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A secondary task is not always costly: Context-based guidance of visual search survives interference from a demanding working memory task

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Repeatedly encountering a visual search display with the target located at a fixed position relative to the distractors facilitates target detection, relative to novel displays – which is attributed to search guidance by (acquired) long-term memory (LTM) of the distractor 'context' of the target. Previous research has shown that this 'contextual cueing' effect is severely impeded during learning when participants have to perform a demanding spatial working memory (WM) task concurrently with the search task, though it does become manifest when the WM task is removed. This has led to the proposal that search guidance by LT context memories critically depends on spatial WM to become 'expressed' in behaviour. On this background, this study, of two experiments, asked: (1) Would contextual cueing eventually emerge under dual-task learning conditions if the practice on the task(s) is extended beyond the short training implemented in previous studies? and given sufficient practice, (2) Would performing the search under dual-task conditions actually lead to an increased cueing effect compared to performing the visual search task alone? The answer is affirmative to both questions. In particular, Experiment 1 showed that a robust contextual cueing effect emerges within 360–720 dual-task trials as compared to some 240 single-task trials. Further, Experiment 2 showed that when dual- and single-task conditions are performed in alternating trials blocks, the cueing effect for the very same set of repeated displays is significantly larger in dual-task blocks than in single-task blocks. This pattern of effects suggests that dual-task practice eventually leads to direct, or 'automatic', guidance of visual search by learnt spatial LTM representations, bypassing

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WM processes. These processes are normally engaged in single-task performance might actually interfere with direct LTM-based search guidance.

Our sensory world typically contains numerous statistical regularities. For example, objects are usually associated with specific environments and positioned at consistent locations, such as a mailbox in the front yard (Palmer, 1975). The visual system can pick up these regularities to optimize goal-directed behaviour. For instance, it has been demonstrated that in visual search, observers become more efficient in detecting target items presented within spatially invariant search array layouts – an effect referred to as contextual cueing (Chun, 2000; Chun & Jiang, 1998). In a typical contextual cueing task, participants are presented with a number of randomly placed L-shaped distractors and a T-shaped target item that is either pointing to the left or the right. Participants' task is to detect and subsequently discriminate the orientation of the target T as fast as possible. Unbeknownst to them, half of the search arrays are repeated and the other half non-repeated, random display arrangements. Over the course of the experiment, participants improve in their reaction time (RT) performance for repeated over non-repeated displays (contextual cueing effect). Moreover, participants' ability to discern repeated from non-repeated layouts is typically only near chance level. This pattern of results indicates that participants acquire an implicit long-term memory (LTM) representation of the regular target–distractor spatial context associations, which are automatically retrieved when encountering a learnt display arrangement, guiding – or cueing – the search process to the target location.

The role of divided attention in contextual cueing of visual search

Previous work has shown that spatial context memory is itself influenced by attention, in terms of both selectivity and processing resources involved (for a review, see, e.g., Goujon, Didierjean, & Thorpe, 2015). For instance, Vickery, Sussman, and Jiang (2010) examined whether contextual cueing is affected by a concurrent, secondary working memory (WM) task, based on the idea that contextual cueing and the secondary WM task share common processes, or draw on a common resource pool (Kahneman, 1973). Their experiments were divided into a training and a test phase. During training, the visual search (contextual cueing) task was coupled with a WM task, which required participants to retain various kinds of perceptual attributes, including spatial arrays, colours, and item sequences, while performing the search. In the test phase, participants performed the visual search task without concurrent WM load. Vickery *et al.* (2010) found a robust contextual cueing effect in the test phase when the repeated display arrangements had been encountered initially, in the training phase, under secondary WM task conditions. This suggests that contextual learning can survive interference from a concurrent WM task.

Following Vickery *et al.* (2010), a number of studies re-investigated the relation between contextual cueing and divided attention. One of the most serious criticisms levelled against the study of Vickery *et al.* (2010) was that they tested for contextual cueing only under single-task conditions (i.e., without secondary WM task in the test phase), following exposure to repeated display arrangements in a dual-task training phase. Accordingly, they could only examine whether the learning of contextual cues is affected by secondary WM load, but not whether the expression – that is, the retrieval – of learned information is dependent on WM. The latter question was investigated in a series of follow-up studies (Annac *et al.*, 2013; Manginelli, Geringswald, & Pollmann, 2011; Manginelli, Langer, Klose, & Pollmann, 2013; Travis, Mattingley, & Dux, 2013), which paired the visual search task with the WM task selectively in either the training or the test phase. The results revealed reliable contextual cueing for both a spatial and a featural (i.e., colour-based) WM task when this task was administered in the learning phase but removed in the test phase (consistent with the results of Vickery *et al.*, 2010), but not when the spatial WM task was administered in the test phase. No effects were found when the featural WM task was applied in the test phase, in which case contextual cueing of visual search was fully functional and comparable to baseline performance. Manginelli and colleagues (Annac *et al.*, 2013; Manginelli *et al.*, 2011, 2013) took this to mean that the expression of learned target–distractor associations is mediated by spatial WM (but see Travis *et al.*, 2013; for a discrepant view). Annac *et al.* (2013) went on to examine another potential source of WM interference effects in spatial contextual cueing, namely: executive WM load. This was based on previous investigations (of different perceptual tasks), which showed that observers' ability to ignore an additional, task-irrelevant, feature singleton distractor in a visual search display is reduced in the presence of an additional WM task (Lavie, Hirst, De Fockert, & Viding, 2004). To investigate this with respect to contextual cueing, Annac *et al.* (2013) manipulated the order of tasks. One group of observers had to maintain a spatial pattern in WM while performing the visual search task (similar to Manginelli *et al.*, 2011, 2013). For another group of observers, the spatial WM task did not overlap with, but was instead performed immediately after the search task on a given trial. Thus, the 'overlapping' group encountered both spatial and executive WM load while observers in the 'non-overlapping' group encountered only executive load, relating to the scheduling of events on a given trial. Annac *et al.* (2013) found contextual cueing to be reduced only in the 'overlapping' group.

Thus, collectively, the findings as to the relationship of spatial contextual cueing and WM load suggest that a concurrent spatial WM task interferes with the retrieval from, but not the acquisition of, context memory for repeated search configurations (Annac *et al.*, 2013; Manginelli *et al.*, 2011, 2013). Further, neither featural (Manginelli *et al.*, 2013) nor executive (Annac *et al.*, 2013) WM load affect the retrieval of learned context cues. Note that in this study we refer to 'retrieval' as both the actual process of retrieving information from long-term (LT) context memory as well as matching LT context representations (held in WM) against the current display input in order to facilitate search (elaborated in the next paragraph).

