

Memory under pressure: Secondary-task effects on contextual cueing of visual search

Efsun Annac

Department of Psychology,
Ludwig-Maximilians-Universität, München, Germany



Angela A. Manginelli

Otto-von-Guericke-Universität, Magdeburg, Germany



Stefan Pollmann

Otto-von-Guericke-Universität, Magdeburg, Germany



Zhuanghua Shi

Department of Psychology,
Ludwig-Maximilians-Universität, München, Germany



Hermann J. Müller

Department of Psychology,
Ludwig-Maximilians-Universität, München, Germany
Department of Psychological Sciences, Birkbeck College
(University of London), London, UK



Thomas Geyer

Department of Psychology,
Ludwig-Maximilians-Universität, München, Germany



Repeated display configurations improve visual search. Recently, the question has arisen whether this contextual cueing effect (Chun & Jiang, 1998) is itself mediated by attention, both in terms of selectivity and processing resources deployed. While it is accepted that selective attention modulates contextual cueing (Jiang & Leung, 2005), there is an ongoing debate whether the cueing effect is affected by a secondary working memory (WM) task, specifically at which stage WM influences the cueing effect: the acquisition of configural associations (e.g., Travis, Mattingley, & Dux, 2013) versus the expression of learned associations (e.g., Manginelli, Langer, Klose, & Pollmann, 2013). The present study re-investigated this issue. Observers performed a visual search in combination with a spatial WM task. The latter was applied on either early or late search trials—so as to examine whether WM load hampers the acquisition of or retrieval from contextual memory. Additionally, the WM and search tasks were performed either temporally in parallel or in succession—so as to permit the effects of spatial WM load to be dissociated from those of executive load. The secondary WM task was found to affect cueing in late, but not early, experimental trials—though only when the search and WM tasks were performed in parallel. This pattern suggests that

contextual cueing involves a spatial WM resource, with spatial WM providing a workspace linking the current search array with configural long-term memory; as a result, occupying this workspace by a secondary WM task hampers the expression of learned configural associations.

Introduction

Attention and memory interact in many ways. In recent years, the contextual cueing paradigm (Chun, 2000) has become a promising approach in cognitive psychology for studying the interactions between the two functions. Contextual cueing refers to the observation of faster reaction times (RTs) to targets presented in repeatedly encountered, relative to non-repeated, visual search displays. In a typical contextual cueing experiment, participants are presented with an array of items, one of which is the target and the others are distractors. Unbeknownst to the observers, half of the displays contain repeated and the other half nonrepeated item arrangements. Participants' task is to

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detect and subsequently discriminate the orientation of the target letter, a left- or right-oriented “T”; the distractors are letters “L” in various orthogonal orientations. RTs are analyzed as a function of display repetition and experimental “epoch.” The standard finding is that RTs become generally faster over the course (epochs) of the experiment—an effect reflecting nonconfigural, procedural learning. Importantly, this speeding up of RTs is more pronounced for repeated compared to nonrepeated displays—an effect reflecting configural learning. Interestingly, when observers are asked to discern repeated from nonrepeated displays in a recognition test performed at the end of the search experiment, they typically perform at chance level. This dissociation between RT and recognition measures has been taken to indicate that contextual cueing is supported by an implicit memory system (Chun & Jiang, 1998; see also Chun & Phelps, 1999, for evidence pertaining to this claim using amnesic patients, or Greene, Gross, Elsinger, & Rao, 2007, using functional imaging). However, more recent investigations of the cueing effect using larger numbers of recognition trials, in addition to obtaining different recognition measures, have found that observers do actually have some explicit knowledge of repeated displays (Smyth & Shanks, 2008; Schlagbauer, Müller, Zehetleitner, & Geyer, 2012). Smyth and Shanks (2008) took this to suggest that contextual cueing is supported by a general memory system that is mediated by conscious processes.

Other research has shown that the configural memory underlying contextual cueing involves associations between the target location and the configuration formed by the distractors (Jiang & Wagner, 2004)—in particular, though not exclusively, associations of the target to individual distractors in its narrower vicinity (Olson & Chun, 2002; Brady & Chun, 2007). Another set of studies has shown that contextual cueing acts mainly by facilitating focal-attentional selection of the target item (Chun & Jiang, 1998; Johnson, Woodman, Braun, & Luck, 2007; Geyer, Zehetleitner, & Müller, 2010), though contextual cueing appears to also influence response selection (Kunar, Flusberg, Horowitz, & Wolfe, 2007).

Selective and divided attention in contextual cueing

Many studies have argued for a gateway role of attention in conscious perception (Mack & Rock, 1998), explicit learning (Voss, Baym, & Paller, 2008), and implicit memory (Jiang & Leung, 2005). Concerning the latter, studies of implicit learning that used the serial reaction time task (e.g., Nissen & Bullemer, 1987) have suggested a distinction between the learning of

repeated information (i.e., acquisition of memory traces) and the expression of learned information (i.e., retrieval of memory traces; see also Frensch, Lin, & Buchner, 1998). More recently, Jiang and Leung (2005; see also Jiang & Chun, 2001) demonstrated the distinction between learning and the expression of learning also for contextual cueing. In more detail, Jiang and Leung (2005) had observers detect and subsequently discriminate the orientation of a black “T” presented amongst black and white “Ls.” In Jiang and Leung’s terms, the black Ls were the attended or target set distractors and the white Ls the ignored or nontarget set distractors. The experiment was divided into a training and a test phase. At the intersection of the two phases, the colors of the distractors were swapped: the black Ls became white and the white Ls black. There were three repetition conditions (with “repetition” referring to the spatial arrangement of the items): repetition of both target and nontarget set distractors (both-old condition), of only target set distractors (attended-old condition), or of only nontarget set distractors (ignored-old condition). Contextual cueing effects were assessed by comparing RTs in these three (repetition) conditions to RTs in a nonrepeated (both new) condition. In the learning phase, contextual cueing was found to manifest in the both-old and attended-old, but not the ignored-old, conditions. Interestingly, the magnitude of contextual cueing was comparable between the both-old and attended-old conditions, suggesting that the cueing effect (in the both-old condition) was due to repetition of the attended context alone (see also Geyer, Shi, & Müller, 2010, for an influence of color-based grouping on contextual cueing). However, in the test phase (i.e., after the swapping of the distractor colors), contextual cueing was observed only in the ignored, but not the both-old and attended-old, conditions. Jiang and Leung (2005) concluded from this pattern that contextual memory is formed independently of (feature-based) attention—as evidenced by reliable contextual cueing in the ignored-old condition, importantly, already at the start of the test phase (this fact indicates that the locations of the to-be-ignored distractors had been successfully learnt in the training phase); by contrast, the expression of learnt target-distractor configurations is under the control of selective attention—as evidenced by significant cueing effects in the both-old and attended-old condition in the learning phase and contextual cueing in the ignored-old condition in the test phase.

