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RESEARCH ARTICLE

Executive working memory involved in the learning of contextual cueing effect

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Abstract

Implicit learning of spatial layouts occurs when target–distractor configurations repeat during a visual search task [contextual cueing; Chun and Jiang in Cogn Psychol 36(1): 28–17, 1998]. This study addressed the extent to which contextual cueing depends on executive working memory (WM). In three experiments, participants performed a contextual cueing visual search task concurrently with a WM task. The WM task was either executive (subtract 3 from each digit in WM) or non-executive (hold digits in WM), and was either low load (Experiment 1) or high load (Experiment 2). Contextual cueing was attenuated in the high-load executive WM condition. Experiment 3 replicated our findings using a within-subjects design, and confirmed the interpretation that executive functions of WM are required in contextual learning.

Keywords Contextual cueing effect · Executive working memory · Storage working memory

Introduction

Visual attention is colloquially thought to be guided by intentional planned behaviour, or captured by important environmental stimuli. However, an additional predictor of visual attention referred to previously as "memory-based automaticity" (Chun and Jiang 1998), or "selection history" (Awh et al. 2012) has become prominent in theories of visual attention. This additional factor represents automatic memory influences on attention that are learned and expressed without awareness. Despite occurring without awareness, it is possible that implicit encoding and retrieval functions are supported by working memory (WM), just as WM functions support encoding and retrieval of explicit information (Manginelli et al. 2013). Indeed, a handful of researchers have investigated the role of WM in implicit spatial learning using a contextual cueing paradigm (Chun and Jiang 1998), but consensus on whether WM is involved in implicit spatial learning has not been reached.

In a contextual cueing experiment, observers search for a letter T amongst scattered L's (Chun and Jiang 1998). Unknown to participants, half the scenes shown in the first block of 24 trials repeat in every block throughout the experiment. For each block after the first, there are 12 repeated scenes that were encountered in every block prior, and 12 novel scenes that will be encountered only once throughout the experiment. Search RTs are faster for repeated scenes than for novel scenes, constituting a contextual cueing effect (CCE; Chun and Jiang 1998). Recognition tests on search stimuli have been used to confirm participants are unaware of scenes repeating throughout the experiment. According to Chun and Jiang (1998), repeated presentation of specific target–distractor configurations allows participants to learn implicit associations between distractor layouts and their corresponding target locations. On repeated scenes presented later in an experiment, this contextual learning facilitates search. We will herein use contextual learning to denote the collection of implicit spatial learning processes hypothesized to drive the CCE. Of note, the CCE persists up to 1 week after initial training (Chun and Jiang 2003; Zellin et al. 2014), indicating that contextual information

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learned during visual search is stored in the form of long-term memory (LTM).

One way that information from long-term memory can interact with current experience is via WM (Baddeley and Hitch 1974; Baddeley 2012). WM is thought to allow attention to prioritize task-relevant information for subsequent behaviour (LaRocque et al. 2014; Soto et al. 2014) and has been shown to affect implicit learning (Janacsek and Nemeth 2013; Martini et al. 2013). WM has also been shown to correlate with attention and LTM (Wang et al. 2017). Therefor in terms of contextual learning, WM may support the implicit encoding of target–distractor configuration information, and retrieval of such information from LTM when repeated scenes are encountered. Thus, contextual learning may depend on WM resources to mediate retrieval of contextual information from long-term memory.

Extant work examining the relation between WM and contextual learning has used WM tasks that varied in load, task type (spatial or non-spatial), and whether the two tasks were integrated concurrently or sequentially[1] (Annac et al. 2013; Manginelli et al. 2012; Travis et al. 2013; Vickery et al. 2010). For example, Vickery et al. (2010) had participants hold items in memory while performing visual search in a CCE procedure. WM load and presentation style (concurrent or sequential) were manipulated experimentally, and no effect of visuospatial WM on the CCE was observed (Vickery et al. 2010). It was concluded that the CCE is robust to changes in WM load, task type (spatial vs non-spatial), and presentation style. However, other studies have produced contradictory findings on the relation between WM load and contextual learning. For example, using a similar dual-task paradigm, Travis et al. (2013) had participants remember the presentation order of a stimulus set as the WM task; in this case, recruitment of WM resources during visual search attenuated the CCE.

In addition to WM load, WM tasks that are spatial or non-spatial affect contextual learning differently. Manginelli et al. (2013) had participants perform visual search while engaging in a WM task that was either non-spatial (memorizing letters or colors) or spatial (memorizing the locations of squares or the orientations of Gabor patches). When participants performed visual search concurrently with either the spatial or non-spatial WM tasks, a CCE was observed. In another condition, participants began the experiment (i.e., learning phase) by performing only the visual search task. Then in a subsequent phase, a spatial or non-spatial concurrent WM task was introduced. Under these conditions, a CCE was observed in the initial phase, but attenuated in the subsequent dual-task phase when participants engaged in the spatial WM task. These results suggest the spatial or non-spatial WM did not affect contextual learning itself. Rather, spatial WM seems to interfere with the expression of contextual learning.

Non-spatial WM demands do not seem to have any influence on contextual learning (Manginelli et al. 2012; 2013; Travis et al. 2013; Vickery et al. 2010), suggesting that short-term storage functions of WM are not involved contextual learning. In contrast, it is still unknown whether executive WM processes are involved in implicit learning. Executive WM processes allocate attention to and manipulate information in short-term storage (Baddeley 1992), and include temporary activation of long-term memory (Baddeley et al. 1998), coordination of multiple tasks (Baddeley 1997), shifting between task or retrieval strategies (Baddeley 1996), and selective attention and inhibition (Baddeley et al. 1998). More recently, three key executive functions have been highlighted: mental set shifting, information updating and monitoring, and inhibition of prepotent responses (Miyake et al. 2000).

