takes into account event
6 probabilities, one would expect the strength of memory-based guidance to be higher in
7 environments with many repeated, as compared to many non-repeated, displays (regular vs.
8 irregular environments). This may be so because in regular environments, a higher number of
9 repeated displays is detected and subsequently stored in memory – thus increasing the mean
10 contextual-cueing effect. Of note in this regard, several contextual-cueing studies have shown
11 that only very few repeated displays are actually learned (i.e., represented in context
12 memory); in other words, many repeated displays are searched as inefficiently as non-
13 repeated displays (e.g., Colagiuri & Livesey, 2016; Geyer, Müller, Assumpcao, & Gais, 2013;
14 Johnson, Woodman, Braun, & Luck, 2007; Peterson & Kramer, 2001; Schlagbauer, Müller,
15 Zehetleitner, & Geyer, 2012; Smyth & Shanks, 2008). If regular environments indeed
16 increase the number of displays producing contextual cueing, one would expect an increased
17 overall contextual-cueing effect (averaged across all repeated displays). We refer to this as the
18 ‘strength’ hypothesis. Alternatively, it is possible that regular environments, rather than
19 changing the strength of contextual guidance, do increase the speed with which observers
20 acquire contextual memory representations. This ‘acceleration’ hypothesis would predict that
21 repeated contexts are learned faster in regular as compared to irregular environments;
22 however, once the acquisition is completed (after a learning phase of variable length),
23 context-based search guidance would be comparable in effect magnitude irrespective of the
24 regular or irregular search environment.

25 In Experiment 1a, observers performed a visual search task in which they encountered
26 repeated and non-repeated (i.e., randomly generated) display arrangements that were
27 presented in random order across trials within a given block. Thereafter, a recognition test
28 was administered: participants were presented with a display arrangement and had to indicate
29 whether or not they believed having seen this display in the previous search task (two-
30 alternative forced-choice, 2AFC, task; cf. Chun & Jiang, 1998). Each trial of the search task
31 was equally likely to contain a repeated or a non-repeated arrangement. Thus, Experiment 1a
32 served as ‘baseline’ against which contextual-cueing effects were compared in the other two
33 experiments, which manipulated environmental regularities. Experiments 1b and 1c tested

1 whether different probabilities of repeated and non-repeated displays would influence the
2 contextual-cueing effect. Two conditions were used: in Experiment 1b, repeated displays
3 occurred with higher probability than non-repeated displays: 80% versus 20% (regular
4 condition). These probabilities were reversed in Experiment 1c, presenting only 20% repeated
5 and 80% non-repeated displays (irregular condition). Importantly, the total number of trials
6 with repeated displays was held constant in all experiments. Thus, variations of the
7 probability with which repeated displays were encountered were achieved by manipulating
8 the number of non-repeated displays. With this approach, we were able to equate the absolute
9 number of presentations of repeated displays across the regular, irregular, and baseline
10 conditions.

11 In Experiment 1d, we went on to compare contextual cueing in ‘stable’ versus ‘volatile’
12 environments. Volatile environments are in essence identical to typical conditions in
13 contextual-cueing experiments: each block of trials presents 50% repeated and 50% non-
14 repeated displays, with the probability of a repeated or non-repeated display being the same
15 on a given trial. In the volatile (default) environment, changes from repeated to non-repeated
16 displays (and vice versa) were frequent, occurring, on average, in 50% of the trials (i.e. about
17 8 times per block of 16 trials; see below for further details). By contrast, in stable
18 environments, each block was composed of two “mini-blocks” (or streaks) of 8 repeated and 8
19 non-repeated displays, respectively (the order of repeated and non-repeated streaks was
20 counterbalanced across observers). With this manipulation, in stable environments a change
21 from repeated to non-repeated displays (or vice versa) was rare, occurring in only ~ 6% of the
22 trials (once per block). One could assume that environmental regularities become evident
23 more strongly under conditions of rare changes, thus increasing the detection of repeated
24 displays as “repeated”. In such a stable environment, contextual cueing should be overall
25 stronger (strength hypothesis) and / or develop earlier (acceleration hypothesis) as compared
26 to the volatile environments.

27 **General Method**

28 **Participants**

29 The same 13 participants (6 male, mean age: 26.8 years; all reporting normal or
30 corrected-to-normal vision) took part in Experiments 1a through 1d. Sample size was
31 determined on the basis of previous studies that investigated perceptual learning of the target

1 in relation to an invariant context of distractor elements, importantly also including M. Chun's
2 pioneering work (e.g., Chun & Jiang, 1998; Chun & Jiang, 1999; Chun & Phelps, 1999).
3 These studies (see also Assumpção, Shi, Zang, Müller, & Geyer, 2015; Geringswald, Herbik,
4 Hofmüller, Hoffmann, & Pollmann, 2015; Geyer, Zehetleitner, & Müller, 2010; Zellin, von
5 Mühlennen, Müller, & Conci, 2013a; Zellin, von Mühlennen, Müller, & Conci, 2014) typically
6 tested between 5 and 14 participants on the visual search/ contextual-cueing task. On the basis
7 of effect size measures provided in these studies (Assumpção et al., 2015; Geringswald et al.,
8 2015; Zellin et al., 2013a; Zellin et al., 2014), we determined that our sample size would be
9 appropriate to detect an $f(U)$ effect size of 1.0 with 85% power (partial $\eta^2 = 0.4$, groups = 2,
10 number of measurements = 4), given an alpha level of .05 and a nonsphericity correction of 1.
11 To minimize transfer effects, the experiments were performed in individual sessions, which
12 were separated by at least 10 days. Further, the experimental manipulations were administered
13 in two counterbalanced orders: each participant started with Experiment 1a (to obtain an
14 unbiased baseline measure initially), followed by Experiments 1b/c (with Experiments 1b and
15 1c performed in counterbalanced order across participants) and finally, Experiment 1d. The
16 relative fixed order of experiments was necessary to first establish a baseline contextual-
17 cueing effect in all participants against which the subsequent experimental variations could
18 effectively be compared. Additionally, a within-subjects design was essential for the purpose
19 of the study, as individual differences in the rate of contextual learning (i.e., in the between-
20 subject design) could have obscured potential systematic effects as induced by our
21 environmental manipulations. One participant could not attend further experiments after
22 Experiment 1a (this means that the total number of initially recruited observers was 14, but all
23 analyses reported are based on the 13 observers who completed all experimental parts). All
24 participants provided written informed consent prior to the experiment and received 8 € per
25 hour or course credit for participating in this study. Before the start of each experiment,
26 participants performed one practice block of 24 trials (data not recorded).

27 **Apparatus and stimuli**

28 The experimental routine was programmed in Matlab with Psychtoolbox extensions
29 (Brainard, 1997; Pelli, 1997) and was run on a PC under the Windows 7 operating system.
30 Participants were seated in a dimly lit room in front of a 23-inch LCD monitor (ASUS,
31 Taiwan; refresh rate 60 Hz; display resolution: 1920 x 1080 pixels) at a viewing distance of
32 approximately 80 cm (unrestrained). The search displays consisted of 12 dark grey items

1 (luminance: 1.0 cd/m²; 1 “T”-shaped target and 11 “L”-shaped distractors) presented against a
2 black background (0.11 cd/m²). All stimuli extended 0.35° of visual angle in width and height.
3 The items were arranged on four (invisible) concentric circles around the display center (with
4 a radius of 1.74°, 3.48°, 5.22°, and 6.96°, for circles 1 through 4, respectively). The target was
5 always positioned on the third circle. There were overall 16 possible target locations, 8 of
6 which were used for repeated displays with constant distractor layout throughout the
7 experiment (2 in each quadrant). The other 8 target locations (also 2 in each quadrant) were
8 used for non-repeated displays with random distractor arrangements. The “T” target was
9 rotated randomly by 90° to either the left or the right. The 11 remaining items were L-shaped
10 distractors rotated randomly by 0°, 90°, 180°, or 270°.