The notion of attention-independent configural learning was examined further by Vickery, Sussman, & Jiang (2010), who tested whether contextual cueing is affected by a secondary working memory (WM) task—based on the idea that if contextual cueing and the secondary WM task share common processes, or draw

on common resources (Kahneman, 1973), they would interfere with each other when performed in combination. A related idea is to conceive of WM as an integral part of long-term memory (Cowan, 1999). Applied to contextual cueing, there would also be a functional overlap between the long-term memory underlying contextual cueing and WM—as evidenced by recent neuroscientific studies that revealed the two forms of memory to be linked within a common neural structure: the medial temporal lobes (e.g., Chun & Phelps, 1999; Axmacher et al., 2007; Geyer, Baumgartner, Müller, & Pollmann, 2012). On this background, Vickery et al. surmised that if contextual cueing is dependent on (e.g., spatial) WM—for example, because WM is necessary for strengthening associations between the target and nearby distractors (Brady & Chun, 2007)—then a secondary WM task should attenuate contextual cueing. Alternatively, or in addition, it is possible that dividing attention between two similar tasks may introduce difficulties in representing—that is, in the color-based selection of—the target set of items (Jiang & Leung, 2005), which may attenuate the cueing effect. Finally, it is possible that the secondary WM task depletes central resources for search task execution, attenuating contextual cueing. To decide between these alternatives (in particular, spatial vs. color-based WM load effects), Vickery et al. (2010) examined whether WM for spatial arrays, colors, item sequences, etc. would interfere with contextual cueing. However, they actually found contextual cueing to be unaffected by any of the additional WM tasks—which led them to conclude that the cueing effect is not impacted by divided attention.

Spatial, not featural, WM affects the retrieval of contextual cueing

Following Vickery et al. (2010), a number of studies re-investigated the relation between contextual cueing and the performance of a secondary WM task. One limitation of Vickery et al. was that they tested contextual cueing only under single-task conditions, that is, after observers had learned the repeated displays in a dual-task phase. Thus, they could only examine whether the learning of contextual cues is affected by secondary WM load—their results suggest that it is not—but not whether the retrieval of learned information is dependent on WM. For example, as elaborated above, Jiang and Leung (2005) have shown that selective, feature-based attention modulates the retrieval of (previously acquired) configural associations; that is, only the selected items are represented in WM (e.g., Bundesen, 1990) and thus provide effective retrieval cues for stored associations. Given this, it is possible that the addition of some specific type of

secondary WM task in a late test phase of a contextual cueing experiment would interfere with the retrieval from long-term, configural memory.

This hypothesis was tested in a series of follow-up studies (Manginelli, Langer, Klose, & Pollmann, 2013; Travis, Mattingley, & Dux, 2013). The general approach taken in these studies was to divide the experiment into a learning phase (e.g., trials 1–360 in Manginelli et al., 2013) and a test phase (trials 361–480). Importantly, in Manginelli et al. (2013), the search task was combined with a secondary WM task that was applied in either the training or the test phase. The results revealed reliable contextual cueing when the WM task was administered in the learning phase—a result compatible with Vickery et al. (2010), but not when administered in the test phase. Interestingly, Manginelli et al. (2013; see also Manginelli, Geringswald, & Pollmann, 2011) investigated the effects of both featural (i.e., color-related) and spatial WM tasks (between-subject manipulation), but found only the latter task to interfere with contextual cueing. Manginelli et al. (2013) took this to mean that the expression of learned target-distractor associations is mediated by spatial WM. However, the results of Manginelli et al. (2011) and Manginelli et al. (2013) were only partially supported by Travis et al. (2013), who found that a spatial WM task can also interfere with the acquisition of contextual associations in the learning phase (we will return to this study in the General discussion). At the first glance, these results seem to conflict with those of Manginelli et al. However, there are also some critical differences between the studies, such as the type of spatial WM task employed or observers' experience with visual search in general, which complicate any comparisons and conclusions derived from these. Given this, it remains an open issue whether WM influences the learning of configural information or whether a secondary WM task interferes with the retrieval of learned target-distractor associations from long-term memory.

The present study: Interference from spatial and executive WM

The above-reviewed evidence of secondary WM tasks attenuating contextual cueing raises the question as to where the WM interference effects actually arise. In the present study, we draw a distinction between the potential role of spatial and executive WM functions in contextual cueing. The results of Manginelli et al. (2013) strongly suggest that the search and WM tasks compete for *spatial* WM functions; for instance, contextual cueing might be contingent upon loading a set of learnt spatial associations from long-term memory into WM in order to guide visual search. On this assumption, WM provides the workspace that

permits information stored in configural long-term memory to be linked with information contained in the search display. At the same time, however, the secondary task and contextual cueing may also draw on a common pool of *central-executive* WM functions, giving rise to interference because the addition of a secondary task would increase the demands for optimally sharing a limited-capacity *spatial* WM resource between the two tasks. This is predicated on the assumption that executive load is a function of the degree to which the dual tasks to be performed draw on a *common, specific* WM resource (e.g., Pashler, 1994).¹

Of particular relevance in this context are findings from Lavie, Hirst, De Fockert, and Viding (2004), showing separate effects of concurrent WM load and dual-task coordination demands in a selective attention—namely, a variant of the Eriksen flanker (Eriksen & Eriksen, 1974)—task. In more detail, Lavie et al. combined the attention task with a concurrent verbal WM task. There were two conditions: “high” versus “low” WM load, with observers having to maintain six digits versus only one digit in WM while performing the attention task. In the latter task, observers responded to the identity of a letter at the center of the display (e.g., “x” vs. “z” mapped to the left vs. the right hand), which additionally included a second (flanker) letter in the periphery: a distractor that was either compatible (e.g., a peripheral “X” in the presence of a central “x”), incompatible (e.g., “Z”), or neutral (e.g., “N”) with respect to the target letter. Typically, RTs to the target are faster with compatible, and slower with incompatible distractors relative to the neutral condition, suggesting that observers cannot effectively ignore the (task-irrelevant) distractor letter. Of note, in their experiment 1, Lavie et al. (2004) found greater distractor interference (RT incompatible minus RT compatible distractor) in conditions of high versus low working memory load. Interestingly, distractor interference was also greater under dual- relative to single-task conditions, even when the WM task was performed prior to the flanker task (experiment 4: “high” WM condition), so that the phonological loop component of WM (e.g., Baddeley, 2003) was free at time of the attention task. Moreover, when the WM and attention tasks were temporally segregated, greater distractor interference for dual relative to single-task conditions was also found when the demands on WM were minimal (experiment 5: “low” WM condition). Most importantly, under conditions of temporal segregation, the distractor interference was comparable in magnitude between the high and low WM demands (comparison between experiments 4 and 5; Lavie et al., 2004, p. 351). With regard to contextual cueing, this pattern of findings would support the view, outlined above, that (a) secondary WM tasks (non-spatial as well as spatial) do interfere with the attention task and

that (b) the requirement for dual-task coordination (i.e., executive control) is a chief factor in regulating performance in the attention task.²

Importantly, these considerations concerning the role of spatial versus executive WM functions in contextual cueing go beyond what has been shown previously. A closer look at Manginelli et al. (2013) reveals that contextual cueing was actually reduced in the presence of both a featural and a spatial WM task, although the reduction was reliable only with the spatial task. The (numerical) decrease of contextual cueing under featural WM conditions may be taken to suggest that context effects are generally dependent on executive WM functions, too, although, for the reasons elaborated above, executive resources may be particularly challenged when the two tasks draw on a common, spatial WM resource. On this background, the present study was designed to disentangle the role(s) of spatial versus executive WM functions in the contextual cueing of visual search.