Given that executive WM functions are required in visual search (Han and Kim 2004), it is possible that executive WM is involved in contextual learning. To our knowledge there is no existing research on this topic that focuses specifically on executive functions of WM. One study examined executive WM in relation to the CCE (Annac et al. 2013), but executive WM load was operationalized specifically as attention costs related to task-switching. Contextual learning was found to persist as long as spatial WM was not engaged during visual search trials (Annac et al. 2013). These authors took this to mean the CCE was independent from executive WM processes. However, performing WM and visual search tasks in succession (as opposed to concurrently) places little demand on executive WM as we have conceptualized it—as the manipulation of information stored in short-term memory (Baddeley 1992; Han and Kim 2004). Therefore, this manipulation may have failed to impose a sufficient load on executive WM to interfere with implicit spatial learning. The study by Annac et al. (2013) speaks more to the effect of task switching on implicit spatial learning, rather than executive WM demands.

In the present study, storage WM was operationalized by asking participants to maintain three digits in memory during a visual search trial. Executive WM was operationalized by asking participants to do a subtractive task: subtract three from each of the three digits being maintained in memory (Han and Kim 2004; Lee and Kang 2002; St Clair-Thompson and Gathercole 2006). Participants performed a CCE visual search task while maintaining or manipulating information in WM during each trial. In Experiment

[1] Note, in a concurrent presentation style, the visual search trial occurs between the initiation phase and response phase of the WM task—forcing WM processing to occur simultaneously with visual search. Sequential presentation requires participants to perform only one task at a time.

1 and 2, we compared the effects of storage and executive functions of WM on CCE. The only difference between Experiment 1 and 2 was that the WM load for each WM task was increased from three to four digits. In Experiment 3, we used a within-subject design to replicate and extend our findings from Experiment 1 and 2. To explore whether WM affected contextual learning or expression of learned contextual information, a search-only phase followed the dual-task phase in Experiment 3. If executive function of WM is involved in contextual learning, executive WM tasks, but not storage WM tasks, will interfere with the CCE.

Experiment 1

In the storage WM condition (Experiment 1A) participants held three digits in WM while performing the CCE search task. In the executive WM condition (Experiment 1B), participants were required to subtract 3 from each of the three different digits. We expected to observe a CCE in Experiment 1A, and to observe a reduced or eliminated CCE in Experiment 1B.

Method

Participants

Forty-two undergraduate students participated for course credit, with 21 for Experiment 1A (16 females, average age 21.3 years) and 21 for Experiment 1B (12 females, average age 22.3 years). All participants had normal or corrected-to-normal visual acuity and normal color vision. The present study was approved by the Ethical Committee of Liaoning Normal University. Informed consent was obtained from all participants included in this study.

Stimulus and apparatus

Participants were tested in a dimly lit room, at a viewing distance of 57 cm from the screen. Stimuli were presented on a 24-inch LCD monitor with a resolution of 1024 × 768, 60 Hz refresh rate. The background color of the display was set to gray (RGB: 128, 128, 128) across all conditions. Stimuli in the search display were composed of one target (letter T, tilted 90° or 270°, relative to the left or right orientation) and 15 distractors (letter L, rotated 0°, 90°, 180°, or 270°). Each item was subtended 0.7º × 0.7º. The color of each item was randomized (red, blue, yellow or green) but constrained to equal probabilities (25%) in every trial. The 16 items were distributed equally in each quadrant of an invisible 6 × 8 grid (14° × 18.7°).

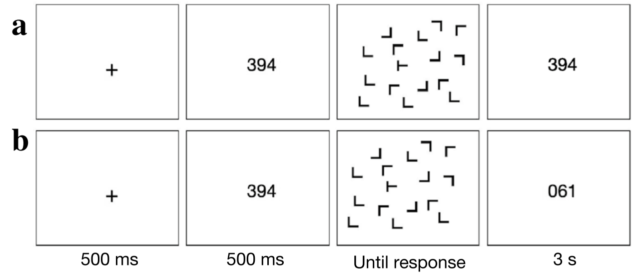

Fig. 1 A schematic illustration of a contextual cueing task combined with the storage WM task (**a**) or the executive WM task (**b**) in Experiment 1. In the storage WM task, participants were required to remember 3 digits and maintain the information while performing the contextual task. In the executive WM task, participants were required to remember and subtract 3 from each of the three digits

Procedure

A practice block of 24 trials was conducted to let participants familiar with the task. No trials seen in practice were used in the actual experiment. The learning phase included 20 blocks of 24 trials, with 480 trials in total. Each block had 12 repeated contexts and 12 novel contexts. To eliminate the possibility of location probability learning, 24 different target locations with equal eccentricity (3 possible location in each quadrant) were applied in repeated and novel displays. The distractor configurations of repeated displays were randomly generated in the first block and repeated with the same target location across blocks. However, for the novel display, the distractor configurations were randomly generated on each trial and target locations repeated across blocks. Target orientation was randomly generated for every trial so that the repeated contexts were not predictive of target orientations. To increase statistical power, every four successive blocks were binned into one epoch. Participants were allowed to take a break after each epoch.

As shown in Fig. 1, each trial began with a fixation cross (0.6° × 0.6°) lasting for 500 ms. Immediately the WM task stimulus appeared: three different numbers, randomly chosen from 0 to 9, were shown at center for 500 ms (each 0.6° × 0.6°). In both conditions, participants remembered the digits and reported them after completing the search task. In the executive condition, participants had additional instructions to subtract 3 from each digit. Then a visual search display appeared, and participants searched for a target letter *T* among distractor *L*s. Participants used the left-handed finger to press the ''F'' ("left") key and right-handed index finger to press ''J'' ("right") key on the keyboard to indicate the orientation of "T". Once participants had made a response, a fixation cross was displayed again and followed immediately by a test display containing 3 digits (e.g., 063). For participants in Experiment 1A, they were required to judge whether these digits were identical (press key ''F'') or different (press key ‘‘J’’) to those digits retained in their mind. The same response scheme was used for the subtraction task. 50% of all trials presented participants with an incorrect answer to the subtraction task, such that participants would correctly respond “different” if they accurately performed the subtraction task. To best integrate the two tasks, the test display lasted for only 2000 ms to prevent participants from releasing the WM load in search task. All participants were required to respond as quickly and accurately as possible. Feedback (“wrong” in red) was given for 3 s after participants made an incorrect response both in search task and WM task. The word “next” would appear in the center of the screen for 500 ms to mark the onset of the next trial.