Contextual cueing as an instance of an automatic retrieval process

The above findings point to a dissociation of the role spatial WM plays in the initial acquisition versus the later expression of context memory: It appears that, while the initial acquisition of context memories is WM-independent, the availability of spatial WM resources is a condition for the later effective retrieval of these memories and the guidance of visual search to the target location within learned target–distractor configurations. In this context, it is important to note that context cueing is almost entirely supported by memory of individual target–distractor associations formed in the local vicinity of the target, that is, within the quadrant of the target in repeated displays (provided that the 'local' quadrant is available together with peripheral 'global' information; see, e.g., Brady & Chun, 2007; Shi, Zang, Jia, Geyer, & Müller, 2013): Once scanning enters the target quadrant (after a phase of relatively unguided search), the eye and focal attention tend to home in rapidly on the target location. Taken together with the evidence of the spatial WM dependence of the expression of contextual cueing, it would appear plausible that spatial

WM is required for the comparison of the currently scrutinized local region of the search array with 'local' target-context associations retrieved from – that is, activated in – LTM. According to this view, spatial WM would be required for the matching of stimulus-derived information with LTM contents – where, in case of a match, the context representation in spatial WM can act as a kind of 'spatial template' specifying a path to the target location. When spatial WM is occupied by search-task-irrelevant information, it may be that relevant LTM representations, even if activated, cannot be loaded into short-term memory (because access is blocked due to the requirement to maintain the spatial information for the secondary WM task) and/or the currently scrutinized region of the search display cannot be adequately represented in spatial WM (for the same reason). As a result, the matching process would be compromised and context-based search guidance rendered ineffective. Henceforth, we will refer to this as impaired 'retrieval' (for effective usage) of context memories. By contrast, if spatial WM is available, LTM context representations can make contact with the process of search guidance and facilitate a whole cascade of processes, from more efficient target localization (e.g., Johnson, Woodman, Braun, & Luck, 2007) over expedited target discrimination (e.g., Sewell, Colagiuri, & Livesey, 2017) to more rapid target response decisions (e.g., Kunar, Flusberg, Horowitz, & Wolfe, 2007).

However, while this provides a plausible account of WM-dependent expression of contextual cueing, it leaves out an important branch of research on learning and automatization in visual search tasks over the past decades (see, e.g., Schneider & Shiffrin, 1977; Logan,1988; for more recent evidence specifically relating to 'template-based' search guidance, see Woodman, Carlisle, & Reinhart, 2013). Collectively, these studies show that the effective use of LTM representations can eventually bypass capacity-limited WM stores given sufficient practice on the search task, for instance, owing to practice-dependent development of more efficient, 'automatic' retrieval operations (Shiffrin & Schneider, 1977).

Rationale of the present study

The present study was designed to re-evaluate the dependency of the expression of contextual cueing on spatial WM in the light of the beneficial effects of training in a typical contextual cueing visual search task, thereby contributing to a better understanding of the relation between contextual cueing and spatial WM. If one considers contextual cueing as a form of skilled performance – that is, a form of automatic processing (e.g., Chun & Phelps, 1999) – one would expect 'automatic' context cueing of visual search to eventually emerge as the number of search trials performed and, thus, the level of practice is increased. With regard to the findings reviewed above, namely that context learning is attention-dependent, the implication would be that these do not signify a general inability of the cueing effect to survive a demanding spatial WM task performed concurrently with the search task. Rather, a secondary WM task might just delay the development of automatic search guidance from long-term context memory.

The current study was designed to test this hypothesis by having observers perform the visual search task in combination with a demanding spatial WM task under different (short vs. long) training schedules and comparing the cueing effects obtained with that arising in a baseline, that is, single-task, search condition. In all experiments, half the trials contained repeated, or 'consistent', arrangements of the search stimuli and half non-repeated arrangements (presented in random order). Context learning was assessed by comparing RTs between displays with and displays without consistent arrangements. Experiment 1a served as a baseline, in which observers only performed the visual search task without a secondary spatial WM task. In Experiment 1b (a different group of), observers performed the search task while having to maintain the spatial material in WM. Importantly, Experiment 1b used an extended training schedule, in which the number of trials on the combined visual search and spatial WM task was effectively doubled compared to previous investigations (e.g., Annac *et al.*, 2013; Manginelli *et al.*, 2013; Travis *et al.*, 2013). We were thus able to assess whether extended practice on the dual task eventually leads to automatic search guidance by context memory, evidenced by a reliable contextual cueing effect in the search task even in the presence of a demanding secondary WM task. To preview the results: with extended training, contextual cueing of search performance did become manifest in Experiment 1b and was, in fact, statistically undistinguishable from the baseline effect (in Experiment 1a).

This novel finding was further explored in Experiment 2, in which observers performed the visual search task with and without a concurrent spatial WM task in separate, alternating blocks of trials. This made it possible to investigate the role the secondary task plays for practised (automatic) retrieval from context memory (in addition to secondary-task effects on the development of automatic cueing investigated in Experiment 1b). Here, the hypothesis was that automatic retrieval is more efficient (i.e., works faster) than controlled retrieval and only dual-task conditions engage automatic retrieval, because these conditions consume available resources that may otherwise spill over to the (then controlled) retrieval in search tasks. Experiment 2 confirmed this prediction: Context cueing was significantly enhanced in dual-task blocks, even though the very same repeated search arrays were shown in both dual- and single-task blocks.

After each experiment, a recognition test was administered (cf. Chun & Jiang, 1998): Participants were presented with repeated and non-repeated display arrangements and had to indicate whether or not they believed having seen the displays in the previous search task.

General method

The present study comprised three experiments: the single-task Experiment 1a, which consisted of three epochs of training, and the dual-task Experiments 1b and 2, which both consisted of six epochs. Note that an ‘epoch’ was composed of five blocks of 24 search trials each; that is, five blocks of (120) trials were collapsed into one epoch to obtain reliable estimates of contextual cueing (cf. Chun & Jiang, 1998; see Figure 2). Experiment 1a, which presented only search trials, served as the baseline against which the contextual cueing effects in the dual-task Experiment 1b were compared. Annac *et al.* (2013) had shown that contextual cueing was reduced in dual-task relative to baseline conditions and this pattern was found across all individual epochs of the combined visual search/spatial WM task. This suggests that the secondary task interferes with contextual cueing throughout the entire search experiment rather than affecting the rate at which observers acquire contextual memory representations. For this reason, we collapsed the mean RTs to repeated and non-repeated displays across all epochs and compared overall contextual cueing effects (i.e., RT [non-repeated display] minus RT [repeated display]) between the baseline Experiment

1a and the dual-task Experiment 1b (between-group comparison) and the single-task and dual-task blocks of Experiment 2 (within-group comparison). Any secondary-task effects should be revealed by differences in overall contextual cueing effects between these conditions. Differences in RTs (contextual cueing) were also examined in separate ANOVAs (with experiment, epoch, and context as factors).