To this end, in the current experiments, we combined a visual search with a concurrent spatial WM (sWM) task. The secondary sWM task was applied either early (early trials) or late (late trials) during search performance, to permit secondary task effects to be reexamined on the acquisition and, respectively, retrieval of search-guiding configural information (Manginelli et al., 2013). However, our main focus was on whether WM interference effects on contextual cueing are solely due to spatial WM load or to executive WM load. To investigate this, one group of observers had to maintain a spatial pattern in WM while performing the visual search task (Experiments 2a, 2b). For another group of observers, the sWM task did not overlap with, but instead was performed immediately after (Experiments 2c, 2d) or before (Experiments 3a, 3b), the search task. Thus, only in the while group was the spatial (and executive) short-term memory resource occupied during the search task. In contrast, in the after and before groups, sWM was not occupied at the time observers performed the search task. Thus, the after and before conditions imposed only demands on dual-task coordination (Lavie et al., 2004). Based on the findings of Manginelli et al. (2013), we assumed that the sWM task hampers retrieval from configural memory. This would lead to two interesting predictions: (a) Contextual cueing should be reduced under dual-task conditions in a late test phase, that is, after the effect has been reliably developed under single-task conditions in an early training phase. (b) Conversely, contextual cueing should become manifest under single-task conditions in the test phase, even when the sWM task was paired with the search task in the training phase. Regarding the effects of spatial versus executive WM load, we hypothesized that if sWM interference effects are due to increased demands for scheduling multiple tasks

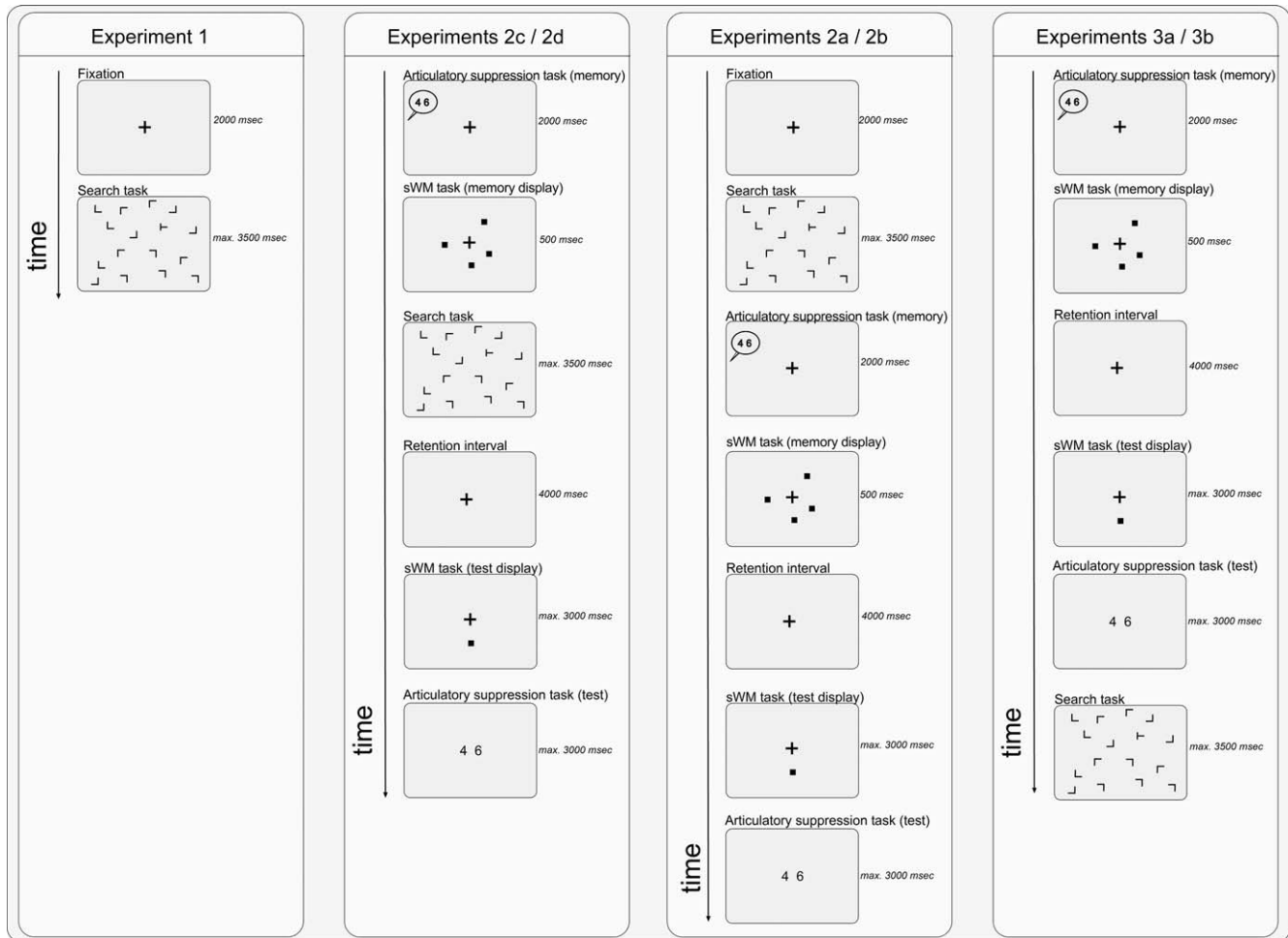


Figure 1. Illustration of the baseline, while, after, and before conditions. The single-task Experiment 1 was intended to provide a baseline measure of contextual cueing, unconfounded by secondary task effects. In the other, dual-task experiments, the search task was combined with a secondary spatial working memory (sWM) task performed in early (training) or late (test) trials either in parallel with (while condition: Experiments 2c, 2d) or temporally segregated from the search task (after condition: Experiments 2a, 2b; before condition: Experiments 3a, 3b; in the after condition the sWM task was performed after, and in the before condition prior to the search task). In all dual-task experiments, the search and sWM tasks were accompanied by a third, articulatory suppression task.

(executive-load hypothesis), the addition of the secondary sWM task should reduce contextual cueing in all (i.e., the “while,” “after,” and “before”) groups—because in all groups, observers would at least have to coordinate the two tasks. By contrast, if secondary task effects are due to increased sWM demands (spatial-load hypothesis), the cueing effect should be reduced particularly for observers in the while group—because only in this group are the two tasks performed concurrently and the secondary task could take away spare WM capacity required for contextual cueing.

General method

The present study comprised of seven experiments (see Table 1 and Figure 1). Each experiment was

divided into three epochs of training and one epoch of test. Each epoch included five blocks of 24 search trials each. Experiment 1 served as the baseline condition, including only search trials, against which we compared contextual cueing in the other, dual-task Experiments: 2a, 2b, 2c, 2d, 3a, 3b. In doing so, first we computed mean contextual cueing scores (RT nonrepeated minus RT repeated display); second, we entered these values in mixed-design analyses of variance (ANOVAs) with group (baseline vs. dual task; between-subject factor) and phase (training vs. test; within-subject factor) as variables. Note that for the training session, only RTs values for Epoch 3 were entered in this analysis. We reasoned that any secondary-task effects should be revealed by an interaction between the two variables. In Experiments 2a and 2b (3a, 3b), the sWM task was applied in close succession to the search task. These experiments were intended to examine the effects of

executive, i.e., dual-task coordination, load on configural learning (Experiments 2b, 3b) or the expression of configural cues (Experiments 2a, 3a). In Experiments 2c and 2d, observers had to maintain a spatial pattern in WM by the time they performed the search task. These experiments aimed at testing whether concurrent spatial load attenuates configural learning (Experiment 2d) or the expression of learned contextual cues in the visual search task (Experiment 2c). In each experiment (and for each experimental condition), $RT \pm 2.5$ standard deviations from the mean were discarded as outliers (overall 2.99% of trials). Further, error response trials were also excluded from analysis (overall, 2.46% of trials; see statistics below).