After completing the visual search task, participants were asked to perform a recognition test. First, a question “Have you ever notice that there were repeated configurations in search task?” was presented in the screen (press “Q” key for answer “yes” and “P” key for “not”). Then, a block of 24 trials with 12 repeated and 12 novel search arrays were presented. Participants were asked to make a forced choice to decide whether a given display was a repeated (press “Q” key) or a novel one (press “P” key). Neither time pressure nor feedback was given in this explicit recognition task.

Results

Three participants’ data from Experiment 1A were excluded from analysis for not following the experimental instructions. Trials with incorrect response and trials with RTs above 3 standard deviations from mean RT were excluded. About 2% of trials were removed with this outlier criterion. Same outlier criterion was applied to the following experiments.

Accuracy

Search task Mean accuracy was near ceiling in both storage (99.2%) and executive (99.5%) WM task conditions. An independence-sample t test revealed no significant differences on accuracy among the experiments, $t(37) = -1.28$, $p > 0.05$.

WM task Accuracy for WM task was well above chance (50%) in both Experiment 1A (98.1%), $t(17) = 126.8$, $p < 0.001$, and Experiment 1B (88.6%), $t(20) = 23.6$, $p < 0.001$. The accuracy of Experiment 1A was significantly higher than Experiment 1B, $t(37) = 22.09$, $p < 0.001$, indicating that the executive WM task was more difficult than the storage WM task if assuming that accuracy is an index of task difficulty.

Search time

Figure 2 illustrates mean RTs for repeated and novel configurations as a function of epoch for 3 items storage WM task and executive WM task (top left and bottom left panel of Fig. 2, respectively). A mixed-design repeated-measures ANOVA on the mean RTs treated context (repeated vs. novel) and epoch (1–5) as within-subject factors, and experiment (storage vs. executive) as a between-subject factor. The results showed a significant main effect of context, $F(1, 37) = 21.05$, $p < 0.001$, $\eta^2 = 0.36$ and epoch, $F(4, 148) = 61.06$, $p < 0.001$, $\eta^2 = 0.62$, indicating a CCE emerged over the learning phase. The main effect of experiment was significant, $F(1, 37) = 6.42$, $p = 0.016$, $\eta^2 = 0.15$, indicating the executive WM task was more difficult than storage task. The epoch × experiment interaction was significant, $F(4, 148) = 4.38$, $p < 0.01$, $\eta^2 = 0.10$, likely due to the broadly slower RTs in Experiment 1B relative to Experiment 1A. No other interactions were statistically significant.

To shed light on the detail of contextual learning on the experiment, we performed a 2 (context: repeated vs. novel) × 5 (epoch: 1–5) repeated-measures ANOVA separately in Experiment 1A and 1B. In Experiment 1A the main effects were significant for context, $F(1, 17) = 13.63$, $p < 0.01$, $\eta^2 = 0.45$, and epoch, $F(4, 68) = 42.99$, $p < 0.001$, $\eta^2 = 0.72$, indicating the CCE emerged in the 3 items load storage WM task condition. Similarly, we also found a significant main effect of context, $F(1, 20) = 9.78$, $p < 0.01$, $\eta^2 = 0.33$, and epoch, $F(4, 80) = 35.29$, $p < 0.001$, $\eta^2 = 0.64$ in Experiment 1B, indicating that CCE emerged in the 3 items load executive WM task condition. The interactions between epoch and context were not significant in Experiment 1A, $F(4, 68) = 0.55$, $p = 0.70$ and Experiment 1B, $F(4, 80) = 1.37$, $p = 0.25$.

Discussion

The CCE seems robust across storage and executive WM task conditions. In light of the late emergence (from epoch 4) of CCE in Experiment 1B (executive task), it is possible that adding additional executive WM load would impair contextual learning process. In terms of storage WM, there is evidence to suggest increasing WM load will not impact contextual learning (Vickery et al. 2010). Although, in another study, CCE was impaired when high-load working memory was imposed on the search task (Travis et al. 2012). If executive WM is functionally related to contextual learning, then we are more likely to observe effects of load manipulations with concurrent executive WM tasks.

It is likely that the concurrent WM task used in Experiment 1 failed occupy the limited executive WM resource sufficiently, leaving enough resources available for contextual learning and applying the repeated contextual