Data analysis was performed using R (R Core Team, 2017). In each experiment, and for each participant, RTs deviating by more than ±2.5 standard deviations from the respective condition mean were discarded as outliers (overall 2.39% of trials). Trials with response errors were also excluded from analysis. Across all experiments, mean response accuracy was higher for repeated relative to non-repeated arrays, 95.7% versus 95.1%, one-tailed $t(50) = 2.17$, $p = .02$, Cohen's $d = 0.18$ (per individual: 97.0 vs. 96.1%, 96.8 vs. 96.9%, and 93.4 vs. 92.2% in Experiments 1a, 1b, and 2, respectively), in line with the contextual cueing effect in the RTs (see below), effectively ruling out speed-accuracy trade-offs.

Participants

A total of 52 volunteers (37 female; mean age: 25.7 ± 4.42 years) participated in the experiments (17 in each experiment; Exp 1a: 14 female, mean age: 27.8 ± 7.74, Exp 1b: 15 female, mean age: 25.8 ± 4.97, Exp 2: 10 female, mean age: 23.8 ± 1.16). All had normal or corrected-to-normal vision, including colour vision, which was confirmed by participants' verbal reports. Participants gave written informed consent and were fully debriefed after the experiment in accordance with the experimental protocol. They received either course credit or monetary payment (8 Euro, i.e., ~10 USD/hr) for their service. The experiment was conducted in a single session lasting about 30 min (Experiment 1) or 2–2.5 hr (Experiments 1b, 2).

Apparatus

The experiments were programmed in Matlab (version 8.0.0.783 R2012b), in combination with the OpenGL-Psychtoolbox extension (version 3.0.12, Brainard, 1997) and run on an Intel computer controlled by the Windows 7 operating system. The stimuli were presented on a 22″ TFT-monitor (60 Hz refresh rate), positioned at a distance of ~55 cm from the participant. Responses were recorded via the computer mouse (search task) and the computer keyboard (WM tasks). Following their search task response, observers were presented with a high (2,000-Hz) or a low (300-Hz) tone through headphones, indicating correct and incorrect responses, respectively. Auditory feedback was also given on the spatial WM task (see below), which was performed under conditions of articulatory suppression involving the repetition of two stimuli that were also presented via headphones.

Stimuli

WM task

The spatial WM task was carried out under conditions of articulatory suppression: Participants were presented (via headphones) with two sequential digits (randomly selected between 1 and 9) at the beginning of a trial, which they had to retain and repeat, first loud and then subvocally (see below), until a test at the end of the trial. Repetition of the digits was intended to occupy the articulatory rehearsal process and so prevent verbal coding of the to-be-remembered spatial stimuli.

The spatial WM task required participants to remember the locations of four items (see Figure 1). In detail, following the articulatory suppression stimuli, participants were presented with a memory display of four black squares (size: 0.6° × 0.6°) on a grey background (RGB = 128,128,128; 45.9 cd/m^2); the squares were located on an imaginary circle (of radius 3.1°), at four locations chosen randomly on each trial from amongst eight equidistant locations around the circle. Participants had to retain the squares' positions for a test after the search task response (see below).

Search task

The search stimuli were the target letter 'T' (tilted 90° vs. 270° relative to the upright orientation) and the distractor letters 'L' (0°, 90°, 180°, and 270°). The size of each stimulus was 0.6° × 0.6°. The screen background was grey (RGB = 128,128,128; 45.9 cd/m^2). The colour of the items was chosen randomly from a set of four easily discriminable colours: red (RGB = 255,0,0; 45.8 cd/m^2), blue (RGB = 0,0,255; 12.5 cd/m^2), yellow (RGB = 255,255,0; 232.0 cd/m^2), and green (RGB = 0,255,0; 183.0 cd/m^2), with the restriction that each colour occurred equally frequently (25%) in the display. Note that these 'multicolour' search arrays, in combination with 'monocolour' (black) WM displays

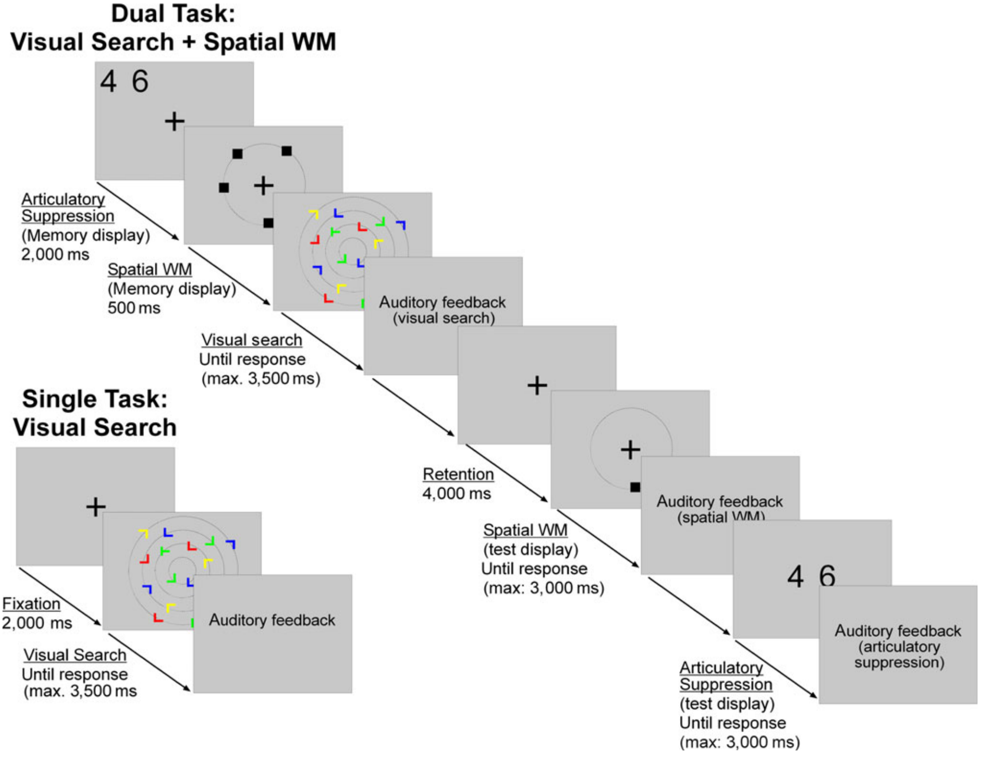

Figure 1. Illustration of events on a given trial of the single-task and dual-task conditions (left and right panel, respectively) implemented in the present Experiments 1a, 1b, and 2. Explanations are provided in the text. The dotted black circle(s) in the visual search and (spatial) working memory displays are shown for illustrative purposes only.