Participants

A total of 119 volunteers (17 in each experiment) from Ludwig Maximilian University Munich (41 males, 78 females; mean age = 25.6, $SD = 5.8$ years) participated in the experiment. Participants were either paid 8 Euro per hour (approx. 11 USD) or received course credits for their participation. All observers had normal or corrected to normal vision. Six observers were left handed. Instructions were presented in the German language.

Apparatus

Stimuli were presented on a 19-in. CRT-monitor (AOC, Amsterdam, NL), positioned approximately 55 cm away from observers. Participants' head was stabilized by means of a chin rest. The experiments were programmed in Matlab (version 7.3.0.267 R2006b; The MathWorks, Sherborn, MA), in combination with the OpenGL-Psychtoolbox extension (version 3.0.9; Brainard, 1997), and run on a standard (Intel) computer controlled by a Windows XP Professional operating system. Participants executed their responses via computer mouse and computer keyboard. Headphones were used to provide auditory feedback in the search and WM tasks, that is, the sWM task plus an articulatory suppression task. The stimuli for the latter task—two digits—were also presented via the headphones: participants had to vocally repeat two digits until (the test at) the end of the trial, so as to occupy the articulatory rehearsal process and thus prevent verbal coding of the to-be-remembered spatial stimuli.³

Stimuli

Spatial working memory task

The sWM task required participants to remember spatial locations (Oh & Kim, 2004; Manginelli et al.,

2011; see also Figure 1). On each trial, a memory display of four black squares (size: $0.6^\circ \times 0.6^\circ$) was presented on a gray background (RGB = 128, 128, 128). The positions of the four items were randomly chosen among eight equidistant locations on an imaginary circle (radius approximately 3.0°).

Search task

The search stimuli were the target letter T (tilted 90° vs. 270° relative to the vertical, upright orientation) and the distractor letters L (0° , 90° , 180° , and 270°). The size of each stimulus was $0.6^\circ \times 0.6^\circ$. The screen background was gray (RGB = 128, 128, 128). The color of the items was chosen randomly among red, blue, yellow, green, with the restriction that each color occurred equally frequently (25%) in the display. Each search display consisted of one target and 15 distractor items, presented on four imaginary (concentric) circles with different radii of 1.7° , 3.4° , 5.1° , and 6.8° (see Figure 1). Targets appeared only on the second or the third circle. Further, the distribution of the 16 items was balanced across the four quarters, such that there were four items in every quarter.

Procedure

Participants were tested in a dimly lighted room. Each experiment lasted approximately 2 hr (except the baseline Experiment 1, which took some 30 min to complete) and comprised of four phases: (a) training on the search task (12 trials; data not recorded); (b) learning phase (360 trials, divided into 15 blocks of 24 trials each); (c) test phase (120 trials, divided into 5 blocks of 24 trials); and (d) explicit recognition test (24 trials). Experiments 2–5 included a fifth phase, in which observers were provided with training on the search and sWM 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 in the learning and test phases, 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 nonrepeated displays were shown. In repeated displays, the position, orientation, and the colors of distractors were kept constant, in addition to the position and color of the target. In contrast, the orientation of the T target letter (left vs. right) varied randomly on each trial in order to avoid response preparation (learning) effects. To equate target location repetition effects between repeated and nonrepeated displays, targets in nonrepeated 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.

Baseline condition (Experiment 1)

This experiment comprised of 15 blocks of learning (360 trials) and five blocks of test (120 trials). In each trial of the training and test phases, observers performed only the search task. They were encouraged to detect, and subsequently discriminate, the orientation of the T target letter (left vs. right) presented amongst differently oriented L distractor letters. Response feedback was provided in the form of a brief tone of 2000 Hz (correct answer) or 300 Hz (wrong answer). On a given trial, the order of events was as follows: (a) presentation of fixation cross for 2000 ms, (b) presentation of search stimuli until response or for a maximum duration of 3500 ms, (c) auditory response feedback, and (d) inter-trial interval of 500 ms. During this time, a white fixation was shown in the display center.

sWM-after condition (Experiments 2a and 2b)

In the sWM-after condition (see Figure 1), the search task preceded the sWM task. Each trial started with the presentation of a fixation cross for 2000 ms. Thereafter, the search items were presented until observers' response or a maximum of 3500 ms. Correctness of response was indicated by auditory feedback (correct answer: 2000 Hz tone; incorrect answer: 300 Hz tone). Next, two random auditory digits, ranging from one through nine, were presented for 2000 ms. Observers were instructed to rehearse the two digits until the end of the trial. The auditory stimuli were followed by the sWM items, plus a white fixation cross, presented for 500 ms. After a retention period of 4000 ms (only fixation cross shown), a memory test display was presented consisting of one black square presented at one out of eight possible locations on the virtual memory circle. Observers' task was to indicate, by button press, whether or not the test square was at the location of a previous memory square. Following their response or a maximum of 3000 ms, they received auditory feedback regarding the correctness of their sWM response. The same tones were used as in the search task. Next, a fixation cross was shown for 1000 ms. Following this event, participants performed a memory test on the articulatory suppression task. In doing so, two white digits were displayed in the center of the screen on a gray background for a maximum of 3000 ms and subjects had to indicate whether or not they matched the two digits they had been rehearsing during the trial. Again, auditory feedback was provided. During the inter-trial interval, of 500 ms, a white fixation cross was shown. Experiment 2a (sWM after test) contained 15 blocks of training (360 trials), in which only the search task was administered.

In the subsequent five blocks of the test phase (120 trials), observers performed the search in combination with the sWM task. In contrast, in Experiment 2b (sWM after training), the search and sWM task were combined in training, but the sWM task was removed in test trials (see Figure 1).

sWM-while condition (Experiments 2c and 2d)

In this condition, observers performed the search task while they maintained the four black squares in working memory. On a given trial, the order of events was as follows (see Figure 1): (1) presentation of a white fixation cross for 2000 ms. During this time, participants also heard the two digits for articulatory suppression (i.e., they had to repeat them aloud until the end of the trial). (2) Presentation of the sWM stimuli plus a fixation cross for 500 ms; (3) appearance of the search display until response or a maximum of 3500 ms; (4) auditory feedback on the search task; (5) presentation of a white fixation cross for a variable length between 500 ms and 4000 ms, depending on the observer's RT in the search task, in order to determine a constant retention period of 4000 ms for the sWM items; (6) application of the sWM memory test; (7) auditory feedback on the sWM task; (8) presentation of fixation cross for 1000 ms; (9) probing memory for the articulatory suppression items by the presentation of two digits; (10) feedback on articulatory memory task; and (11) inter-trial interval of 500 ms plus presentation of white fixation cross. In Experiment 2c (sWM while test), early training trials contained only the search task and late test trials both the search and sWM tasks. In Experiment 2d (sWM while training), the search and sWM tasks were paired in training trials, but the latter task was removed in test trials (see Figure 1).