11 **Trial sequence**

12 A trial started with the presentation of a fixation cross (size: 0.10° luminance: 1.0 cd/m²)
13 for 500 ms, followed by a blank interval of 200 ms before the onset of the search display.
14 Observers were instructed to respond as quickly and accurately as possible to the orientation
15 of the “T” (left vs. right). Each search display stayed on the screen until the observer’s
16 manual choice response was registered. Observers responded to the left/right orientation the
17 “T” target by pressing the left/right arrow button on a computer keyboard with their
18 corresponding index finger. Following an erroneous response, a red minus sign appeared on
19 the screen for 1000 ms. Each trial was followed by a blank inter-trial interval of 1000 ms.

20 **Design and procedure**

21 In all experiments, the repeated condition was composed of 8 randomly arranged target-
22 distractor configurations, generated at the beginning of the experiment. These arrangements
23 were repeatedly presented on randomly selected trials throughout the search task, with the
24 restriction that each repeated display was shown only once per block. Displays in the non-
25 repeated condition were generated at the beginning of a given trial. In Experiment 1a,
26 repeated arrangements were presented in half of the trials, and non-repeated arrangements in
27 the other half. Trial order was randomized in each block. To equate target location repetition
28 effects between the two types of displays, the target appeared equally often at each of 16
29 possible locations throughout the experiment: 8 locations were used for repeated displays and
30 the remaining 8 for non-repeated displays. Furthermore, item density was controlled for each
31 display, presenting three search items per quadrant (see Annac, Conci, Müller, & Geyer,

1 2017). The orientation of the target in a given repeated display was selected at random on
2 each trial, whereas the non-targets were held constant across repetitions (cf. Chun & Jiang,
3 1998). Figure 1 depicts example search displays for the repeated and non-repeated conditions.
4 The experiments were divided into 16 blocks each, with a variable number of trials dependent
5 on the number of non-repeated displays (see below). Participants had the opportunity to take a
6 short break between blocks or continue directly with the next block. To acquire reliable
7 estimates of contextual cueing, we collapsed 4 consecutive blocks into one epoch for analysis.

8 In Experiment 1a, each block contained 16 trials, yielding a total of 256 trials. In each
9 block, 8 trials presented repeated target-distractor arrangements and the other 8 trials non-
10 repeated layouts. Experiment 1a served as baseline against which the effects of the
11 environmental manipulations in Experiment 1b/c and 1d were compared. In Experiment 1b
12 (regular condition), each block contained 10 trials, resulting in a total of 160 trials. Each block
13 consisted of 8 repeated and 2 non-repeated trials, yielding a ratio of repeated to non-repeated
14 displays of 80:20. In Experiment 1c (irregular condition), each block contained 40 trials, that
15 is, 640 trials in total. Each block contained 8 repeated and 32 non-repeated displays, with a
16 repeated- to non-repeated-display ratio of 20:80. In other words, the crucial difference
17 between Experiments 1b and 1c was the number of non-repeated displays (32 vs. 512), while
18 the number of repeated displays was constant (always 128). Experiment 1d was similar to
19 Experiment 1a in that half of the trials in a given block contained repeated displays and the
20 other half were non-repeated displays (the total number of trials was 256 as in Experiment
21 1a). However, in contrast to Experiment 1a, Experiment 1d introduced ‘stable’ environments
22 where repeated and non-repeated displays were presented in sequences, or streaks (of 8 trials)
23 of repeated and non-repeated displays. The sequence of repeated and non-repeated displays
24 was controlled: half of the participants started the experiment with a sequence of repeated
25 displays followed by a sequence of non-repeated displays (and they continued with this order
26 throughout the experiment), while the other half started with a sequence of non-repeated
27 displays followed by repeated displays. Note that the order of individual old and new
28 configurations was randomized within the streaks.

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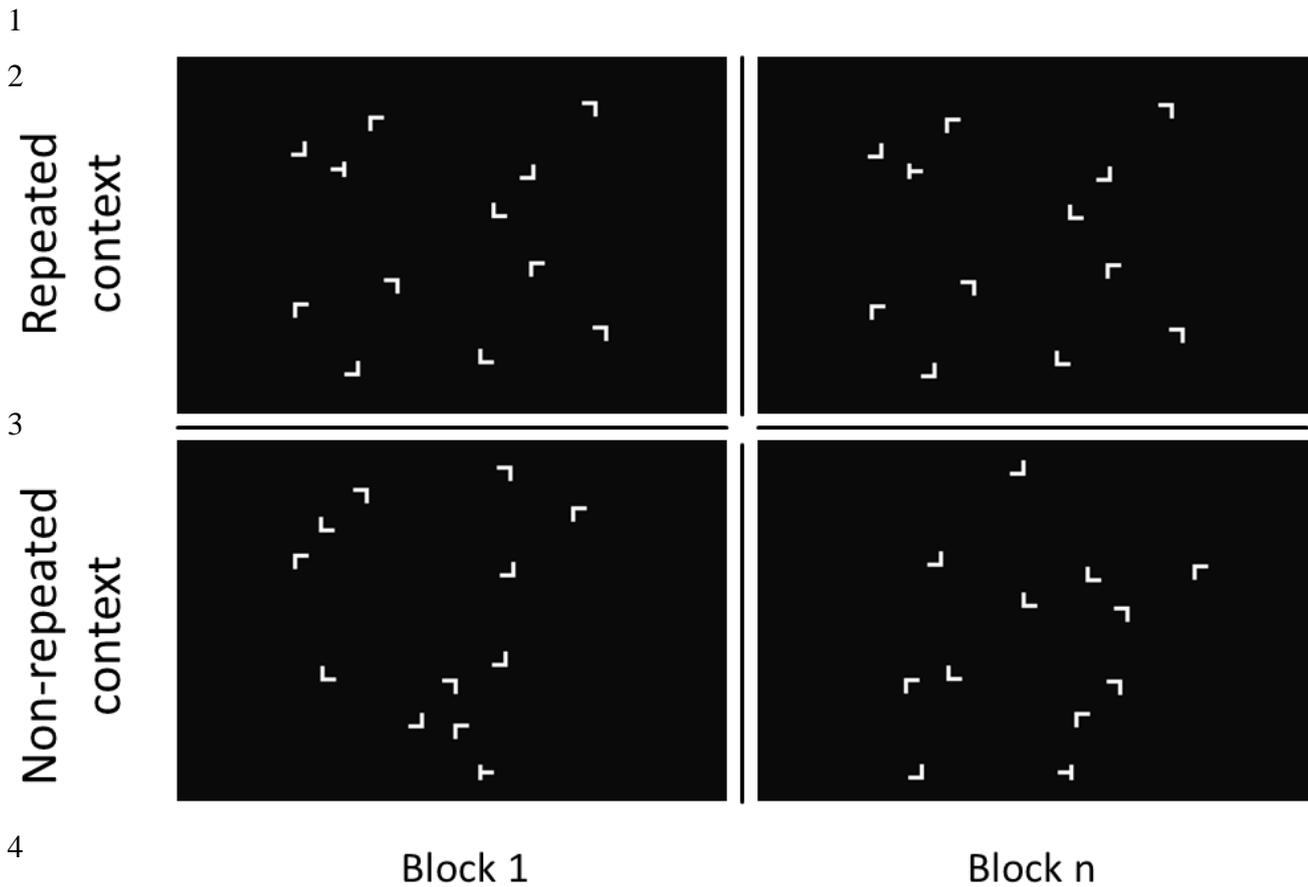


Figure 1. Example search displays with repeated and non-repeated target-distractor configurations (top and bottom panels, respectively).