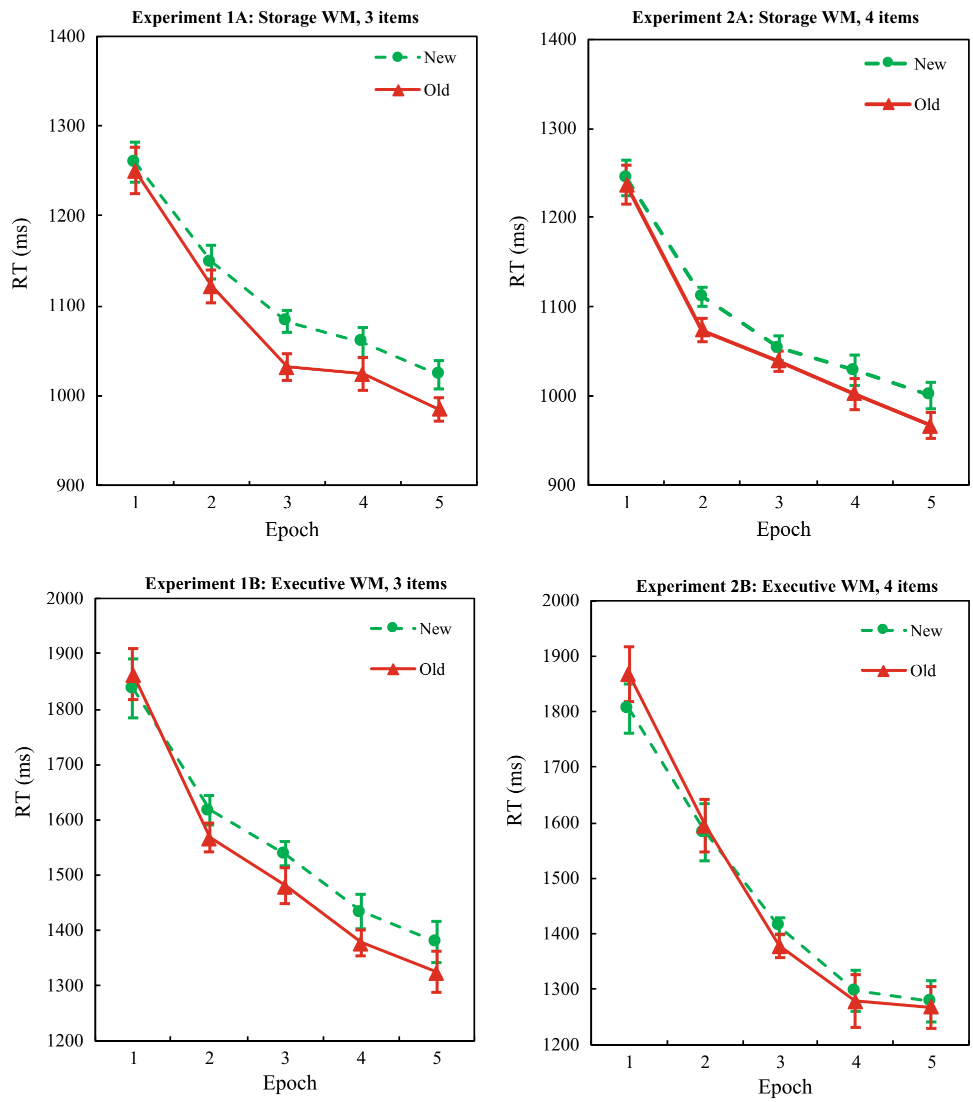

Fig. 2 Mean reaction times (RTs) in each epoch for repeated and novel contexts in the 3 items storage WM task (top left) and the 3 items executive WM task (bottom left) in Experiment 1. Mean RTs in each epoch for repeated and novel contexts in the 4 items storage WM task (top right) and the 4 items executive WM task (bottom right) in Experiment 2. Error bars reflect standard errors corrected for within-participant variation (Morey 2008)

information in search task. To examine whether CCE is impacted by higher executive WM load, we increased the storage WM (Experiment 2A) and executive WM (Experiment 2B) load from 3 to 4 items.

Experiment 2

Experiment 2 increased WM load from three items to four times with the purpose of limiting the availability of storage and executive WM resources. We expected that increasing of storage WM load would not affect contextual learning whereas increasing the executive WM load would affect contextual learning.

Method

Participants

A new group of 20 participants volunteered in Experiment 2A (Storage WM task, 16 females; average age 20.1 years) and another 20 students took part in Experiment 2B (Executive WM task, 14 females; average age 20.4 years). All participants had normal or corrected-to-normal visual acuity and normal color vision. The present study was approved by the Ethical Committee of Liaoning Normal University. Informed consent was obtained from all participants included in this study.

Stimuli and procedures

The design of Experiment 2 was in exactly the same way as Experiments 1, except for the storage and executive load of WM tasks were increased to 4 digits.

Results

Two participants from Experiment 2A who did not complete the whole experiment were excluded from further analysis. One participant from Experiment 2B was excluded from analysis due to poor performance on executive WM task (50% in accuracy).

Accuracy

Search task The mean accuracy was 98.9% and 98.48% in Experiment 2A (storage WM condition) and in Experiment 2B (Executive WM condition), respectively, there was no significant difference of accuracy between 2A and 2B, $t(35) = 0.72$, $p = 0.48$.

WM task The accuracy for the storage WM task was 95.6% (Experiment 2A) and 82.7% for the executive WM task (Experiment 2B). WM task accuracy was significantly better in Experiment 2A than in 2B, $t(35) = 6.06$, $p < 0.001$. Assuming that accuracy is an index of task difficulty, the executive WM task appears to be more difficult than the storage WM task.

Search time

Figure 1 illustrates the mean RTs for repeated and novel configurations as a function of epoch for 4 items storage WM task and executive WM task (top right and bottom right panel of Fig. 2, respectively). To examine the effects of storage and executive WM task on the CCE, we conducted a 2 (context: repeated vs. novel, within-subject) × 5 (epoch:1–5, within-subject) × 2 (Experiment 2A vs. 2B, between subjects) mixed-design ANOVA. There was a significant main effect of epoch, $F(4, 140) = 58.55$, $p < 0.001$, $\eta^2 = 0.62$, indicating a general practice and learning effect. The main effect of experiment was also significant, $F(1, 35) = 6.28$, $p = 0.017$, $\eta^2 = 0.15$, indicating the RT for the executive WM task was significantly slowed compared to the storage WM task. Importantly, the interaction of context × experiment was significant, $F(1, 35) = 4.68$, $p < 0.05$, $\eta^2 = 0.12$, indicating that the difference between repeated and novel contexts varied across the storage and executive WM task; a CCE emerged in the storage WM condition but not in the executive WM condition. The interaction of epoch × experiment also reached significance, $F(4, 140) = 10.13$, $p < 0.001$, $\eta^2 = 0.22$, indicating that the RT difference across learning epochs varied between storage and executive WM task. None of other main effects and interactions were significant, $ps > 0.05$.