sWM-before condition (Experiments 3a and 3b)

This condition was near identical to the sWM-after condition (Experiments 2a and 2b), except that the search task was administered after participants performed the sWM task. In this regard, the sWM-before condition was similar to Lavie et al.'s (2004) experiments 4 and 5 (2004). Experiments 3a and 3b were motivated by the idea that the presentation of the search task at the beginning (sWM-after condition), as compared to the end (sWM-before condition), of a given trial would impose only minimal requirements for dual-task coordination, simply because the search task would always be the first task to be performed (Glyn Humphreys, personal communication, July 20, 2012). That is, the sWM-after condition may provide only a weak condition for tapping executive WM functions, likely underestimating the requirements for dual-task coordination. Therefore, in the sWM-before condition, the sWM task was administered prior to the search task in

Experiment	sWM task	Verbal suppression task
Experiment 2a “sWM after test”	87%	98%
Experiment 2b “sWM after training”	82%	90%
Experiment 2c “sWM while test”	79%	97%
Experiment 2d “sWM while training”	80%	95%
Experiment 3a “sWM before test”	84%	96%
Experiment 3b “sWM before training”	86%	98%
ANOVA results	$F(5, 96) = 1.34, p = 0.25$	$F(5, 96) = 0.96, p = 0.44$

Table 1. Mean accuracy performance in the sWM and articulatory suppression tasks in the dual-task Experiments 2a–3b. The dependent variables were compared by means of two separate ANOVAs, each with experiment as between-subject factor. The ANOVA results are presented in the last table row.

order to increase the demands on dual-task coordination. Using such a design, Lavie et al. (2004) showed reliable effects of dual-task coordination on performance of the primary task (in their case, the Eriksen flanker task; in the present case, the contextual cueing task). In the sWM-before condition, each trial started with the auditory stimuli: two auditory digits (randomly chosen from the set of one through nine) were presented for 2000 ms, and participants were asked to rehearse the digits until the end of the trial. Next, four black to-be-remembered squares appeared for 500 ms. The retention period was 4000 ms and followed by the sWM and articulatory suppression (digit) tests (response time maximum 3000 ms for both tests). This was followed by the search task (maximum display presentation: 3500 ms). In Experiment 3a, the sWM task was administered in the late test phase (Trials 361–480; Trials 1–360 only search task); in Experiment 3b, the sWM task was performed in combination with the search task in the training phase (Trials 1–360; Trials 361–480 only search task) (see Figure 1).

Explicit recognition test

At the end of each experiment, participants performed a recognition test querying observers’ explicit knowledge of repeated displays. The recognition test contained 24 trials, half of which presented a repeated display and the other half a nonrepeated display (random order). Observers’ task was to indicate whether they believed having seen a given display already in the search task. With this old-new test, the chance rate for recognizing a repeated display is 50%.

To preview the results, the main finding of the present study was that of concurrent spatial—but not executive—WM load interfering with the expression, rather than the acquisition, of contextual associations. In Experiment 2c, contextual cueing was attenuated when a concurrent sWM load (i.e., a secondary sWM task) was introduced in late experimental trials. In Experiment 2d, concurrent sWM load suppressed cueing in training trials; however, when this secondary

task was removed in late trials, contextual cueing recovered (see Figure 2).

Results

Accuracy performance in the WM tasks

Table 1 shows mean accuracy performance in the two WM tasks, sWM and articulatory suppression, in Experiments 2a–3b. Overall, accuracy was quite high: 95% in the articulatory suppression task and 83% in the sWM task. Analyses of variance (ANOVAs) revealed no accuracy differences among the experiments, articulatory suppression: $F(5, 96) = 0.96, p = 0.44$; sWM: $F(5, 96) = 1.34, p = 0.25$. From this, one can conclude that Experiments 2a–3b were comparable in terms of articulatory and WM performance.

Accuracy performance in the search task

Response accuracy in the search task was also high overall: 97.5%. A mixed-design ANOVA on the error rates with the factors display type (repeated vs. nonrepeated displays; within-subject factor), epoch (1–4; within-subject factor), and experiment (1–3b; between-subject factor) only revealed the effect of display type to be significant: $F(1, 112) = 8.61, p < 0.01$. This main effect was due to response errors being lower for repeated than for nonrepeated displays (2.26% vs. 2.67%, respectively).

Contextual cueing in the baseline Experiment 1

Experiment 1 was intended to yield a measure of contextual cueing “uncontaminated” by the secondary sWM task. Recall that observers performed the search task (only) in a total of 480 trials (training: 360 trials; test: 120 trials). Figure 2 presents the results. RTs were

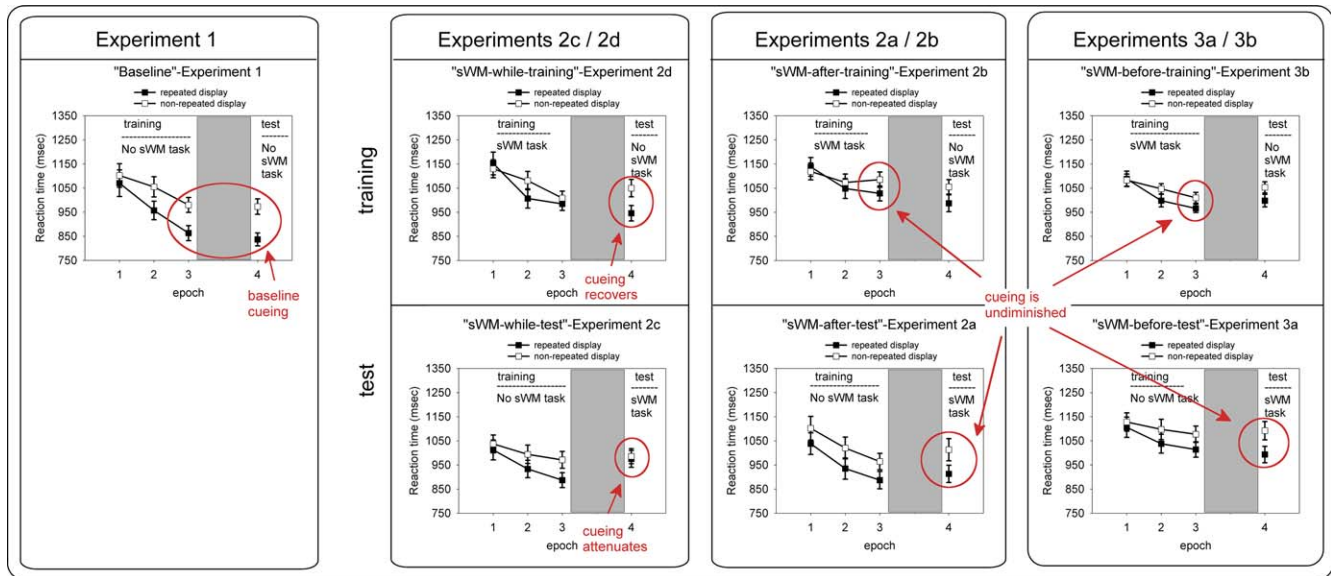


Figure 2. Mean reaction times (RTs) and associated standard errors to repeated and nonrepeated displays (black and white symbols, respectively) as a function of experimental epoch (1–4). The upper and lower panels show RTs for the conditions with the sWM task administered in training and test trials, respectively.