Recognition test

At the end of each experiment, observers performed a yes/no recognition test, intended to examine whether they had (any) explicit memory of the repeated configurations (a standard procedure in contextual-cueing experiments; cf. Chun & Jiang, 1998). To this end, 8 repeated displays from the search task and 8 newly composed displays were shown and observers were asked to indicate whether or not they had seen a given display previously (by pressing the left or the right mouse key, respectively, without time pressure). The 8 repeated and 8 non-repeated displays were presented in random order for four times (i.e., in 4 separate blocks), yielding a total of 72 recognition trials. Note that the 8 non-repeated displays were also repeated during the 4 blocks of the recognition test in order to equate display repetitions between repeated and non-repeated displays. The response was non-speeded, and no error feedback was provided.

1 Results

2 In order to gain a coherent picture of the effects of environmental manipulations on
3 contextual cueing, it was necessary to test for the absence of effects. Since non-significant
4 results as such can only be interpreted as absence of evidence, we used Bayes factors which
5 can also be interpreted as evidence of absence given they are sufficiently small (see Dienes,
6 2013; Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayes Factors allow for an
7 assessment of the degree to which the observed data favor the alternative hypothesis (Jarosz
8 & Wiley, 2014; Jeffreys, 1961). In the present analyses, we used the Bayes Factor algorithms
9 implemented in the JASP software (Marsman & Wagenmakers, 2016), with BF_{10} based on a
10 directional H_1 (pre > post) and a Cauchy prior width of 0.707 (default). A Bayes factor of > 3
11 is considered as substantial evidence against the absence of effects, while a factor of < 1 is
12 evidence for the null effect. Finally, Bayes factors between 1 and 3 are typically taken as
13 inconclusive evidence and thus neither the null nor the alternative hypothesis is supported.

14 Individual mean error rates were calculated for each experiment and factor (epoch x
15 context) combination. The mean error rate was very low (<1%), and no main effects or
16 interactions were significant (all p 's > 0.1, BF_{10} < 1).

17 Next, individual mean RTs were calculated for repeated and non-repeated contexts
18 separately for each epoch (1-4). Error trials and RTs exceeding the individual's mean RT by
19 2.5 standard deviations were excluded from analysis. This outlier criterion led to the removal
20 of < 5% of all trials. Greenhouse-Geisser corrected values are reported in case Mauchley's
21 test of sphericity was significant (p < 0.05).

22 Experiment 1a: baseline

23 Experiment 1a was performed to acquire a baseline measure of contextual cueing,
24 presenting 8 repeated and 8 non-repeated displays per block (ratio: 50:50). Fig. 2 shows mean
25 RTs for repeated and non-repeated contexts as a function of epoch together with the
26 corresponding contextual-cueing effects (RT[non-repeated] minus RT[repeated]). RTs were
27 subjected to a 2 (context: repeated, non-repeated) x 4 (epoch: 1-4) repeated-measures
28 ANOVA, which revealed a main effect of context: repeated displays elicited overall shorter
29 RTs compared to non-repeated displays (Figure 2; contextual-cueing effect: 131 ms; $F(1,12)$
30 = 17.24, p < 0.01, η_p^2 = 0.590, BF_{10} > 1841). In addition, the context x epoch interaction was
31 significant ($F(3, 36) = 7.69$, p < 0.01, η_p^2 = 0.391, $BF_{10} = 14.52$). As revealed by follow-up
32 analyses, repeated contexts facilitated visual search from epoch 2 onwards (contextual-cueing

1 effects > 130 ms; all p 's < 0.01, $BF_{10} > 12.00$), but not in epoch 1 (contextual-cueing effect: -
2 1.6 ms; $F(1, 12) = 0.001$, $p > 0.9$, $\eta_p^2 = 0.001$, $BF_{10} = 0.27$).

3 This pattern is in line with previous investigations of contextual guidance of visual
4 search, which indicate that context information can serve as a strong cue for the detection
5 (and subsequent processing) of the target in repeated displays, also expressed in expedited
6 guidance of the eyes to the target (e.g., Geyer, Zehetleitner, & Müller, 2010; Kunar, Flusberg,
7 Horowitz, & Wolfe, 2007; Peterson & Kramer, 2001; Zellin, von Mühlennen, Müller, & Conci,
8 2013b).

9 **Experiment 1b/c: effects of repetition probability**

10 Experiment 1b/c was designed to examine whether the memory underlying contextual
11 cueing is sensitive to the probability with which repeated displays occur. To carry this out, we
12 kept the total number of repeated displays constant (thus equating the number of to-be-learned
13 displays across different levels of probability) and instead manipulated the number of new
14 displays: either presenting relatively few (Experiment 1b) or relatively many (Experiment 1c)
15 non-repeated displays together with (a constant number of) repeated displays. In Experiment
16 1b (henceforth referred to as 'regular' condition), there were 32 trials with non-repeated and
17 128 trials with repeated displays, leading to a ratio of 20:80 (non-repeated: repeated displays).
18 In Experiment 1c ('irregular' condition), there were 512 non-repeated and 128 repeated trials
19 [80:20 ratio]. Prior research had shown that contextual cueing is influenced by the frequency
20 with which a given repeated display appears in a given block of trials (with larger contextual-
21 cueing effects for frequently repeated displays; cf. Tseng, Hsu, Tzeng, Hung, & Juan, 2011).
22 Given this, investigating the effects of expectations arising from the relative repetitions of
23 repeated and non-repeated displays on context-based guidance of search would require that
24 the effects of absolute repetitions of individual target-distractor arrangements are equated
25 across the critical learning conditions. For this reason, in Experiments 1b and 1c, we realized
26 variations of the relative occurrence of repeated displays by manipulating the number of non-
27 repeated displays. According to the strength hypothesis, contextual cueing should be stronger
28 in Experiment 1b (regular condition) and weaker in Experiment 1c (irregular condition),
29 relative to the baseline Experiment 1a. The acceleration hypothesis predicts a faster
30 development of the cueing effect in Experiment 1b, as compared to an intermediate
31 development in the baseline Experiment 1a, and a slow development in Experiment 1c. Of
32 course, these two hypotheses are not mutually exclusive, as it is possible that environmental

1 regularities increase both the onset and asymptotic strength of the cueing effect. Note that a
2 preliminary analysis comparing mean RTs (and standard deviations) of new – baseline –
3 displays in Experiments 1b and 1c revealed no differences between the experiments, $F(1, 25)$
4 $= 1.19, p > 0.28$; Levene's test $F = 0.028, p > 0.86$. This suggests that any differences in
5 contextual-cueing performance between Experiment 1b and 1c are unlikely to be due to
6 differences in observers' overall response speed.