A repeated measure ANOVA was conducted on Experiment 2A and Experiment 2B, respectively. In Experiment 2A, the main effect of context, $F(1, 17) = 7.81$, $p = 0.012$, $\eta^2 = 0.32$, and epoch, $F(4, 68) = 56.05$, $p < 0.001$, $\eta^2 = 0.77$, were significant, indicating that participants acquired CCE while retaining information in WM. However, in Experiment 2B, except for the main effect of epoch, $F(4,72) = 33.75$, $p < 0.001$, $\eta^2 = 0.65$, none of other main effects or interactions were significant, indicating that concurrent engagement of executive WM functions hindered contextual cueing learning.

To examine how the difficulty of WM tasks affected contextual learning, we compared contextual learning with the same WM processes but different WM load. Specifically, we made a comparison between Experiment 1A and 2A, and comparison between Experiment 1B and 2B.

Experiment 1A (storage task, 3 items WM load) vs. 2A (storage task, 4 items WM load) The accuracy on search task did not differ from Experiment 1A and 2A, $t(34) = -0.93$, $p = 0.36$. But the performance on WM task in Experiment 1A (3 items WM load) was significantly better than 2A (4 items WM load), $t(34) = -2.57$, $p < 0.05$, an evidence that increasing WM load from three to four items significantly increased the storage WM task difficulty.

A repeated-measure ANOVA on mean RT was conducted with context (repeated vs. novel) and epoch (1–5) as within-subject factors, and experiment (1A vs. 1B) as between-subject factor. Results showed a significant main effect of context, $F(1,34) = 21.08$, $p < 0.001$, $\eta^2 = 0.38$ and epoch, $F(4,136) = 97.06$, $p < 0.05$, $\eta^2 = 0.74$. The other main effects and interactions were not significant, indicating that CCE was comparable under different storage WM loads, even though the difficulty of storage WM task significantly increased. In other words, CCE was not affected by the storage WM function irrespective of the WM load.

Experiment 1B (executive task, 3 items WM load) vs. 2B (executive task, 4 items WM load) Similarly, participants in Experiment 1B completed the search task as well as those in Experiment 2B, $t(38) = 1.69$, $p = 0.10$. But better performance on the executive WM task was shown in Experiment 1B (3 items WM load) relative to Experiment 2B (4 items WM load), $t(38) = 1.93$, $p = 0.06$.

The same analysis method was applied on Experiment 1B vs. 2B as mentioned above in Experiment 1A vs. 2A, which revealed a main effect on context, $F(1, 38) = 5.79$, $p = 0.02$, $\eta^2 = 0.13$ and epoch, $F(4, 152) = 68.81$, $p < 0.001$, $\eta^2 = 0.64$, and the epoch × context interaction also reached significance $F(4, 152) = 3.29$, $p = 0.01$, $\eta^2 = 0.08$. Importantly, the interaction between context and experiment also reached significance, $F(1, 38) = 7.02$, $p < 0.05$, $\eta^2 = 0.16$, indicating a CCE occurred on Experiment 1B (executive task, 3 items WM load) but not in Experiment 2B (Executive task, 4 items WM load). None of other main effects and interactions were significant, $F\text{s} < 1.07$, $p\text{s} > 0.37$.

Discussion

A CCE appeared in Experiment 1A (retain 3 digits), Experiment 2A (retain 4 digits), and Experiment 1B (subtract 3 digits), but not in Experiment 2B (subtract 4 digits). One interpretation of this empirical pattern is that the CCE diminishes when executive WM resources have been sufficiently occupied by a secondary executive WM task. However, the actual learning itself can be differentiated from the expression of that learning (Jiang and Leung 2005). The attenuation of the CCE may be accounted for by executive WM processes impairing the expression of information that was learned instead of the contextual learning itself. To date, multiple studies have reported that participants can learn implicit contextual information with a concurrent task, but are hindered in their expression of that learned information (Manginelli et al. 2012, 2013). Thus, it is essential to explore further how the executive processes affect the contextual learning.

Experiment 3

The purpose of Experiment 3 was twofold: to replicate and extend our findings using a within-subject design, and to determine whether the high-load executive WM condition (Experiment 2B) prevented contextual learning or impaired the expression of learned information. To do so, we modified the procedure to include a search-only phase following the dual-task phase. If executive WM function impairs contextual learning itself, we expect to observe no CCE in the following search-only phase; if executive function of WM impairs the expression of contextual learning, there would be CCE in the search-only phase.

Method

Participants

21 undergraduate students (17 females; average age 21 years) participated this experiment, after giving informed consent. They all reported normal or corrected-to-normal visual acuity and normal color vision. The present study was approved by the Ethical Committee of Liaoning Normal University. Informed consent was obtained from all participants included in this study.

Stimuli and procedures

In Experiment 3, participants performed contextual cueing trials in combination with the executive WM task. Trials were randomized and divided equally into two conditions in each block: low-load (subtractive task for 3 items) and high-load (subtractive task for 4 items). Half the repeated search arrays were allocated to low-load WM task and the other half of the repeated search arrays were allocated to high-load WM task, and this allocation remained consistent across blocks. Alike Experiments 1 and 2, in the first four epochs, the dual-task paradigm was used, in which participants performed the search task concurrently with the executive WM task (learning phase). After the learning phase (Epoch 1–4), there was a search-only testing phase (Epoch 5). The other details of design, stimuli, and procedures were identical to Experiment 1 and 2.

Results

Accuracy

Search task The accuracy for CC search task was 99.03% (low-load) and 99.25% for low-load and high-load conditions, respectively, indicating that CC visual search task was not unaffected by executive WM load, $t(20) = -1.31$, $p = 0.80$.