analyzed by means of a repeated-measures ANOVA, with display type (repeated vs. nonrepeated) and epoch (1–4) as factors. The main effect of epoch was significant, $F(3, 48) = 25.435, p < 0.01$: RTs became faster as the experiment progressed (Epoch 1: 1086 ms; Epoch 4: 905 ms). The general improvement in task performance can be attributed to nonconfigural procedural learning, such as the mapping of a particular stimulus onto a response (Schneider & Shiffrin, 1977). The main effect of the display type was also significant, $F(1, 16) = 20.695, p < 0.01$: RTs were faster for repeated relative to nonrepeated displays (932 vs. 1028 ms). Importantly, the interaction was significant, too, $F(3, 48) = 6.049, p < 0.01$. Paired sample t test revealed the difference between repeated and nonrepeated displays to be significant in Epoch 2 and all subsequent epochs (all $ps < 0.001$). This indicates that contextual cueing emerges after sufficient training on the task. A further t test (paired samples) showed that the cueing effect was comparable between Epoch 3 (last epoch of training phase) and Epoch 4 (test phase): 118 versus 137 ms, $t(16) = 0.670, p = 0.50$ (see also Figure 2 and Table 2).

Contextual cueing in dual-task Experiments 2a–3b

Contextual cueing was also explored for the dual-task Experiments 2a through 3b by a further $6 \times 4 \times 2$ mixed-design ANOVA, with experiment (Experiment 2a–3b; between-subject variable), epoch (1–4; within-subject variable), and display type (repeated, non-

repeated; within-subject variable) as factors. This ANOVA revealed a main effect of epoch, $F(3, 288) = 46.51, p < 0.001$, due to RTs becoming overall faster as the experiments progressed (1094 vs. 1005 ms in Epoch 1 vs. Epoch 4). Further, the display type effect was significant, $F(1, 96) = 46.11, p < 0.001$: RTs were overall faster for repeated relative to nonrepeated displays (1003 vs. 1053 ms). Furthermore, the Epoch \times Display Type interaction was significant, $F(3, 288) = 9.20, p < 0.001$. Post-hoc (least significant difference—LSD) revealed contextual cueing (RT nonrepeated minus RT repeated display) to be reliable in Epochs 2–4 (all $ps < 0.001$), but not in Epoch 1 ($p = 0.25$). This pattern of results indicates that contextual cueing was operating under secondary task conditions. But how did the magnitude of the cueing effect vary across the dual-task experiments in relation to the single-task (baseline) Experiment 1?

Contextual cueing in the baseline Experiment 1 versus the dual-task Experiments 2a–3b

The baseline Experiment 1 suggests that learned target-distractor associations can successfully be transferred from the training to the test phase—at least under single-task conditions. The dual-task experiments combined the search with a secondary sWM task to be performed on either the training trials (Experiments 2b, 2d, 3b) or the test trials (Experiments 2a, 2c, 3a). Furthermore, the sWM task could be administered after (Experiments 2a, 2b), before (Experiments 3a, 3b), or simultaneously with the search task (Experiments 2c,

Experiment	Application of sWM task		Contextual cueing		2 × 2 ANOVA Group × Phase, $F(1, 32)$	Experimental objective: Result
	Training	Test	Training (Epoch 3)	Test (Epoch 4)		
Experiment 1 “Baseline”	No	No	118 ms	137 ms	–	Providing a baseline measure of contextual cueing unconfounded by secondary task effects
Experiment 2a “sWM after test”	No	Yes	77 ms	101 ms	0.01, $p = 0.91$	Assessment of executive WM effects on the retrieval of learned configural associations: Contextual cueing is undiminished in the test phase
Experiment 2b “sWM after training”	Yes	No	57 ms	68 ms	0.03, $p = 0.86$	Assessment of executive WM effects on the acquisition of configural associations: Contextual cueing is undiminished in the training phase
Experiment 2c “sWM while test”	No	Yes	84 ms	11 ms	5.61, $p < 0.02$	Assessment of spatial WM effects on the retrieval of learned configural associations: Contextual cueing is reduced in the test phase
Experiment 2d “sWM while training”	Yes	No	24 ms	104 ms	3.30, $p < 0.05$	Assessment of spatial WM effects on the acquisition of configural associations: Contextual cueing is reduced in the training phase, but recovers in the test phase
Experiment 3a “sWM before test”	No	Yes	63 ms	100 ms	0.14, $p = 0.70$	Further investigation of executive WM effects on the retrieval of learned configural associations: Contextual cueing is undiminished in the test phase
Experiment 3b “sWM before training”	Yes	No	44 ms	55 ms	0.31, $p = 0.86$	Further investigation of executive WM effects on the acquisition of configural associations: Contextual cueing is undiminished in training phase

Table 2. Mean contextual cueing values (RT nonrepeated minus RT repeated display) in the training and test trials of Experiments 1 through 3b. Each dual-task Experiment 2a–3b was compared against the single task (baseline) Experiment 1 in separate group (single vs. dual task) × Phase (training vs. test) mixed-design ANOVAs. The column “2 × 2 ANOVA” gives the theoretically important interactions.

2d). This design allowed us to disentangle WM effects in the learning versus the retrieval of configural information (Experiments 2b, 2d, 3b vs. 2a, 2c, 3a), and importantly, examine whether WM effects are due to spatial or executive load (Experiments 2c, 2d vs. 2a, 2b, 3a, 3b). The baseline experiment was used to assess the costs of adding a secondary task on training and, respectively, test trials, separately for conditions in which the sWM task was performed after or at the time of the search task. The dependent variable was contextual cueing, determined by subtracting RTs to repeated from RTs to nonrepeated displays. This resulted in six mixed-design ANOVAs, each with phase (learning, test) and experiment (single task, dual task) as factors. Note that for computing contextual cueing

in the learning phase, only RTs from the last epoch (Blocks 11–15) were included.

The results of these ANOVAs are summarized in Table 2 (see also Figure 2). There are three notable findings: First, the secondary task attenuated contextual cueing when administered on test trials, $F(1, 32) = 5.61, p < 0.05$; interaction Experiment (1—baseline vs. 2c—sWM while test) × Phase (training vs. test). Second, contextual cueing recovered when the secondary task was removed at the transition from the learning to the test phase, $F(1, 32) = 3.30, p = 0.05$; interaction Experiment (1—baseline vs. 2d—sWM while training) × Phase (learning vs. test). Third, while these effects were observed when the sWM task was to be performed simultaneously with the search task,