(see Figure 1) were successfully used in previous investigations on the role spatial WM plays for long-term context learning (e.g., Annac *et al.*, 2013; Manginelli *et al.*, 2011, 2013). Each search display consisted of 1 target and 15 distractor items, presented on four imaginary (concentric) circles with radii of 1.7°, 3.4°, 5.1°, and 6.8°, respectively. Note that the size of the items was held constant across radii/display eccentricity levels. Targets appeared only on the (intermediate) second or the third circle in order to minimize 'extreme' RTs due to the placement of the target at foveal versus extra-foveal/peripheral display locations. Further, the distribution of the 16 items was balanced across the four display quadrants; that is, there were four items in every quadrant.

Procedure

Each experiment comprised of three phases: (1) practice of the search task (12 trials; data not recorded); (2) training phase (360 trials in Experiment 1a, 720 trials in Experiment 1b, and 720 trials in Experiment 2; and (3) explicit recognition test (24 trials). Note that the visual search configurations used for practice were not re-used in the following experimental session. Experiments 1b and 2 included a fourth phase, in which observers were provided with training on the search and spatial WM task (12 trials; data not recorded); this phase preceded the training on the search task. At the beginning of each phase, participants received instructions displayed on the screen about which task they were going to perform. Between blocks (of 24 trials), participants were allowed to take a rest, until they pressed a key on the computer keyboard starting the next block. In each block of trials, 12 repeated and 12 non-repeated displays were shown. In repeated displays, the position, orientation, and colours of distractors were kept constant, in addition to the position and colour of the target. In contrast, the orientation of the 'T' target letter (left vs. right) was determined randomly on each trial, so as to avoid participants learning a contingency between a given spatial configuration and the search task response. To equate target location repetition effects between repeated and non-repeated displays, targets in non-repeated displays appeared also in a limited set of 12 locations. However, in these displays, the locations of the distractors, and thus the configuration of the items, were randomly generated on each trial.

Experiment 1a ('baseline')

Experiment 1a consisted of 15 blocks of learning (360 trials in total). On each trial, observers performed only the search task. They were instructed to discriminate the orientation of the 'T' target (left vs. right) in the search display presented amongst differently oriented 'L' distractors. On a given trial, the order of events was as follows (see Figure 1): (1) presentation of the white fixation cross for 2,000 ms; (2) presentation of the search stimuli until response or for a maximum duration of 3,500 ms; (3) auditory response feedback; (4) intertrial interval of 500 ms (during which the fixation marker was shown in the display centre).

Experiment 1b ('contextual cueing under WM load')

In Experiment 1b, observers performed the search task while they had to maintain the locations of four black squares in WM. This experiment consisted of 30 blocks of 24 trials each (720 trials in total). The scheduling of events on a given trial was as follows (see Figure 1): (1) Presentation of a white fixation cross for 2,000 ms; during this time, participants also heard the two digits for articulatory suppression and had to repeat them first aloud (until the end of the 2,000-ms period) and then subvocally until the end of the trial. (2) Presentation of the spatial WM (square) stimuli plus a fixation cross for 500 ms. (3) Appearance of the visual search items until response or a maximum of 3,500 ms. (4) Auditory feedback on the search task. (5) Presentation of a white fixation cross for a variable length between 500 and 4,000 ms, depending on observers' RTs in the search task, in order to ensure a constant retention period of 4,000 ms for the spatial WM items. (6) Presentation of a single black square at one of the positions around the fixation cross to probe spatial WM; the probe stimulus coincided with the position of a previously presented spatial WM item in 50% of the trials; participants pressed the 'A' key to indicate that the square location was the same as before, or the 'D' key to indicate that the location was different. (7) Auditory feedback on the spatial WM task. (8) Presentation of two digits intended for the probing of articulatory memory; participants indicated whether the two digits were same or different relative to the two digits presented at the beginning of the trial, again using the 'A' and 'D' keys, respectively. (9) Feedback on articulatory memory task. Note that the same procedure (1–9) had been used by Annac *et al.* (2013).

Experiment 2 ('contextual cueing in alternating single- and dual-task blocks')
Experiment 2 was a 'hybrid' of Experiment 1a and 1b: Baseline and dual-task trials were administered in alternating blocks of (24) trials. Odd (even) numbers of blocks contained baseline (dual-task) trials, which was counterbalanced across participants (see Figure 1). There were again 30 blocks in total, each consisting of 24 trials, yielding a total of 720 trials (i.e., 360 repeated and 360 non-repeated displays). Of note: in Experiment 2, the very same set of repeated displays was presented under both single-task and dual-task conditions.

Explicit recognition test
At the end of each experiment (1a, 1b, and 2), participants performed a recognition test, testing their explicit memory for repeated displays (a standard procedure in contextual cueing experiments; cf. Chun & Jiang, 1998). The recognition test consisted of 24 trials, half of which presented a repeated display and half a non-repeated display (random order). Observers' task was to indicate whether they believed having seen a given display already in the search task. With this 2AFC test, the chance rate for recognizing a repeated display is 50%.

Results

Accuracy in the WM task
Mean accuracy was quite high 77% in the spatial WM task and near-perfect, 97%, in the articulatory suppression task and virtually identical in Experiments 1b and 2 (spatial WM: both 77%; articulatory memory: both 97%), confirming that the two experiments are essentially comparable in terms of observers' engagement in the WM tasks. These results are in line with the values in Manginelli *et al.* (2013) and Annac *et al.* (2013). Since these studies found that contextual cueing of visual search was attenuated in the presence of a secondary (spatial) WM task, we assume that also the current WM tasks were sufficiently taxing to potentially impact on contextual cueing.