Executive WM task A paired-sample t test for WM accuracy revealed a significant difference of WM load, $t(20) = 4.50$, $p < 0.001$, showing better performance on low-load executive WM tasks (92.3%) than high-load executive WM tasks (88.6%).

Search time

Figure 3 illustrates the mean RTs for repeated and novel configurations in the learning phase (left panel) and the testing phase (right panel) for low-load (top panel) and high-load (bottom panel) conditions. We analyzed the CCE for the first four epochs (learning phase) and the last epoch (testing phase) separately to examine the change of CCE performance after the WM task was removed.

In the learning phase, we used a three-way repeated-measures ANOVA (context: repeated vs. novel; epoch: 1 ~ 4; load: low-load vs. high-load). There were significant main effects of epoch, $F(3, 60) = 10.33$, $p < 0.001$, $\eta^2 = 0.34$, and load, $F(1, 20) = 28.13$, $p < 0.001$, $\eta^2 = 0.34$. The interaction between context and epoch was significant, $F(3, 60) = 3.86$, $p = 0.014$, $\eta^2 = 0.16$, indicating that participants had gradually acquired and applied the repeated context information to search more efficiently across the learning epochs. Importantly, the interaction of context and load was significant,

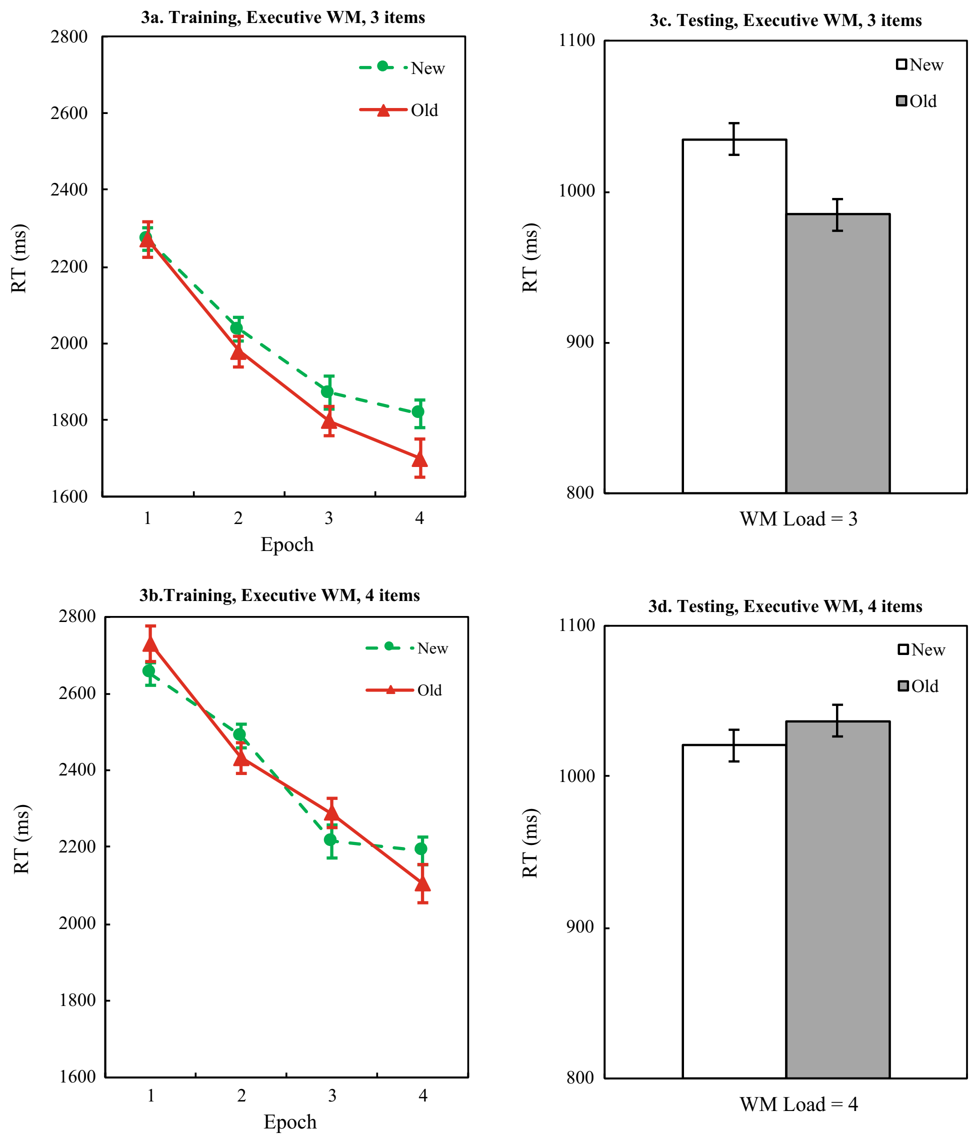

Fig. 3 Mean RTs for repeated and novel contexts at the learning phase (from epoch 1 to epoch 4) and at the testing phase (in epoch 5) for low-load and high-load executive WM conditions in Experiment 3. Error bars reflect standard errors corrected for within-participant variation (Morey 2008)

$F(1, 20) = 4.31$, $p < 0.05$, $\eta^2 = 0.18$. An analysis of simple effects showed that the main effect of context in low-load condition was significant, $F(1, 20) = 10.23$, $p < 0.01$, $\eta^2 = 0.32$, but not in the high-load condition $F(1, 20) = 0.02$, $p = 0.89$, $\eta^2 = 0.001$, indicating that participants acquired a CCE under low-load WM task condition but not in high-load WM task condition. No other interactions were significant, $Fs < 2.57$, $ps > 0.12$.