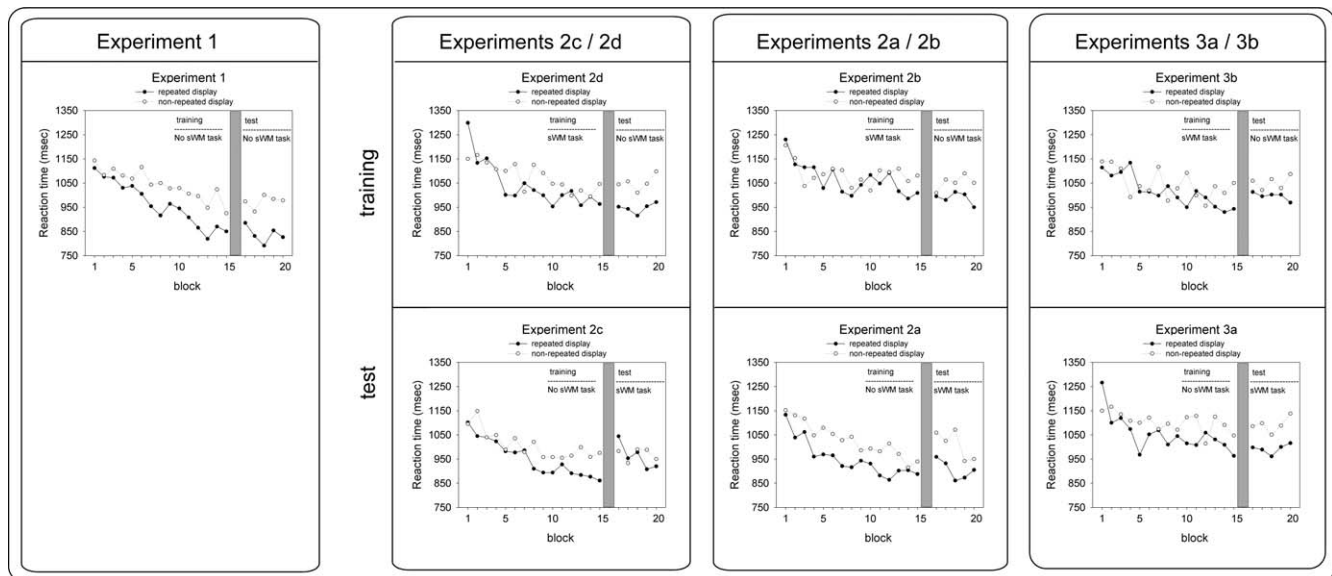


Figure 3. Mean reaction times (RTs) to repeated and nonrepeated displays (black and white symbols, respectively) as a function of experimental block (1–20). The upper and lower panels show RTs for the conditions with the sWM task administered in training and test trials, respectively.

administering the sWM task after the search task had almost no effect on contextual cueing, on either training trials, $F(1, 32) = 0.028$, $p = 0.86$; interaction Experiment (1—baseline vs. 2b—sWM after training) \times Phase (learning vs. test), or test trials, $F(1, 32) = 0.012$, $p = 0.91$; interaction Experiment (1—baseline vs. 2a—sWM after test) \times Phase (training vs. test). And even the presentation of the sWM task before the search task did not affect contextual cueing, in either the training phase, $F(1, 32) = 0.14$, $p = 0.70$; interaction Experiment (1—baseline vs. 3b—sWM after training) \times Phase (learning vs. test), or the test phase, $F(1, 32) = 0.031$, $p = 0.86$; interaction Experiment (1—baseline vs. 3a—sWM after test) \times Phase (training vs. test). Note that this pattern of results was confirmed in additional analyses taking into account RT data across two epochs of training (i.e., Epochs 2, 3)—rather than only one epoch (i.e., Epoch 3) as in the above analysis.⁴ This is also illustrated in Figure 3, which shows RTs to repeated and nonrepeated displays as a function of each block (1–20) for Experiments 1 through 3b.

In summary, the results reveal a specific secondary task effect on contextual cueing performance. The cueing effect was attenuated, particularly when the secondary task was added late, on test trials. Interestingly, the effect recovered when the sWM task was removed on late test trials. This suggests that the formation of configural long-term memory occurs regardless of a secondary WM task. Instead, the results indicate that the expression of learned information is affected by the WM task. Moreover, given that contextual cueing was almost unaffected by the

addition of sWM task when added after or before the search task, the findings demonstrate that it is not the requirement of the observers having to coordinate the two tasks, but rather the fact that the two tasks rely on a common spatial pool of resources that causes the sWM interference.

Recognition performance

Observers' ability to explicitly recognize repeated displays was assessed by calculating the hit rates (correct classification of repeated displays as repeated, i.e., seen before) and false alarm rates (incorrect classification of nonrepeated displays as repeated) on recognition trials. More hits than false alarms would indicate that observers could tell apart repeated from nonrepeated displays. Interestingly, the mean hit rate was larger than the false alarm rate, 0.53 versus 0.46; $F(1, 112) = 7.69$, $p < 0.05$, as confirmed by a mixed-design ANOVA with Response Type (hit vs. false alarm; within-subject variable) and Experiment (1–7; between-subject variable) as factors. No other effect was significant. Although the difference between hit and false alarm rates was small in magnitude, it suggests that at least some observers have explicit knowledge of repeated displays. Moreover, the use of larger numbers of observers (Experiments 1–7: $N = 119$ participants, compared to typically just 8–16 in standard contextual cueing experiments) could explain this positive finding, as larger sample sizes increase the power of the recognition test.

General discussion

The aim of the current study was to investigate whether a secondary spatial WM task would interfere with configural learning or the expression of learned configurations in visual search, and to which mechanism—spatial versus executive WM—interference effects would have to be attributed. The critical findings were: (a) contextual cueing was reliably reduced under dual-task compared to single-task (i.e., baseline) conditions on late trials of the experiments (Experiment 1 vs. Experiment 2c). (b) Contextual cueing, on late trials, was as large as in the baseline condition when the sWM task was administered in early, but removed in late, experimental trials (Experiment 1 vs. Experiment 2d). (c) Contextual cueing was almost unaffected by the addition of a secondary sWM task when the WM task was performed after the search task (Experiments 1 vs. Experiments 2a and 2b). This pattern of results supports the view that a secondary, spatial WM task attenuates the expression of learned configural cues in visual search (Manginelli et al., 2013). Furthermore, they confirm the sWM-load hypothesis and rule out the WM executive-load hypothesis.

However, one might object that the manipulation of executive load was lacking in power at least in Experiments 2a and 2b, because in the relevant conditions, the search task was always the first one to be performed, followed by the sWM task. As a result, there may have been only few, if any, demands placed on dual-task coordination. This issue was addressed in Experiments 3a and 3b, in which the sWM task was performed before, rather than after, the search task (adopting the approach of Lavie et al., 2004). The results were a replication of those in Experiments 2a and 2b: Contextual cueing was as large as under single-task conditions, indicative of the effect being largely uninfluenced by the increased cognitive load for scheduling multiple (spatial) tasks.

This set of results is novel because the dissociation between the acquisition and retrieval of target-distractor contingencies, most importantly: The effects of spatial versus executive WM load has never been unequivocally demonstrated before. In contrast to previous claims that contextual cueing is unaffected by the requirement to perform a secondary task (Vickery et al., 2010), we found that a secondary sWM task does have a crucial influence on the cueing effect: Contextual cueing was affected by the addition of the secondary task, though this effect manifested only when observers performed the search task while they maintained an unrelated configural pattern in visuospatial WM. Moreover, secondary task effects were observed only on late experimental trials. Therefore, we take the results to mean that (the availability of) spatial, and not executive, WM resources affects contextual cueing,

particularly the retrieval of learned target-distractor contingencies from configural long-term memory (also see Manginelli et al., 2011; Manginelli et al., 2013).