7 **Experiment 1b: high repetition probability**

8 In Experiment 1b, non-repeated displays occurred only rather infrequently (in 32 trials).
9 Given this, in order to achieve a reasonably stable estimate of RTs in the non-repeated
10 condition, we combined RTs to non-repeated displays across Experiments 1b and 1c (see,
11 e.g., von Mühlenen & Conci, 2016, for a comparable procedure).

12 For the RT analysis, we first examined contextual cueing as a function of epoch in
13 Experiment 1b. A 2 (context) x 4 (epoch) repeated-measures ANOVA revealed a main effect
14 of context: repeated displays gave rise to faster RTs relative to non-repeated displays
15 (contextual-cueing effect: 138 ms; $F(1, 12) = 22.24, p < 0.01, \eta_p^2 = 0.650, BF_{10} > 1430$). The
16 main effect of epoch was also significant: RTs decreased with increasing number of epochs
17 (epoch 1: 1154 ms, epoch 4 = 1091 ms; $F(3, 36) = 7.55, p < 0.01, \eta_p^2 = 0.386, BF_{10} = 1.56$).
18 Interestingly, the context x epoch interaction was not significant ($F(3, 36) = 0.565, p > 0.6,$
19 $\eta_p^2 = 0.045, BF_{10} = 0.150$): Contextual cueing emerged already in epoch 1 (cueing effect: 123
20 ms) and remained strong in all subsequent epochs (cueing effect averaged across epochs 2-4:
21 143 ms; p 's < 0.05 ; see Fig. 2). However, a finer grained analysis comparing the first 8 blocks
22 (of the first 2 epochs) revealed a borderline-significant block x context interaction (further
23 considered below).

24 Next, we compared contextual learning in Experiment 1b with learning in Experiment 1a
25 (baseline condition) by means of a 2 (experiment) x 2 (context) x 4 (epoch) repeated-
26 measures ANOVA. This analysis revealed a main effect of context: repeated displays yielded
27 faster RTs than non-repeated displays (contextual-cueing effect: 134 ms; $F(1, 12) = 50.98, p <$
28 $0.001, \eta_p^2 = 0.809, BF_{10} > 2954$). The main effect of epoch was also significant: RTs became
29 faster with increasing duration of the experiment (epoch 1 = 1201 ms, epoch 4 = 1144 ms;
30 $F(3, 36) = 5.56, p < 0.01, \eta_p^2 = 0.317, BF_{10} = 0.09$). Finally, and most importantly, the three-
31 way interaction was significant ($F(3, 36) = 3.72, p < 0.05, \eta_p^2 = 0.237, BF_{10} = 4.18$). This
32 interaction reflects the results reported above: whereas contextual cueing was reliable only

1 from epoch 2 onwards in the control Experiment 1a (-1.6 ms effect in epoch 1), cueing was
2 already (almost) fully developed in epoch 1 in the regular condition in Experiment 1b (123 ms
3 effect in epoch 1; non-significant context x epoch interaction: $F(3, 36) = 0.565, p > 0.6, \eta_p^2 =$
4 $0.045, BF_{10} = 0.150$). This suggests that, unlike in Experiment 1a, repeated displays
5 facilitated visual search to an equal amount in all epochs when these displays constituted the
6 majority of trials. In other words, a high proportion of repeated displays facilitated the initial
7 build-up of the contextual-cueing effect.

8 **Experiment 1c: low repetition probability**

9 In Experiment 1c, repeated displays were presented together with many non-repeated
10 displays. Under these conditions, there was no evidence for a reliable contextual-cueing
11 effect. A 2 (context) x 4 (epoch) repeated-measures ANOVA revealed no significant main
12 effect or interaction (all p 's $> 0.1, BF_{10} < 1$; see Fig. 2).

13 Next, we contrasted the irregular condition (Experiment 1c) with the baseline
14 (Experiment 1a). A 2 (experiment) x 2 (context) x 4 (epoch) repeated-measures ANOVA
15 revealed a significant experiment x context interaction ($F(1, 12) = 6.69, p < 0.03, \eta_p^2 = 0.358,$
16 $BF_{10} = 6.02$): repeated contexts facilitated visual search for the baseline experiment (cueing
17 effect: 132 ms), but not in the irregular condition (cueing effect: 4 ms; p 's $> 0.1, BF_{10} < 1$).
18 In addition, the experiment x context x epoch interaction was significant ($F(3, 36) = 3.64, p <$
19 $0.03, \eta_p^2 = 0.233, BF_{10} = 0.04$), owing to the finding (already reported above) that contextual
20 cueing was reliable from epoch 2 onwards in the Experiment 1a, whereas there was no
21 reliable effect at all in Experiment 1c (no significant main and interaction effects: all p 's $>$
22 $0.1, BF_{10} < 1$).

23 Taken together, the results of Experiments 1b and 1c show that increasing the probability
24 of encountering a repeated context facilitates the acquisition of contextual information
25 (Experiment 1b). Conversely, reducing the probability completely eliminates contextual
26 learning. Importantly, these results were obtained despite a constant absolute number of
27 repeated displays across the regular, irregular, and baseline conditions – ruling out that any
28 differences in contextual cueing are attributable to differences in the total number of repeated
29 displays in these conditions. In addition, the difference in cueing performance between the
30 regular and irregular conditions is also unlikely to be due to carryover effects resulting from
31 previous training: recall that observers initially performed the baseline condition followed by
32 the (counterbalanced) regular or irregular conditions. It is thus possible that initial experience

1 with repeated displays affected contextual cueing in later conditions. However, what is at
2 odds with this proposal is that context cueing was completely opposite in the regular and
3 irregular conditions, despite these conditions being preceded by an identical training schedule
4 (Experiment 1a). Accordingly, the findings from the regular Experiments 1b and irregular
5 Experiment 1c indicate that contextual cueing is highly sensitive to within-experimental
6 factors that pertain to the proportion (or distribution) of repeated and non-repeated displays.

7 Next, for Experiment 1d we continued to examine whether a manipulation of the
8 temporal distance within which observers encountered individual repeated displays would
9 exert comparable effects on the context-based guidance of visual search. It should be noted
10 that an inescapable feature of the probability manipulations used in Experiments 1b/c is that
11 they also introduce variations in the inter-trial temporal distance of presentations of individual
12 repeated displays. This inter-trial spacing is either decreased (10.4 trials; Experiment 1b) or
13 increased (41.8 trials; Experiment 1c) relative to the baseline Experiment 1a (16.7 trials). It
14 might therefore, in principle, be possible that differences in the temporal spacing of individual
15 repeated displays are responsible for differences in contextual-cueing performance. For
16 instance, findings from explicit learning studies show that memory performance is typically
17 better with distributed over massive presentation of studied material (see, e.g., Dempster,
18 1987). Applying this to (implicit) contextual cueing, it is possible that participants may also
19 learn more with spaced relative to dense presentations of repeated items, e.g., because spaced
20 presentations engage qualitatively different – and deeper – levels of processing (considered
21 further in the General Discussion section). However, more efficient learning of repeated
22 displays may also come along with the disadvantage of increasing the interference between
23 individual displays (recall that the repeated condition consists of a set of 8 repeated displays)
24 and/or led to greater difficulty in matching a given display to a representation in context
25 memory. This may lead to a situation in which the beneficial effects of item spacing are
26 outperformed by interference from other non-repeated displays. In a nutshell then, the
27 temporal spacing account predicts that as the distance between repeated displays increases,
28 learning of repeated displays becomes more efficient. At the same time, however, interference
29 from concurrent displays representations increases, which would effectively decrease
30 contextual-cueing performance. As a consequence, contextual cueing should be relatively
31 constant for conditions of identical spacing of individual repeated displays. An alternative
32 account would predict that the context-based guidance of visual search increases in regular
33 environments whether or not these regularities are confounded by temporal spacing. This idea

1 was tested in Experiment 1d by employing a volatility, instead of a probability, manipulation.