Two potential accounts can explain the lack of CCE when visual search was paired with the high-load WM task. One account is that executive WM affected the learning process of contextual information; the other is that executive WM only affected the expression of contextual learning. If a CCE does not emerge when executive WM resources are engaged, it is possible that learning is still occurring, but not being expressed. This possibility was tested by comparing the CCE between Epoch 4 (the last epoch of the dual-task phase), and Epoch 5 (search-only task phase). A 2 (context: repeat vs. novel) × 2 (load: low vs. high) × 2 (task type: epoch 4 vs. epoch 5) repeated-measures ANOVA was conducted to compared CCE with epoch 4 and epoch 5, and revealed a significant main effect of load, $F(1, 20) = 14.61$, $p = 0.001$, $\eta^2 = 0.42$, task type, $F(1, 20) = 26.07$, $p < 0.001$, $\eta^2 = 0.57$ and context, $F(1, 20) = 11.25$, $p < 0.01$, $\eta^2 = 0.36$. The three-way interaction between context and load and task type failed to reach significance, $p > 0.05$. The interaction of task type × context, $F(1, 20) = 5.63$, $p < 0.05$, $\eta^2 = 0.22$, and task type × load $F(1, 20) = 16.08$, $p = 0.001$, $\eta^2 = 0.45$, reached significance indicating that the context benefit emerged in epoch 4 and epoch 5 between low-load and high-load was varied.

An analysis of simple effects showed that for low-load WM condition there was CCE both in epoch 4, $p < 0.001$ and epoch 5, $p < 0.05$. The magnitude of CCE (RT_{novel}

Table 1 The accuracy of recognition test (mean ± SD)

	Accuracy (%)	*t*	*p*
Experiment 1A (*N* = 18)	50.0 ± 5.3	0.05	0.94
Experiment 1B (*N* = 21)	50.1 ± 5.3	0.47	0.64
Experiment 2A (*N* = 17)	48.4 ± 4.3	1.52	0.15
Experiment 2B (*N* = 19)	49.8 ± 4.5	− 0.32	0.76
Experiment 3 (*N* = 21)	49.8 ± 4.5	− 0.15	0.88

$-\ RT_{repeated}$) between epoch 4 and epoch 5 (115.5 ± 25.6 ms vs 50.3 ± 19.6 ms) did not reach significant difference, $p = 0.079$, indicating that contextual learning could transfer from dual-task to single-task. In contrast, we did not find an RT difference between repeated and novel contexts in high-load condition in epoch 4, $p = 0.15$ and epoch 5, $p = 0.47$, indicating that participants did not show the CCE in the learning phase or in the testing phase. These results support that the executive WM affected the contextual learning itself (learning account) instead of the expression account. Participants did not learn the contextual information when limiting the availability of executive WM resources, indicating that executive WM resources may be involved in learning process of CCE.

Recognition performance

All participants completed the recognition test, except for one participant from Experiment 2A. As shown in Table 1, the overall mean accuracy on recognition tasks for all Experiments was at chance level (50%), *p*s > 0.15, and there were no significant differences across experiments, $F(4, 91)$, $p = 0.74$, indicating a nature of implicit context learning in the present studies.

Discussion

A CCE persisted under low executive load but was attenuated by a concurrent high-load executive task. Because a CCE did not emerge in epoch 5, we can assume the executive WM task hindered contextual learning itself in epoch 1–4. These within-subject findings lend support to the finding from Experiments 1 and 2, that occupying executive WM to its capacity with an executive WM tasks obstructs contextual learning.

General discussion

This study examined the relation between WM and implicit spatial learning. The results from three experiments are clear: compared to maintaining information in WM, manipulating information in WM attenuates the CCE; and such executive WM processes affect implicit spatial learning processes, not the expression of learned information. This was found specifically when executive WM was operating at high capacity.

Experiment 1A and 2A involved short-term storage WM tasks in which participants maintained three or four digits in WM. Maintaining information in WM did not affect contextual learning even when WM load was 4 items—which is considered to use WM resources near full capacity (Cowan 2001, 2010; Luck and Vogel 1997). Experiment 1B and 2B involved executive WM tasks that required participants to subtract 3 from each WM item. In the high-load, but not low-load executive WM conditions, contextual learning was significantly impaired. Our results are in line with Han and Kim (2004), who showed no effect maintaining items in WM on visual search, but a strong effect of actively manipulating items in WM. The executive WM tasks used in our experiments are similar to the executive WM task adopted in Han and Kim (2004); participants were required to subtract 3 from each digit. Han and Kim (2004) found that performing an executive WM tasks such as a backward counting task, or a letter sorting task impaired visual search efficiency. We found that contextual learning was impaired while performing an executive WM task concurrently. It should be noted that executive WM processing only affected CCE when WM was occupied to capacity. When executive WM load was low, the dual task only slowed down the contextual learning process, i.e., the CCE did not occur until the last epoch in Experiment 1A (Epoch 4).

Experiments 1 and 2 used a between-subjects design, and it is possible that the differences observed between groups are due to sampling differences. To eliminate this potential confound, we conducted a within-participant design in Experiment 3 to replicate and strengthen the results of Experiment 1 and 2. In Experiment 3, half the scenes were combined with three-item executive WM load, and the other half of the scenes were combined with four-item executive WM load. As predicted, a CCE was observed for scenes paired with the low-load executive WM task, but was not observed on scenes paired with the high-load executive WM task. These results indicate that executive WM functions interfere with contextual learning, but only when executive WM resources are in high demand.

We also used Experiment 3 to determine whether the executive WM task affected the acquisition or expression of learned contextual information (Annac et al. 2013; Manginelli et al. 2012, 2013). This was done by adding a search-only task after the dual-task phase. The rationale here is that a concurrent WM task could theoretically interfere with the CCE in two ways: by preventing the encoding of contextual information during initial scene exposures, or by preventing the retrieval/utilization of learned contextual information during search (Jiang and Leung 2005). If the concurrent executive WM task interferes with only the expression of learned contextual information, we ought to observe a CCE when the secondary task is removed in a set of final experimental blocks. We showed that in a following search-only phase a CCE did not emerge. This indicates that executive WM was involved in contextual learning.