Contextual cueing in Experiment 1a (single-task condition)

The Experiment 1a was meant to provide a baseline measure of contextual cueing uninfluenced by the secondary-task effects (by having observers perform the search tasks only, for 360 trials) for comparison with the search-plus-spatial-WM task of Experiment 1b. The results are presented in Figure 2. To examine the development of contextual cueing, RTs were analysed by means of a 2 (context: repeated, non-repeated) × 3 (epoch: 1–3) repeated-measures ANOVA, which revealed both main effects and the interaction to be significant: epoch, $F(2, 32) = 20.78, p = 1.65\text{e-}06, \eta^2_G = 0.14$; context, $F(1, 16) = 16.85, p = 8.28\text{e-}04, \eta^2_G = 0.06$; interaction, $F(2, 32) = 5.95, p = 6.36\text{e-}03, \eta^2_G = 0.02$. Concerning the latter, direct (t) tests revealed the difference between repeated and non-repeated displays to be significant only in epochs 2 and 3: $t(16) = 3.82$, $p = 1.5\text{e-}03$, Cohen's $d = 0.58$ (epoch 2); $t(16) = 4.89, p = 1.6\text{e-}04$, Cohen's $d = 0.92$ (epoch 3). That is, under baseline – single-task – search conditions, reliable contextual cueing emerges after some 120 trials (i.e., some five repetitions of each of the 12 repeated display arrangements).

Contextual cueing in Experiment 1b (dual-task conditions)

In Experiment 1b, the search task was combined with a secondary spatial WM task to be performed across the entire set of (720) trials. A comparison of the dual-task Experiment 1b against the baseline (single-task) Experiment 1a was meant to reveal the detrimental impact of the secondary task on the acquisition or the retrieval of context memories in the visual search task. Recall that Annac *et al.* (2013) had found no reliable cueing effect when the search task was combined with the demanding WM task across three epochs of (360) training trials, but the effect became suddenly manifest when the WM task was removed from the search task in a subsequent epoch of (120) test trials; importantly, under (single-task) test conditions, the cueing effect was comparable in magnitude whether the initial training had taken place under dual-task (as described) or under single-task conditions. Annac *et al.* (2013) concluded from this pattern of results that the addition of the secondary task selectively interferes with the expression, but not the acquisition, of context memory. However, Annac *et al.*'s (2013) findings do not rule out the possibility that context retrieval might survive a taxing spatial WM load, especially when observers are provided with sufficient dual-task practice. To examine for this, Experiment 1b implemented an extended training schedule (of 720 trials, as compared to 360 trials in Annac *et al.*, 2013), permitting the effects of both a short training (trials 1–360) and an extended training (trials 361–720) to be tested. For this, we performed two direct (t) tests comparing the overall contextual cueing effect in the single-task baseline in Experiment 1a with the cueing effects in Experiment 1b arising from short (trials 1–360) and extended training (trials 361–720), respectively. The results were as follows: (i) The secondary task depressed contextual cueing with the short training, one-tailed $t(31.98) = 1.79, p = .04$, Cohen's $d = 0.61$, with the cueing effect being by two-thirds reduced under dual-task (as compared to single-task) conditions, 28 ms (Experiment 1b) versus 76 ms (Experiment 1a; see Figure 2) and not reliably different from zero, one-tailed $t(16) = 1.50$, $p = .07$, Glass' $\Delta = 0.29$. This essentially replicates prior findings (Annac *et al.*, 2013; see also Manginelli *et al.*, 2011, 2013). Second, with extended training, there was a reliable cueing effect under dual-task conditions, which was statistically indistinguishable from the effect under single-task conditions, $t(26.63) = 1.00$, $p = .32$, Cohen's $d = 0.61$. Accordingly, we take this pattern of results to show that, after extended dual-task practice, contextual cueing of visual search can manifest even when attentional resources are occupied by a resource-demanding secondary spatial WM task. Additional analyses (ANOVAs)

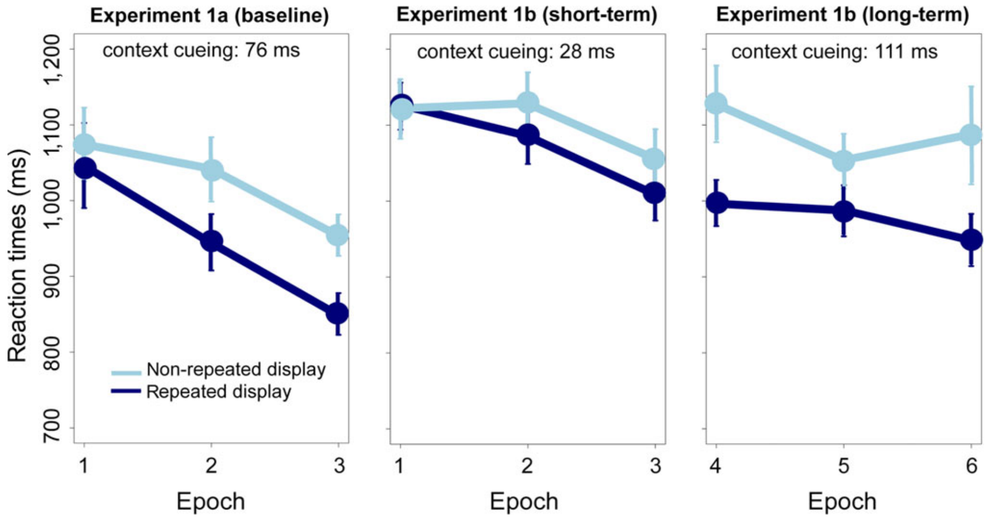

Figure 2. Results of Experiments 1a/1b. Mean reaction times and associated standard errors for repeated and non-repeated displays as a function of epoch (an epoch contained 120 trials, 50% with repeated and 50% with non-repeated displays). In Experiment 1a ('baseline'), the visual search task was performed in isolation in a total of 360 trials. Experiment 1b contained 720 trials of both the visual search and spatial working memory task. Reaction times (RTs) are shown separately for short-term and long-term training (trials 1–360 [epochs 1–3] and 361–720 [epochs 4–6], respectively). The three panels show search performance in the single-task Experiment 1a and that from short- versus long-term training in the dual-task Experiment 1b (left, middle, and right panel, respectively). Context cueing effects are estimated by pooling RTs across individual epochs and subtracting RTs in the repeated condition from that in the non-repeated condition.