2 In the new experiment, individual repeated displays were presented across longer
3 sequences of trials (uninterrupted by non-repeated displays) and followed by another
4 sequence of novel displays (uninterrupted by repeated displays). With this manipulation, the
5 average distance between individual repeated displays was set at 16.7 trials and thus fully
6 comparable to the baseline experiment. However, and in contrast to the baseline experiment,
7 experiment 1d allowed observers more massed experience of individual repeated displays,
8 uninfluenced by temporal spacing effects.

9 **Experiment 1d: low volatility**

10 In Experiment 1d, repeated and non-repeated displays were presented in streaks of trials
11 (cf. Kristjansson, Wang, & Nakayama, 2002), one after the other. A given streak, of 8 trials,
12 consisted of only repeated or only non-repeated displays, and the sequence of streaks of
13 repeated and non-repeated displays was counterbalanced across observers: they either started
14 with a streak of repeated displays followed by a streak of non-repeated displays (and
15 continued with this order until the end of the search experiment), or vice versa. Importantly,
16 the number of repeated and non-repeated displays was equal in Experiment 1d (128 trials each
17 – as in Experiment 1a), and the absolute number of repeated displays was also comparable to
18 all other experiments (Experiments 1a, 1b, and 1c), which allows investigating whether
19 streaks of trials would affect contextual learning without any confounds due to a variable
20 absolute number of trials across experiments. Furthermore, since each block of trials
21 contained the same number of repeated and non-repeated displays (though these displays were
22 presented in mini-blocks of trials), the temporal distance between individual repeated displays
23 was comparable between Experiment 1d and the ‘baseline’ Experiment 1a. Thus, any
24 variations in contextual cueing between the two experiments are unlikely to result from
25 spacing effects.

26 RTs were subjected to a 2 (context) x 4 (epoch) repeated-measures ANOVA, which
27 revealed a main effect of context: RTs were faster to repeated relative to non-repeated
28 displays (contextual-cueing effect: 119 ms; $F(1, 12) = 18.53, p < 0.01, \eta_p^2 = 0.607, BF_{10} >$
29 1446). The context x epoch interaction was non-significant: $F(3, 36) = 1.91, p > 0.14, \eta_p^2 =$
30 $0.137, BF_{10} = 0.168$: contextual cueing was evident already in epoch 1 (cueing effect: 91 ms;
31 $p < 0.01, BF_{10} = 7.76$) as well as in all subsequent epochs (cueing effect averaged across
32 epochs 2-4: 127 ms; p 's $< 0.01; BF_{10} > 30$; see Fig. 2).

1 Given that contextual cueing was reliable already in the first epoch of both Experiments
2 1b and 1d, we further explored this early onset of the cueing effect by means of a more
3 thorough analysis, comparing reaction times to repeated and non-repeated displays across
4 individual blocks (of the first epoch). Effectively, we performed a 2 x 2 x 8 repeated-measures
5 ANOVA with the within-group factors experiment (1b, 1d), context (repeated, non-repeated)
6 and block (1-8). There was a significant main effect of context ($F(1, 12) = 13.96, p = 0.003,$
7 $\eta^2 = 0.54$) in addition to a marginally significant interaction of context and block ($F(7, 84) =$
8 $1.89, p = .082, \eta^2 = 0.14$). Follow-up analyses across blocks showed that the main effect of
9 context was significant in all blocks (all p 's < 0.05), except for blocks 1 ($t(25) = -0.39, p >$
10 0.6) and block 5 ($t(25) = -1.75, p = 0.092$). There was, however, no interaction of context and
11 experiment ($F(1, 12) = 0.36, p = .56, \eta^2 = 0.03$), as well as no three-way interaction ($F(7,$
12 $84) = 0.99, p = .447, \eta^2 = 0.08$). The results of this finer grained analysis suggest that
13 contextual cueing was comparable in terms of temporal development (and overall magnitude)
14 between the 'environmentally-rich' Experiments 1b and 1d (see Table 1).

15 In a final analysis, we compared Experiments 1a and 1d in a 2 (experiment) x 2 (context)
16 x 4 (epoch) repeated-measures ANOVA. The results revealed main effects of experiment and
17 context: RTs were overall shorter in Experiment 1d than in Experiment 1a (971 ms vs. 1228
18 ms; $F(1, 12) = 9.82, p < 0.01, \eta^2 = 0.450, BF_{10} > 16$) and the repeated context facilitated
19 search performance overall in both experiments ($F(1, 12) = 57.38, p < 0.001, \eta^2 = 0.827,$
20 $BF_{10} = 4.82$). Of theoretical importance, the experiment x context x epoch interaction turned
21 out to be significant ($F(3, 36) = 5.51, p < 0.01, \eta^2 = 0.315, BF_{10} = 46.15$), reflecting the fact
22 that repeated (relative to non-repeated) displays facilitated search from epoch 1 onwards in
23 Experiment 1d (epoch 1 = 91 ms, epoch 4 = 134 ms) but only from epoch 2 onwards in
24 Experiment 1a (epoch 1 = -1.6 ms, epoch 4 = 139 ms). This pattern suggests that the
25 presentation of repeated and non-repeated displays in streaks of trials facilitates the initial
26 build-up of contextual cueing, even if temporal distances between individual repeated
27 displays are equated between the critical learning conditions. This finding supports the
28 acceleration hypothesis and further supports the results obtained in Experiment 1b.