Several studies have examined the relation between contextual learning and WM, and there is a discrepancy in the conclusions that have been drawn. Vickery et al. (2010) found that neither WM load or WM type impacted contextual learning, whereas other researchers have shown effects of concurrent spatial WM load on contextual cueing (Manginelli et al. 2013; Travis et al. 2013). The foci of these prior studies have been WM load (Manginelli et al. 2013; Vickery et al. 2010) and spatial verse non-spatial WM tasks. Our study presented a novel comparison between the short-term store function and executive functions of WM. Given the observed influence of executive WM on contextual learning in the present study, it may be possible to better understand previous findings in by considering which previously used tasks tapped executive WM processes (as opposed to focusing on the spatial vs non-spatial distinction). For instance, Travis et al. (2013) observed an attenuated CCE when visual search was paired with a concurrent spatial WM task. The spatial WM task required participants to judge whether the presentation order of a series of probe dots matched the sequence in the encoding display. This sequence matching task likely requires executive functions of WM. To encode the location order of the two dots, one might remember the locations of the two dots first, then, manipulate the two dots' spatial location in memory by, for example, creating a linear representation from the first dot to the second dot to more efficiently encode the spatial information. From this view, the spatial WM task in Travis et al. (2003) would tap into executive WM resources. In line with our finding, the Travis et al. (2003) spatial WM task interfered with contextual learning itself, rather than the expression of learning. Therefore, the finding in Travis et al. (2003) may best be interpreted in terms of executive WM function, instead of whether the WM function is spatial or non-spatial.

In terms of WM task difficulty, we noted that the executive WM task only affected the CCE when the WM load was four items. Assuming that accuracy is a good index of task difficulty, the executive WM accuracy decreased from 88.6 to 82.7% when the load was changed from 3 to 4 items, reflecting an increase in difficulty. For the maintenance WM task, although there was a significant decrease between the three and four item storage WM task accuracy, 98.10% vs 95.6%, respectively, there was a CCE in both Experiment 1A and 2A. An important question is whether the storage WM task would also interfere with contextual learning if the storage WM task load was increased substantially. We recognize that performance on the executive WM task is significantly lower than on storage the WM task in our experiments. This makes it temping to interpret the effect of executive WM as an effect of difficulty. However, there are sufficient reasons to believe that increasing the difficulty of storage WM task would not interfere with contextual learning.

First, in the present experiments, increasing storage WM loads from three to four items significantly increased the WM task difficulty, but did not interfere with contextual learning. Second, a consistent finding in this field is that maintaining a non-spatial WM stimuli does affect contextual learning, irrespective of WM load (Manginelli et al. 2012; 2013; Travis et al. 2013; Vickery et al., 2010). For example, WM loads up to 10 items have been shown not to interfere with contextual learning (Vickery et al. 2010). A motivation for manipulating WM load in general is to help reduce possibility that task difficulty confounds our results. For instance, because we demonstrated an effect of executive WM load on contextual cueing (CCE observed under low-, but not high-load) using a within-subject load manipulation we can say that the finding about the executive function of WM in contextual learning is not confounded by WM task difficulty. However, a more compelling comparison that ought to be carried out in future research would be between a storage WM task and executive WM task, wherein the storage WM load is higher than the executive WM load. Such a comparison would provide a compelling answer to whether the effect of executive WM on contextual learning ultimately owes to difficulty of the concurrent WM task.

It is worth noting the existence of a piece of evidence suggesting contextual cueing is unaffected by executive WM load (Annac et al. 2013). We can explain this inconsistent result by referring to the methods of the particular study (Annac et al. 2013), which operationalized executive WM load as task switching demands (contextual cueing trials and spatial WM task trials). That is, their task did not require active manipulation of information in WM to occur concurrently with visual search. We assume they would have observed an influence of executive WM on contextual learning if the executive WM task was implemented such that the WM and search task competed for resources.

The novel finding of the present study is that executive WM processes, rather maintenance WM processes, impaired the contextual learning processes. In the context of visual search, search studies found that executive processes, rather than the simple maintenance function of WM, interfered with visual search (Han and Kim 2004; Oh and Kim 2004). An fMRI study also revealed that there was greater activation of dorsolateral prefrontal activation when performing on manipulation WM trials than performing on maintenance trials (D'Esposito et al. 1999). Tuholski et al. (2001) also found that executive WM processing might be more involved in controlled processing, which has been closely related to attention.

Taken together, these findings imply that executive WM processes may facilitate contextual learning. Recall the associative learning account of CCE (Chun and Jiang 1998), which holds that participants learn multiple associations between each spatial configuration and a corresponding target location. For instance, a typical CCE paradigm will utilize twelve different repeated configurations that are randomly mixed with twelve novel configurations in each block. For each repeated configuration, one may develop a distinct memory representation—an attentional set that shifts attention to corresponding target locations. In contextual learning, participants need to repeatedly update current attentional settings using available visual information. Efficient retrieval of an attentional set that matches current contextual information will decrease RT for that configuration. Executive WM systems are thought to be actively matching current contextual information with learned associations stored in long-term memory, updating the actor's attentional set. Occupying executive WM resources with the subtractive task may reduce the availability of executive resources, resulting in an interference of implicit spatial learning.

Conclusion

In summary, maintaining information in WM does not affect contextual learning irrespective of the WM load, whereas executive function of WM affected contextual learning when executive WM resources are at capacity. We demonstrated that executive WM processes interfere with the acquisition of contextual information—rather than the expression of this information. Together, this study supports the view that executive WM processes are related to processes of contextual learning, and may even facilitate them.

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Author contributions MC and CW contributed equally to this work. MC, CW, and GZ designed the experiments. MC, CW, and XL prepared the materials and performed the experiments. MC, CW, BS, GZ, and XL analyzed the data and wrote the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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