comparing contextual cueing effects arising from short-term and, respectively, long-term training with baseline performance confirmed these results (and conclusions). For short-term training, the experiment (1a, 1b; between-subject factor) $\times$ epoch (1, 2, 3; within-subject factor) $\times$ context (repeated, non-repeated; within-subject factor) mixed-design ANOVA revealed the (theoretically important) experiment $\times$ context interaction significant, $F(1, 32) = 4.26$, $p = .047$, $\eta^2_G = 0.01$. This suggests that LT context memory was weaker under dual-task relative to single-task (baseline) conditions. For long-term training, the experiment (1a, 1b) $\times$ epoch (1–3 in Experiment 1a; 4–6 in Experiment 1b) $\times$ context (repeated, non-repeated) ANOVA revealed a significant three-way interaction, $F(2, 64) = 3.45$, $p = .038$, $\eta^2_G = 0.01$. This interaction was due to the fact that cueing was functional already at the beginning of long-term training: epoch 4 of dual-task versus epoch 1 of single-task: 131 versus 28 ms, one-tailed $t(29.36) = 2.65$, $p = .006$, Cohen's $d = 0.91$ (no other epoch-wise comparisons were significant). The latter finding was substantiated by another ($2 \times 3 \times 2$) repeated-measures ANOVA, which directly compared the cueing effect between the two 'within-subject' conditions – short-term versus long-term training – of Experiment 1b. This ANOVA revealed a significant training $\times$ epoch $\times$ context interaction, $F(1, 32) = 6.90$, $p = .013$, $\eta^2_G = 0.02$. Direct (t) tests showed that the interaction was due to reliably greater cueing in epoch 4 compared to epoch 1 of the dual-task: 131 versus -4 ms, one-tailed $t(16) = 4.77$, $p = .0001$, Cohen' $d = 1.11$ (see Figure 2). In a final test, we compared mean RTs between short-term and long-term training in Experiment 1b, separately for repeated and non-repeated displays. As shown in Figure 2, while RTs to repeated displays became expedited with increased task practice (suggesting practice-related gains in context cueing), RT to non-repeated – baseline – displays tended to be slower under practised conditions (compare epochs 1–3 with epochs 4–6, respectively). This raises the question about whether task practice up-modulates context learning or whether the secondary WM task particularly interferes with baseline RTs, for example, by weakening the representation of the target template and thus make visual search less efficient with these displays and/or interfere with other forms of LT statistical memory in these displays. Concerning the latter, prior research showed that besides context learning (in repeated displays), observers are well able to acquire other forms of – target-position – memory (in both repeated and non-repeated displays since also target positions are repeated in the latter displays; cf. method section) and subsequently prioritize these positions over other, non-target positions (i.e., probability cueing effect; Geng & Behrmann, 2005; Jiang, Swallow, & Rosenbaum, 2013). We found a significant facilitation of RTs to repeated displays from short- to long-term training, 1,074 versus 978 ms; one-tailed $t(16) = 4.41$, $p = 2.1\text{e-}04$, Cohen's $d = 0.74$. But RTs to non-repeated displays were essentially stable across the two practice levels, short-term training: 1102, long-term training: 1,088 ms, one-tailed $t(16) = .51$, $p = .30$, Cohen's $d = 0.08$. An additional JZS Bayes Factor (t) test (Rouder, Speckman, Sun, Morey, & Iverson, 2009), estimating the likelihood of the null relative to the alternative hypothesis, revealed a Bayes Factor (BF) of 78.11 for the comparison of RTs, between practice levels, for repeated displays and .28 for non-repeated displays. Note that only values greater than 3 would favour the alternative hypotheses – of differences in RTs between short-term and long-term training (Jeffreys, 1961). For this reason, we interpret the results from BF tests (and frequentist tests) as evidence for the hypothesis that context cueing comes to the fore in repeated displays – and is even greater in these displays – with long-term as compared to short-term training in Experiment 1b.

Contextual cueing in Experiment 2 (interleaved single- and dual-task blocks)

Experiment 1b showed that context cueing can be 'expressed' under secondary-task conditions – and in fact as well as under single-task conditions in Experiment 1a – at least after extended dual-task practice. On the background of the account outlined in the Introduction, contextual memories are formed regardless of whether the search task is performed under undivided or divided conditions, but the effective retrieval of context memories for search guidance is hampered under conditions of a heavy, search-task-irrelevant spatial WM load (cf. Annac *et al.*, 2013). However, with an extended training regime, contextual retrieval may be automatized; that is, it may come to bypass the spatial WM stage where the spatial relations amongst display items in the focus of attention are matched with learnt (and activated) target–distractor associations in some 'controlled process'. In fact, automatization of contextual retrieval may not work as well with single-task practice as with dual-task practice. Under single-task practice, there would be less pressure to develop automatic retrieval routines, as 'cognitive control' resources are plentifully available and the task is therefore always performed involving at least some component of controlled processing. In a sense, this is similar to Lavie's (e.g., Lavie *et al.*, 2004) proposal that when spare attentional resources are available (i.e., under conditions of low 'perceptual load'), processing spreads to information that is irrelevant (and may in fact be detrimental) to performing the task at hand. Applied to the present investigation, this could actually mean that when fully automatized as a result of dual-task practice, automatic retrieval of contextual memories for search guidance (bypassing spatial WM) may be more effective – and thus, paradoxically, actually engender a larger contextual cueing effect – than controlled search-display-to-context-memory matching involving spatial WM. Some evidence of this was seen in Experiment 1b, where the mean cueing effect after extended practice was numerically larger compared to single-task practice (111 versus 76 ms). However, this difference is qualified by the facts that the dual- and single-task practice conditions were of different length (720 versus 360 trials) and involved different groups of participants (exhibiting a difference in general RT performance, which may be attributable to the two samples or the specific conditions they performed). Given this, Experiment 2 was designed to realize a condition that permitted an uncompromised comparison of contextual cueing between single- and dual-task performance by using a within-subject design, equating the length of practice under single- and dual-task conditions (360 trials in total per conditions), and presenting single- and dual-task conditions in alternating mini-blocks (with starting condition counterbalanced across participants). Of note, since in Experiment 2 the very same set of (12) repeated displays were shown in single- and dual-task blocks, the practising of these displays was effectively doubled and thus comparable to that of long-term training in Experiment 1b (720 trials). However, only in half of the trials, the repeated displays were presented together with the demanding secondary WM. On the 'paradoxical' hypothesis sketched above, we expected the contextual cueing effect to be increased in dual-task blocks as compared to single-task blocks, because only in the former would the performance of the search task rely fully on the most efficient, automatic context retrieval for search guidance.