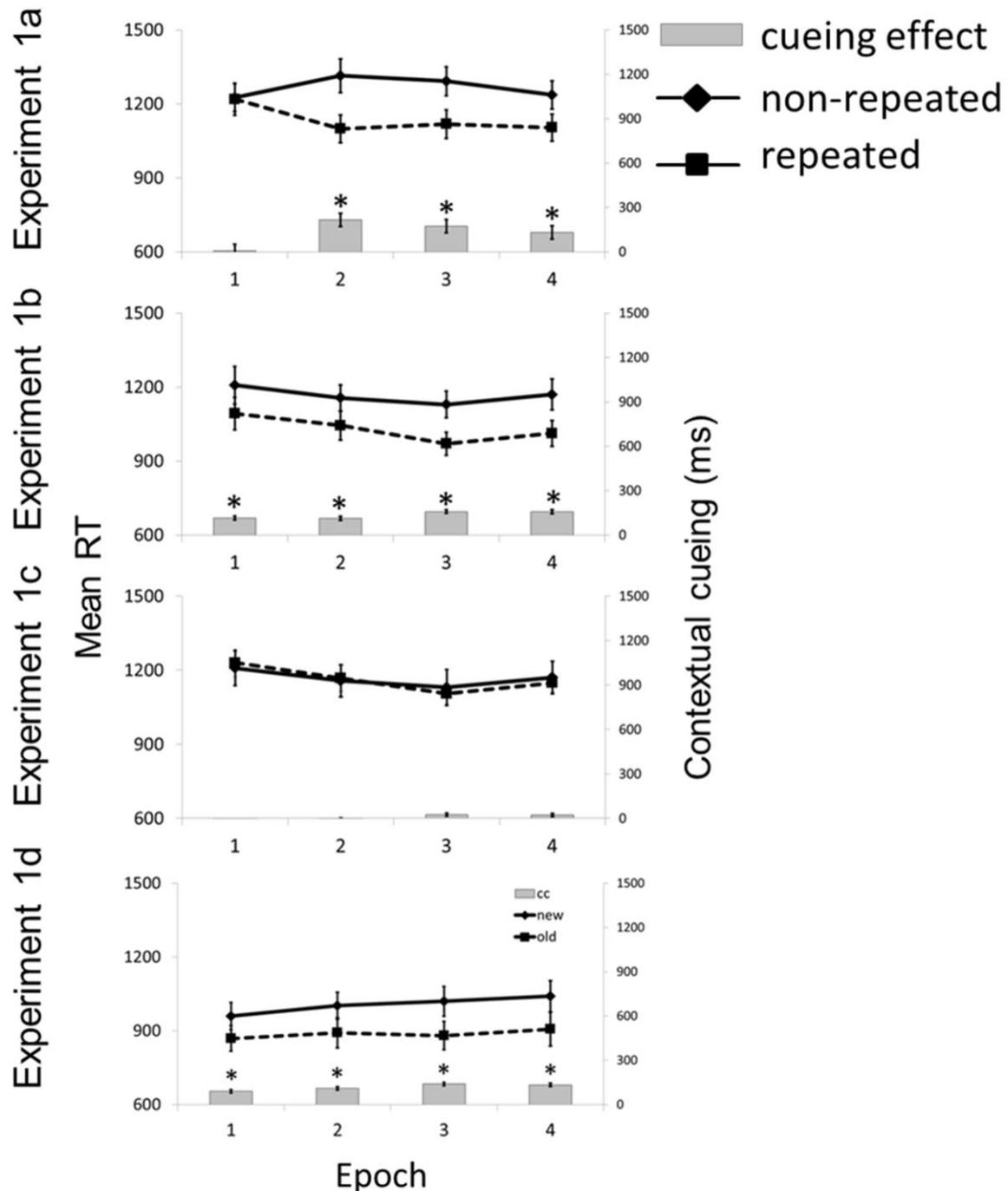
29 **Cross-session transfer**

30 Despite of the counterbalanced order in which the experiments were presented, in a final
31 set of analyses, we examined the possibility that cross-experimental variations in contextual
32 cueing nevertheless may reflect differences in the order with which participants performed the

1 individual experiments. Recall that the current study used a within-subject design, which
2 makes it possible that at least parts of the cueing effect transferred across conditions.
3 Although we used relatively large inter-session separations (of at least 10 days) and
4 counterbalancing, there remains the possibility that order effects contributed to the observed
5 results. For instance, it is possible that observers' beliefs about the presence (or absence) of
6 statistical regularities in the current search environment are carried over from one to the other
7 session. This idea is feasible given recent investigations of contextual cueing that showed that
8 the effect can emerge on several consecutive days (e.g., Jiang, Song, & Rigas, 2005; Zellin et
9 al., 2013a). However, none of these studies reported increased contextual-cueing scores across
10 subsequent days, as one might expect for the present investigation (e.g., from the baseline
11 Experiment 1a to the regular Experiment 1b). Instead, contextual cueing in the
12 aforementioned studies was either relatively constant (Jiang et al., 2005) or even reduced
13 (Zellin et al., 2013a) across subsequent days.

14 In an attempt to directly address the transfer issue, we re-analyzed RT performance in
15 Experiments 1a-d dependent on the order in which observers experienced the respective
16 environmental manipulations. There were two counterbalanced orders (see Method section):
17 'ascending' (1a→1b→1c→1d) and 'descending' (1a→1c→1b→1d). Since all observers
18 started with the baseline Experiment 1a (thus contextual cueing in the baseline could not be
19 affected by a previous experiment), we then performed three separate repeated-measures
20 ANOVAs, for Experiment 1b, 1c, and 1d, in which we included order (ascending,
21 descending) as a variable, besides display type (repeated, non-repeated) and epoch (1-4).
22 However, none of these ANOVAs revealed a significant effect of order (neither main effects
23 nor interactions; all F 's < 1.87). As a second check, we computed contextual-cueing effects in
24 the 'early' blocks 2-8 of the initial experimental epoch and compared contextual-cueing
25 scores across Experiments 1b-1d, again dependent on whether observers performed these
26 conditions in ascending or descending order. – The idea being that any cross-session transfer
27 of environmental expectations should be particularly strong in early blocks and thus up- or
28 down-modulate learning of a new set of repeated displays already in these early blocks.
29 However, variations in contextual cueing due to different orders were only small and non-
30 significant (see Table 1). The results of these analyses thus argue against any cross-session
31 transfer of contextual expectations. Instead, variations of contextual cueing seem to arise
32 almost entirely within individual sessions.

33



1
 2 **Figure 2.** Mean RTs (in ms) and associated mean standard errors (SEM) for repeated and
 3 non-repeated displays as a function of epoch in the ‘baseline’ Experiment 1a (50% repeated
 4 and 50% non-repeated displays), and in the ‘regular’ Experiment 1b (80% repeated, 20% non-
 5 repeated trials), the ‘irregular’ Experiment 1c (20% repeated, 80% non-repeated displays),
 6 and in the ‘streak’ Experiment 1d (50% repeated, 50% non-repeated trials). In Experiments 1a
 7 and 1b/c, the type of (repeated versus non-repeated) display could randomly switch after each

1 trial. In Experiment 1d, repeated and non-repeated displays were presented in streaks of 8
2 consecutive trials, with an alternating order of the streaks.

3

4 **Table 1**

5 Contextual-cueing effects (RT[non-repeated display]-RT[repeated display]) in milliseconds
6 (ms) in ‘early’ blocks 2-4 of epoch 1 for the three Experiments 1b-1d as a function of whether
7 observers participated in these experiments in ascending or descending order
8 (1a→1b→1c→1d; 1a→1c→1b→1d, respectively).