As mentioned in the Introduction, a very recent study by Travis et al. (2013), who also examined the role of WM in contextual cueing, only partially confirms this conclusion. In their experiment 2, observers were initially trained on the repeated displays under dual-task conditions (in the present terms: sWM while training) and then performed the search task under single-task conditions. The results showed reliable contextual cueing on late test trials. However, this result was not replicated in Travis et al.'s experiment 3, in which the sWM task was paired with the search task on early experimental trials, but removed on late trials. Here, contextual cueing was absent even when tested under single-task conditions. One important difference between the two experiments concerns the training trials, which included both repeated and nonrepeated displays (Travis et al., 2013, experiment 3) or only repeated displays (experiment 2). On this background, Travis et al. surmised that task difficulty, that is: The presentation of repeated and nonrepeated versus the presentation of repeated displays only modulates sWM interference. However, this idea is very difficult to distinguish from the notion that the sWM task modulates the learning, rather than the retrieval, of repeated search arrays. So, how could one explain the inconsistencies between these findings? A closer look at the type of sWM task employed in these studies may help answer this question. Travis et al. used a task that was qualitatively different from the current sWM task: maintaining the locations of sequentially presented dots (Travis et al., 2013) versus maintaining an array of static dots (current task). This difference is likely to relate to dissociable visuospatial WM representations, in terms of a more visual representation, tested by pattern span tasks, versus a more spatial representation, tested by the Corsi block span task (for a review, see Baddeley, 2003). The Corsi block span task, which involves the tapping of a number of spatially laid-out block objects in the correct (i.e., previously presented) sequence, is similar to the task used by Travis et al.; that is, they are likely to have manipulated the spatial component of visual WM. By contrast, our task (as well as that used by Manginelli and colleagues) is more similar to the pattern span task, and so is likely to have measured visual WM. In other words, it is possible that the application of a secondary spatial WM task (Travis et al., 2013) affects configural learning, whereas a visual WM task (Manginelli et al., 2011; Manginelli et al., 2013; present investigation) hampers the retrieval of learned info from configural memory. This hypothesis requires future research.

It is also conceivable that administering a sWM in training trials impedes configural learning, particularly

when the sWM is relatively difficult. However, a comparison of sWM task accuracy between Travis et al. (2013; 94%) and the current study (83%) suggests that this is not a valid thesis. Assuming that accuracy does reliably index sWM task difficulty, the current task would have been even more difficult than Travis et al.'s approach, which should have further reduced contextual cueing—this was, however, not the case. Given this, it is unlikely that sWM task difficulty as such modulates the acquisition of configural long-term memory (of course, this conclusion remains tentative as we did not manipulate sWM task difficulty here). Rather, sWM for sequentially presented dots may be different from sWM for static visual patterns, and the former might particularly interfere with configural learning (as evidenced by Travis et al., 2013, experiment 3), whereas memory for visual patterns hampers the expression of learned contextual associations (current investigation). The methodological implication would be that conclusions from investigations of contextual cueing and sWM require a clear definition of the type of sWM task deployed.

In contrast to prior investigations of the contextual cueing effect, analysis of the recognition performance ($N = 119$ participants) revealed that our observers were, to some extent, aware of repeated displays (see also Schlagbauer et al., 2012, for corroborative evidence pertaining to this claim). However, this conclusion would not be warranted when considering each experiment individually ($N = 17$ participants—here the difference between hit and false alarm rates was only nonsignificant), suggesting that the results—and conclusions—from recognition tests critically depend on the power of the tests (see Smyth & Shanks, 2008, for a similar argument). But note that we neither want to argue for a causal role of awareness in contextual cueing, nor that contextual cueing is supported by a central memory system that is mediated by explicit processes—a thesis advocated by Smyth and Shanks (2008). Instead, the present finding of above-chance recognition may suggest that observers are able to access the memory underlying contextual cueing, but not that the learning of repeated displays requires knowledge of repeated displays. That is, there may be a distinction between the learning and the retrieval of learned configural information, with the latter, but not former, involving explicit processing. Alternatively, retrieval might work automatically (implicitly), but may also, occasionally, generate a sense of explicit awareness in the observer. Further work is necessary to resolve this issue.

In sum, the question of whether WM affects contextual cueing of visual search has received a great deal of interest recently. While some studies found that the effect is independent of a secondary sWM task (Vickery et al., 2010), other investigations found that

contextual cueing is affected by sWM load (Manginelli et al., 2011; Manginelli et al., 2013; Travis et al., 2013). The current study supports the view that in a dual-task situation, the contextual cueing effect, that is, the expression of learned information, is attenuated because the visual search and working memory tasks rely on common spatial WM functions, rather than because observers have an increased need to coordinate the two tasks.

Keywords: perceptual learning, visual working memory, contextual cueing, visual search

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Corresponding author: Efsun Annac.

Email: Efsun.Annac@psy.lmu.de.

Address: Department Psychologie, Allgemeine und Experimentelle Psychologie, Ludwig-Maximilians-Universität, München, Germany.

Footnotes

¹That is, when two tasks draw on separable specific WM resources, such as spatial and, respectively, verbal WM systems, the coordinative demands may be minimal. Accordingly, from the finding that a featural WM task does not, while a spatial WM task does, interfere with contextual cueing (e.g., Manginelli et al., 2013), one cannot conclude that all interference arises from the competition for a capacity-limited spatial WM resource.

²These conclusions receive support from a very recent study (Tsvetanov, Rotshtein, Arvantis, & Humphreys, 2013) that introduced two conditions: working memory (WM) and mere repeat (MR). In the WM condition, observers had to maintain the color and shape of an item in WM (e.g., a red circle) while performing a pop-out search task, namely, to discern the orientation of a line (as left vs. right tilted) presented amongst three vertical lines. The search items were presented inside four colored shapes (e.g., red circle, green square, blue triangle, violet hexagon). The crucial manipulation concerned the reappearance of the WM item in the search display (absent, present) and, if present, the location the target item (inside item

matching vs. not matching WM contents). Typically, RTs to discriminate the target are faster when the target appears at the location of the WM item (WM-based RT facilitation) relative to when it appears at a different location (WM-based RT inhibition); note that both effects are assessed relative to a neutral condition, in which the WM item does not reappear in the search display. In the MR condition, in contrast, observers only had to indicate whether two subsequently presented items were the same or different (the identification task was performed prior to the search task). The MR condition was intended to provide a measure of the effects of executive, or general, load on RT performance. Typically, RTs are slower in the WM than in MR condition, indicating that the maintenance of information in WM, rather than merely identifying items, increases general demands on performance (for a review, see, e.g., Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Tsvetanov et al. (2013) compared content-specific WM effects (RT facilitation, RT inhibition) and content-unspecific WM effects (RT WM condition, RT mere repeat condition) between younger and older participants. They found that content-unspecific WM effects were more pronounced for the older participants (i.e., the slowing of RTs in the WM relative to MR condition was more pronounced for older participants), while content-specific WM effects were larger for younger observers (i.e., RT facilitation and RT inhibition effects were more pronounced for younger observers). This double dissociation led them to surmise that the effects of executive WM load are independent of those of content-based (i.e., featural) WM load in visual pop-out search.

³Although this introduced another task to be performed concurrently with the search and sWM task, this should not have interfered with these tasks as such, given that articulatory suppression occupies a separable WM subsystem (the phonological loop; e.g., Baddeley, 2003). Also, since the articulatory suppression task was added to all experimental conditions, the extra executive demands imposed by this task were essentially equated across these conditions.

⁴In the additional analysis, we did not include RTs from Epoch 1, because contextual cueing typically becomes significant only after Epoch 1 (see Chun & Jiang, 1998; present investigation).

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