The results are depicted in Figure 3. As can be seen, the overall level of search RTs was comparable between the single- and dual-task blocks (in contrast to Experiment 1a/b, where these conditions were performed by different observer groups). Collapsing RTs across the two types of blocks reveals faster performance when the target was presented in repeated displays as compared to non-repeated displays, 1,762 versus 1,861 ms, one-tailed $t(16) = 3.35$, $p = 2.0\text{e-}04$, Cohen's $d = 0.40$ – that is, the overall contextual cueing effect of 99 ms was reliable. However, and of theoretical interest, the effect was significantly larger in dual-task relative to single-task blocks: contextual cueing gains of 131 versus 65 ms; one-tailed $t(16) = 1.88$, $p = .04$, Cohen's $d = 0.47$ (see also Figure 3). That is, the same repeated displays produced differential gains, importantly: in the same participants and after the same amount of task practice, depending on whether they were presented under dual-task or single-task conditions. This difference is in line with the hypothesis that search guidance by learnt context memories is more efficient when the search task is performed in the presence of the secondary WM task.

Two additional analyses were conducted to further explore this result pattern. First, we examined how context-based search facilitation developed across individual epochs in both single-task and dual-task conditions. Judging from Figure 3, more efficient (i.e., increased) context-based facilitation of visual search should manifest across all epochs of the dual-task condition (though it should particularly come to the fore in later epochs, that is, epoch 2 and 3, of this condition). A 2 (task [single, dual]) × 3 (epoch [1, 2, 3]) × 2 (context [repeated, non-repeated] repeated-measures ANOVA (only) found a significant task × context interaction, $F(1, 16) = 4.34$, $p = .04$, $\eta^2_G = 5.3\text{e-}03$, showing stronger contextual cueing under dual-task conditions. However, direct (t) tests showed that context cueing was reliably larger in dual-task relative to single-task trials only in later epochs, epoch 1: 24 versus 38 ms, one-tailed $t(16) = .31$, $p = .38$, Cohen's $d = 0.08$;

epoch 2: 78 versus 184 ms, one-tailed $t(16) = 1.99$, $p = .033$, Cohen's $d = 0.60$; epoch 3: 103 versus 173 ms, one-tailed $t(16) = 1.79$, $p = .046$, Cohen's $d = 0.47$. Second, we tested another observation from Figure 3, specifically that the larger contextual cueing effect in dual-task trials may have been due to both faster responses to repeated displays and slower responses non-repeated displays. Only, the former result would support the idea of a facilitation of RTs due to up-modulations of (the efficiency of) context–memory retrieval. Direct (t) tests showed that RTs were faster for repeated displays in dual-task relative to single-task trials, 1,729 versus 1,790 ms, one-tailed $t(16) = 2.47$, $p = .012$, Cohen's $d = 0.28$. For non-repeated displays, by contrast, the comparison of RTs between these two trial types revealed only a non-significant difference, dual-task: 2,042 ms; single-task: 2,028 ms, one-tailed $t(16) = .50$, $p = .31$, Cohen's $d = 0.06$. Note that the latter findings are supported by additional BF (t) tests, which favoured the alternative hypothesis, of differences in RTs between dual-task and single-task trials, only for repeated displays (BFs of 9.80 and 0.28 for repeated and non-repeated displays, respectively). The pattern of results supports the idea that context-based search guidance from repeated ('learned') displays is more efficient under a secondary task – likely because in this case, guidance can operate directly from LTM without or only minimal involvement of spatial WM.

Recognition performance

Participants' ability to explicitly recognize repeated displays was examined in terms of the signal detection sensitivity measure d prime [$d' = Z$ (hit rate) $- Z$ (false-alarm rate); Green & Swets, 1966]. A hit means that observers correctly recognized that they had already encountered a given (repeated) test display in the previous search task; a false alarm means that they incorrectly judged a newly composed (non-repeated) display as previously encountered. In order to increase the statistical power of the recognition test

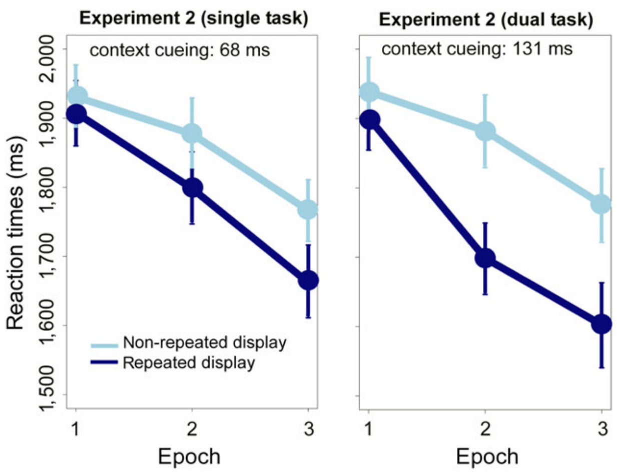

Figure 3. Results of Experiment 2. Mean reaction times and associated standard errors for repeated and non-repeated displays as a function of epoch, when the search task was performed either without or with the spatial WM task in alternating blocks of trials (single-task vs. single-task blocks; 360 trials each in total). Note that the very same set of (12) repeated displays was shown in single- and dual-task blocks, effectively doubling the amount of practice (720 trials) with these displays in each block/condition.

(see, e.g., Vadillo, Konstantinidis, & Shanks, 2016), the analysis of explicit recognition performance was collapsed across the three experiments (N = 51 observers). Mean d prime was 0.10 and not significantly different from zero, one-tailed $t(50) = 1.17, p = .25$, Glass' $\Delta = 0.16$. Further, there were no differences in d prime across experiments/groups: 0.18, 0.02, and 0.09 in Experiments 1a, 1b, and 2, respectively (ANOVA with the single between-subject factor group, $F(2, 48) = .25, p = .78, \eta^2_G = 0.01$). In other words, observers could not reliably tell apart repeated encountered from non-repeated display arrangements.

General discussion

The results of the present study support the idea of practice-dependent automatization of the retrieval of LTM context memories for search guidance. Previously, it was suggested that concurrent spatial WM load interferes with context-based guidance of visual search, where concurrent WM load affects mainly the expression (i.e., the effective retrieval) of acquired context cues from LTM, rather than their acquisition itself (Annac *et al.*, 2013; Manginelli *et al.*, 2011). However, a secondary WM task may not always hamper retrieval from long-term context memory, but may, in fact, come to enhance it. Schneider and Shiffrin (1977) showed that certain, so-called consistent-mapping conditions, search may become automatized as a result of extended practice (due to critical features that consistently distinguish the set of possible targets from the set of distractors come to summon an automatic 'attention response'), making task performance unaffected by short-term memory load. On this background, the development of automaticity in contextual cueing of visual search was investigated in two experiments using extended training schedules. The search task was either paired with a demanding secondary spatial WM task in all training trials (Experiment 1b) or only in half of the trials (Experiment 2), in which case visual search was performed together with the spatial WM task in alternating blocks of trials. Both experiments revealed a reliable contextual cueing effect under spatial WM load, though this effect took considerably longer to develop compared to training under baseline, single-task conditions (Experiments 1b vs. 1a). In Experiment 2, seemingly paradoxically, the cueing effect was even greater under dual-task conditions, suggesting that, once fully practised, effective retrieval of acquired context memories for search guidance actually benefits from spatial WM being occupied by a taxing secondary task.