9

	<i>High-Repetition</i>	<i>Low-repetition</i>	<i>Low-volatility</i>
	<i>1b</i>	<i>1c</i>	<i>1d</i>
<i>Ascending order</i>	149 ms	-22 ms	156 ms
<i>Descending order</i>	135 ms	-52 ms	94 ms

10

11 **Recognition test**

12 As shown by Vadillo, Konstantinidis, and Shanks (2015; see also Smyth & Shanks,
13 2008), the results of (explicit) recognition tests in contextual cueing crucially depend on the
14 power of the respective tests. While standard tests of recognition in contextual-cueing studies
15 typically fail to find evidence of explicit memory (for review see Goujon, Didierjean, &
16 Thorpe, 2015), increasing the test power has been argued to be sufficient for revealing above-
17 chance recognition (Smyth & Shanks, 2008). This is supported by a recent meta-analysis by
18 Vadillo et al. (2015), which showed that, even though explicit memory of repeated search
19 displays might go ‘undetected’ in individual studies, the combined evidence indicates above-
20 chance recognition. For this reason, we combined the performance in the current recognition
21 test across all experiments, comparing the hit rates (repeated display correctly judged as
22 repeated in the recognition task) with the corresponding false-alarm rates (non-repeated
23 display incorrectly judged as repeated in the recognition task) by means of a 2 (type of
24 response: hit, false alarm) x 4 (experiment: 1a, 1b, 1c, 1d) repeated-measures ANOVA. On
25 average, observers correctly recognized repeated displays in 47% of the trials (hit rate), while
26 falsely judging non-repeated displays as repeated in 42% of trials (false-alarm rate). However,

1 the hit rate was not significantly different from the false alarm rate ($F(1, 12) = 2.118, p >$
2 $0.17, \eta_p^2 = 0.150, BF_{10} = 0.39$), and there was also no difference across the three experiments
3 (main effect of experiment: $F(3, 36) = 1.228, p > 0.3, \eta_p^2 = 0.093, BF_{10} = 0.164$; interaction:
4 $F(3, 36) = 0.938, p > 0.4, \eta_p^2 = 0.073, BF_{10} = 0.062$). This suggests that context memory was
5 uninfluenced by explicit knowledge of display repetitions in the present experiments.

6 **General Discussion**

7 The present study examined whether environmental regularities can modulate contextual
8 cueing – a form of statistical learning in visual search. In the baseline Experiment 1a, which
9 was a typical contextual-cueing experiment, half of the trials presented repeated displays and
10 the other half non-repeated displays. Experiment 1b/c then manipulated the display
11 probability, that is, the relative frequency with which repeated target-distractor configurations
12 were presented, while equating the absolute number of repeated displays across experiments.
13 In Experiment 1b, repeated displays occurred in 80% of trials and non-repeated displays in
14 20%; these probabilities were reversed in Experiment 1c. Experiment 1d then examined the
15 effects of a second environmental manipulation on context-based learning in visual search,
16 namely, the ‘volatility’ or the rate of change between repeated and non-repeated displays – by
17 presenting repeated and non-repeated displays each in longer sequences of 8 trials, with
18 alternating sequences of repeated and non-repeated displays throughout the search
19 experiment. This manipulation also served as a critical test for the effects of inter-item
20 spacing on contextual-cueing performance, which may have confounded cueing effects in
21 Experiments 1b/1c.

22 **Environmental regularities and contextual cueing**

23 The main findings were that increasing the probability of repeated relative to non-
24 repeated displays resulted in an earlier development (onset) of the contextual-cueing effect
25 (Experiment 1b), whereas reducing the probability of repeated relative to non-repeated
26 displays completely abolished the cueing effect (Experiment 1c), as compared to the baseline
27 Experiment 1a. Moreover, presenting repeated and non-repeated displays in (separate) streaks
28 of trials expedited the development of contextual cueing, again relative to the baseline
29 condition. The difference in the time course of the cueing effect across the experimental
30 manipulations shows that configural learning is influenced by environmental regularities (or
31 the lack thereof), with regular environments increasing the speed with which observers

1 acquire spatial memory about repeated search displays. On the other hand, the data also show
2 that once a cueing effect has been established, it reaches an asymptotic level – that is, the
3 magnitude of the effect cannot be further improved by statistical regularities (of encountering
4 repeated displays) in the search environment. Thus, ‘expectations’ about the occurrence of
5 invariant displays exert a very specific effect on the context-based guidance of visual search:
6 configural memory is acquired faster and guidance by repeated contexts manifests in earlier
7 epochs when repeated displays occur on the majority of trials or when they are aggregated
8 into longer sequences of trials. Importantly, these results go beyond earlier demonstrations of
9 the effects of statistical properties of the repeated displays. In particular, Tseng et al. (2011)
10 showed that increasing the frequency of the presentation of repeated displays (e.g., 1, 2, or 3
11 times per block) results in an increased magnitude of contextual cueing. In line with this, we
12 observed that regular environments have an advantageous effect on the configural learning
13 process. However, unlike Tseng and collaborators (2011), we found that the asymptotic level
14 of contextual cueing was not influenced by the probability manipulation. Instead,
15 environmental regularities were expressed only in terms of an accelerated development of the
16 contextual-cueing effect.

17 Furthermore, in the present experiment, we equated the frequency of individual repeated
18 displays (which was again different to the approach taken by Tseng et al., 2011). Thus, in
19 each experiment, the total number of to-be-learned displays was identical and differences in
20 contextual cueing across the experiments can ultimately only be attributed to observers’
21 expectations about the occurrence of repeated displays. Of note, we conceive these
22 ‘expectations’ as being implicit in nature (similar to other ‘implicit expectation’ effects in
23 visual search; see, e.g., Wolfe, Butcher, Lee, & Hyle, 2003), specifically because observers
24 were unable to explicitly tell apart repeated from non-repeated displays in the present
25 investigation - even in the case of a regular or structured environment (Experiments 1b and
26 1d).

27 We also found that a decrease of the probability of encountering repeated displays
28 substantially reduced the contextual-cueing effect. This finding may imply that the visual
29 system requires a sufficient amount of predictive information for detecting and subsequently
30 learning contextual associations. Previous studies showed that contextual cueing requires
31 some 100-150 trials (4-6 repetitions of each individual repeated display) in order to become
32 measurable (Chun & Jiang, 2003; Chun & Turk-Browne, 2008). However, our current
33 findings indicate that it is not simply the absolute number of repetitions of a given repeated

1 display that determines the formation of a stable contextual association, but also the *relative*
2 amount of evidence provided by the environment, as the number of repeated displays was
3 identical in all experiments of the present study. In other words, our data imply that when
4 repeated displays are rather infrequent, statistical learning may not operate at all. This is
5 consistent with work by Jungé, Scholl, and Chun (2007), who used a training-test design in
6 their experiment. During training, observers completed either 18 blocks of trials with only
7 repeated displays (regular condition) or 18 blocks of trials with only non-repeated displays
8 (irregular condition), with different groups of observers participating in the two training
9 conditions. In the subsequent test phase (intended for measuring the contextual-cueing
10 effects), both groups received 6 blocks of trials that contained both repeated and non-
11 repeating displays. Interestingly, Jungé et al. reported that repeated contexts expedited visual
12 search (relative to non-repeated contexts) only if participants had encountered the repeated
13 displays initially (regular condition). In the other – irregular – condition, no contextual-cueing
14 effect was evident at all. Jungé et al. took these findings to mean that, in the course of the
15 visual search task, observers develop assumptions about the presence versus absence of
16 contextual regularities. If observers come to the assumption that the current search
17 environment lacks regularities (Jungé et al.’s irregular condition), they “turn off” their
18 learning efforts, even if in the subsequent test phase they are presented with repeated displays
19 on 50% of all trials. The reason for this may be that although contextual memory traces are
20 acquired incidentally (automatically), the retrieval of these traces is an effortful, attention-
21 demanding process (e.g., Annac et al., 2013; Jiang & Leung, 2005). Another explanation
22 might be that configural learning is generally more robust in earlier epochs (sessions),
23 reflecting a kind of primacy effect in statistical learning (Zellin, Conci, von Mühlennen, &
24 Müller, 2013a). Whatever the explanation, the results of Jungé et al. (2007) are in line with
25 the present Experiment 1c, showing that expectations about the absence of repeated displays
26 impede, or entirely prevent, the development of contextual-cueing effects.

27 But probability manipulations inevitably come along with either a decreased (Experiment
28 1b) or increased (Experiment 1c) temporal spacing of individual repeated displays, relative to
29 the baseline Experiment 1a. Previous studies have repeatedly reported that explicit learning is
30 reliably affected by the temporal distribution of study time (Cepeda, Pashler, Vul, Wixted, &
31 Rohrer, 2006). Specifically, distributed relative to massed presentation of to-be-learned items
32 consistently shows learning benefits that increase proportionally with increased distance
33 between individual presentations (Kornell & Bjork, 2008; for an extensive meta-analysis over

1 317 experiments see Cepeda, Pashler, & Rohrer, 2006). When the distance between repeated
2 items is relatively small, the first occurrence of the target evokes a mental representation of
3 that object, while a prompt re-appearance of the target object reduces its semantic processing.
4 Since semantic priming wears off after a period of time (Kirsner, Smith, Lockhart, King, &
5 Jain, 1984), less semantic priming is expected for the second occurrence of a spaced item and
6 the learning is constrained. However, we believe that spacing effects are unlikely to explain
7 the current results. First, we observed that an increase in the distance of presentations of
8 individual repeated displays results in reduced contextual cueing. While this reduction may be
9 due to increased interference from concurrent contextual-cueing representations – which may
10 beat down the facilitatory effects arising from spaced over dense items, in Experiment 1d we
11 again found an up-modulation of contextual cueing, critically, when inter-display spacing was
12 identical between the environmental manipulation and the baseline experiment. But in
13 Experiment 1d, repeated and non-repeated displays were presented in longer streaks of trials,
14 rendering the presence of environmental regularities more salient. This makes an account of
15 (differences in the) temporal spacing of individual search displays unlikely. Instead, it
16 supports a view of contextual cueing according to which context memory takes into account
17 higher-order environmental properties, such as the proportion of repeated displays or the rate
18 of change between repeated and non-repeated displays.

19 Variations in the number of non-repeated displays unescapably come along with a
20 variable length of the individual experiments tested here. It is therefore possible that an
21 increased number of trials particularly in the low-probability Experiment 1c (N=640 trials)
22 resulted in an increased level of fatigue, which could potentially explain why contextual
23 cueing was weakened and even non-significant in this experiment. Jiang and Leung (2005;
24 see also Annac et al., 2013) have shown that the expression (i.e., retrieval) of learned context
25 cues requires selective attention. If now assuming that fatigue is accompanied by a reduction
26 of (sustained) attention, this could also reduce the contextual-cueing effect. But we believe
27 that this explanation is rather unlikely. We base this view on prior investigations of spatial
28 context learning that reported strong cueing effects when using, relative to the current
29 Experiment 1c, comparable or even higher numbers of trials (e.g., N=720 trials in Experiment
30 1 of Chun & Jiang, 1998). Further, significant contextual cueing was reported in
31 neuroscientific studies that used very high numbers of trials (N>1000 trials; e.g., Schankin &
32 Schubö, 2010). Thus, context learning seems to occur even in very long search experiments
33 and thus seems not to be influenced by fatigue or tiredness. In addition, the pattern of results

1 in Experiment 1c is also not compatible with the idea of fatigue in context learning. This
2 experiment revealed no differences in context learning across epochs, which would have been
3 indicative of a possible effect of fatigue on search reaction times/ contextual cueing. – If
4 fatigue would have been at play in this experiment, then the cueing effect should have been
5 reduced with increasing numbers of trials. However, contrary to this prediction, contextual
6 cueing was absent right from the beginning and did not come to the fore until the end of
7 Experiment 1c (see Figure 2). This again indicates that factors related to fatigue or tiredness
8 are unlikely to explain the pattern of results in Experiment 1c.

9 **Predictive coding and contextual cueing**

10 Contextual cueing can be interpreted as a form of statistical learning, revealing striking
11 commonalities with current predictive-coding theories (e.g., den Ouden, Kok, & de Lange,
12 2012, for review). Predictive-coding theories (Friston, 2010) assume that (i) object
13 recognition is largely achieved by taking into account prior object knowledge; and that (ii) in
14 order to successfully, that is, statistically optimally, recognize a certain object, the sensory
15 system must represent the variability, or reliability, of (the occurrence/appearance of) this
16 object. For instance, visual object information is more reliable at day than at night, and
17 auditory signals are less ambiguous in a sound-protected environment than in a busy
18 classroom. These differences in the reliability of sensory objects have a large impact on the
19 way prediction error signals are regulated in perceptual inference and learning. In regular
20 environments, a prediction error will receive a high weight in perceptual inference; in other
21 words, in regular environments, the prediction error serves as a strong learning signal. In
22 irregular environments, by contrast, the prediction error has a relatively small weight – thus
23 less is learned about the sensory environment (in fact, under these conditions, prediction error
24 signals might be effectively suppressed at lower, sensory levels; cf. Den Ouden et al., 2012).
25 Applied to the present study, in the ‘regular’ Experiments 1b and 1d, observers will be
26 confident with the current sensory input such that they can attribute meaning (i.e., ‘signal’) to
27 the input. For this reason, the visual representation of the (invariant) target-distractor relations
28 acts as a strong learning signal for the build-up of contextual memory about this display.
29 When this display is encountered on later occasions, associated configural memory traces are
30 quickly retrieved and come to support visual search. In this scheme, the context-based
31 guidance of visual search may be conceived as an application of the Bayes rule. However,
32 when the current sensory environment contains more ‘noise’ than ‘signal’ trials (i.e., more

1 non-repeated than repeated displays), less is learned about the repeated displays and visual
2 search may be predominantly driven by the featural properties of the search items. This would
3 correspond to a stimulus-based, rather than memory-based, visual search process in irregular
4 environments.

5 **Conclusion**

6 Current proposals in cognitive neuroscience emphasize predictive coding as a mechanism
7 by which the brain can predict events based on learned statistical environmental regularities.
8 However, less is known about the context factors that modulate statistical learning of sensory
9 environments. Here we use a visual search paradigm to unravel the mechanisms that
10 determine statistical learning of spatial target-distractor associations (the “contextual-cueing”
11 effect). We show that reaction time gains resulting from learned target-distractor layouts are
12 influenced by the *relative proportion* of repeated to non-repeated displays. Importantly,
13 variations in statistical context learning were achieved through manipulations of the number
14 of non-repeated trials. The results thus go beyond previous findings that showed that *absolute*
15 *frequency* with which an event occurs are important determinants in statistical learning.
16 Further, the results are unlikely to be explained by differences in the temporal spacing of
17 repeated search displays. The human perceptual system therefore seems to monitor the level
18 of noise associated with a certain sensory environment, which determines statistical learning
19 of critical task parameters, such as the location of the target in relation to the constant
20 distractor background.

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