Implications for the relationship between contextual cueing and divided attention

Previous studies are not unequivocal regarding the contribution of 'attention' to the contextual cueing effect. Repeated displays need to be attended in order to observe a reliable cueing effect (Jiang & Chun, 2001). Further, selective attention may play a role particularly in the retrieval from context memory (Geyer, Shi, & Müller, 2010; Jiang & Leung, 2005). Similar results and conclusions apply to manipulations of divided attention. For instance, the findings of Manginelli *et al.* (2011, 2013) strongly suggest that concurrent search and WM tasks compete for spatial WM functions; for instance, learnt spatial associations may have to be loaded from LTM into WM for memory-based search guidance to become effective. That is, contextual cueing while being LTM-based, relies on 'controlled' WM processes (Schneider & Shiffrin, 1977), where WM provides the 'workspace' that permits information stored in configural LTM to be linked with display information in the focus of attention.

On the other hand, Schneider and collaborators have shown that retrieval from LTM can become an automatic, capacity-free, process, given sufficient practice on the task. Of note in this context, Schneider and Fisk (1982) reported practice-related gains in a consistent-mapping visual search task, which turned out even higher when emphasis was placed on performance of this task via instruction. In their experiments, observers performed either a consistent- or a varied-mapping search task (with distinct vs. overlapping target and distractor sets), which were presented at random occasions within a given block of trials. This finding let Schneider and Fisk to surmise that target detection in seemingly automatic tasks is actually not impenetrable to cognitive control – in Schneider & Fisk's terms, observers may actually 'waste' (p. 276) some cognitive capacity even in automatic tasks without appropriate task instructions. Applying these ideas to contextual cueing of visual search, it is possible that the effect is only initially reduced under spatial WM load (Annac *et al.*, 2013; Manginelli *et al.*, 2011, 2013), for the reasons outlined above. However, with extended training, automatic retrieval of target–distractor associations from context memory can develop and come to directly guide search irrespective of the load imposed by a secondary WM task. In fact, the secondary task might serve an important function for direct LTM-based search guidance: by occupying WM capacity, it may (i) force the automatization of contextual cueing and (ii) prevent the spilling-over of controlled processing to the search task (paradoxically) making memory-based search guidance less efficient. In other words, a secondary task may not always be costly and may even facilitate context cueing in visual search.

Mechanisms of dual-task practice in context cueing of visual search

The major findings of the present investigation were that contextual cueing emerged even while performing a demanding spatial WM task (albeit taking longer to develop under this task) and was ultimately even more effective in dual-task as compared to single-task conditions. While this may be indicative of a practice-dependent transition from a relatively inefficient, capacity-consuming, retrieval process to an efficient, capacity-free process, other accounts may be feasible. The most obvious alternative is that participants, instead of developing automatic (efficient) context cueing, become better in their representation of individual (visual search, spatial WM) tasks and can thus make more efficient use of and/or expand their spare WM resources. This idea borrows from current conceptions of WM (e.g., Oberauer & Hein, 2012; Unsworth & Engle, 2007), according to which WM consists of multiple nodes or components distributed across both 'classical' short-term memory (i.e., broad focus of attention) and long-term memory (i.e., activated part of LTM). Given these components, in dual-task trials, a currently non-relevant WM representation (i.e., the memory display when performing the search) might be 'outsourced' to LTM, freeing capacity in classical short-term memory. This capacity would then be available for the buffering of currently attended items in the search display and the matching of these items against (activated) context representations in LTM. Thus, while this alternative account also assumes a role of practice in contextual cueing, the practice would not necessarily lead to automatic context retrieval. Rather, practice would enhance observers' ability to hold task-critical information (memory items, search items) in individual WM stores (broad focus of attention, activated part of LTM). However, on this account, it would be difficult to explain why the contextual cueing effect in Experiment 2 was greater under dual-task than under single-task conditions. Arguably, on this account, both conditions would engage classical short-term memory in the retrieval of contextual cues and there should be no fundamental differences in the way this storage system is used between the two tasks. Instead, the single- and dual-task conditions should differ particularly with respect to the contribution of LTM stores to task performance: only dual-task situations should recruit additional WM (LTM) stores. Given this, it is unlikely that the present pattern of contextual cueing effect is attributable to differences in the use of (ST-/LT)WM stores across the single- and dual-task conditions.

There is also the possibility that the greater resources required in dual-task trials are associated with greater demands on memory processes, including more robust learning of repeated search arrays. Such a view has been expressed previously, albeit in relation to other forms of procedural (motor) learning (see, e.g., Lee & Magill, 1983). With regard to these, the idea is (see also Lelis-Torres, Ugrinowitsch, Apolinário-Souza, Benda, & Lage, 2017) that demanding (i.e., alternating) training schedules increase observers' need for monitoring the (visual) learning material in order to track the differences between individual learning episodes (trials), and thus keep motor performance at an optimal level. Applied to the current dual-task training regime, it is possible that observers had great difficulty with this schedule at first and had to devote all available capacity to the processing of the various trial events (auditory WM display, spatial WM display, search display; see Figure 1). While this may be detrimental to initial task performance, in-depth processing of these events may eventually enhance the memory for the spatial arrangement of repeated target–distractor arrangements, so that their impact on search guidance not only survives the additional load from a secondary task but is ultimately superior to that for context memories acquired under single-task conditions. However, crucially, this fails to explain the finding of Experiment 2 that contextual cueing was superior in dual-task versus single-task (alternating) blocks for the very same set of repeated search displays, that is, Why would one-and-the-same, 'deeply learnt' context memory give rise to a smaller cueing effect when the search task only is performed compared to when the spatial WM task is performed in addition?

Conclusion

The present experiments investigated the relationship between context learning in visual search and divided attention. We present new evidence that spatial WM load does not necessarily interfere with contextual cueing, as had been assumed based on previous studies. We propose that with specific, dual-task training, direct-automatic retrieval from LT context memory can develop. Thus, while early on during task performance, contextual cueing relies on spatial WM processes, these may come to be bypassed by automatizing the linking of target–distractor associations in context memory with the spatial item configurations in the focus of attention.

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