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Gaze-Based and Attention-Based Rehearsal in Spatial Working Memory

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How do we maintain information about spatial configurations in mind? Many working memory (WM) models assume that rehearsal processes are used to counteract forgetting in WM. Here, we investigated the contributions of gaze-based and attention-based rehearsal for protecting spatial representations from time-based forgetting. Participants memorized 6 locations selected from a grid of 30 scattered dots. Memory was tested after 1.5 or 4.5 s, and this interval was either blank or the grid remained onscreen (which is assumed to provide rehearsal support). In 2 experiments, we monitored eye movements during the retention phase, or asked participants to fixate the screen center. In 3 subsequent experiments, we tested spatial WM under dual-task conditions inhibiting shifts of visuospatial attention or central attention to the memoranda. Memory was better and more resistant to time-based forgetting in the grid than blank condition. Recording of fixations showed more frequent and efficient gaze-based rehearsal in the presence of the grid. Fixations toward distractor locations occurred at a similar frequency in the blank and grid conditions, and it did not predict incorrect recalls. Inhibition of eye-movements or shifts of visuospatial attention impaired memory overall, but it did not change the grid benefit nor the rate of time-based forgetting. In contrast, distracting central attention increased time-based forgetting regardless of grid presence. These results indicate that (a) the grid benefit is only partially explained by rehearsal; (b) gaze-errors (i.e., distractor fixations) do not lead to more forgetting; and (c) the maintenance of spatial representations over time depends on central processing.

Keywords: central attention, eye-movements, rehearsal, spatial working memory, visuospatial attention

How do we maintain information about the spatial configurations of the objects surrounding us? To safely cross the street, to park our car, or to play soccer, we need to keep in mind the locations of the objects/people that are outside of our visual field. Our ability to remember visuospatial configurations over brief intervals is limited by the capacity of working memory, WM (Awh & Jonides, 2001; Baddeley, 1986; Logie, 2003, 2014). WM can only hold a handful of representations accessible concurrently. Information in WM is in an easy-to-retrieve state but, at the same time, it is at constant risk of being lost. If we forget the positions of the approaching cars or the arrangement of the cars in the parking lot, we can get into an accident; if we forget the positions of our teammates in relation to the other players during a soccer match, we cannot make a proper pass or block the adversary passes.

Many WM models assume that WM representations are forgotten over time unless an active process of rehearsal is used to counteract forgetting (e.g., Baddeley, 1986; Barrouillet & Camos, 2012; Cowan, 2010; Page & Norris, 1998; Ricker, Vergauwe, & Cowan, 2016). For verbal representations, many studies have observed evidence against time-based decay in WM (Berman, Jonides, & Lewis, 2009; Jalbert, Neath, Bireta, & Surprenant, 2011; Lewandowsky, Geiger, Morrell, & Oberauer, 2010; Nairne, 2002; Oberauer & Lewandowsky, 2008, 2014; White, 2012). Studies have also provided evidence against a beneficial effect of different forms of rehearsal for verbal WM retention (Bartsch, Singmann, & Oberauer, 2018; Lewandowsky & Oberauer, 2015; Souza & Oberauer, 2018; for a recent review see Oberauer, 2019). Contrary to verbal WM, several studies have observed reductions in visuospatial WM over the course of unfilled retention intervals (Morey & Bieler, 2013; Pertzov, Bays, Joseph, & Husain, 2013; Pertzov, Manohar, & Husain, 2017; Rademaker, Park, Sack, & Tong, 2018; Ricker & Cowan, 2010, 2014; Ricker, Spiegel, & Cowan, 2014; Schneegans & Bays, 2018; Zhang & Luck, 2009). Furthermore, some studies have landed support to the assumption that this time-based forgetting can be counteracted by a visuospatial rehearsal process (Awh, Anllo-Vento, & Hillyard, 2000; Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Baddeley, 1986; Godijn & Theeuwes, 2012; Guérard, Tremblay, & Saint-Aubin, 2009; C. C. Morey, Mareva, Lelonkiewicz, & Chevalier, 2017; Theeuwes, Belopolsky, & Olivers, 2009; Tremblay, Saint-Aubin,

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& Jalbert, 2006). For example, Lilienthal and colleagues (Lilienthal, Hale, & Myerson, 2014, 2016) asked participants to retain in WM the locations of a sequence of red dots that appeared within an irregular (trial-unique) grid of dot locations. When the interdot interval was increased from 1 s to 4 s, the length of the sequence of dots that participants could remember decreased. This forgetting over time was counteracted when the array of possible spatial locations of the dots (i.e., the irregular grid) was visible onscreen during the interdot interval. Indeed, in their studies, performance in the presence of the grid was slightly better with longer interdot intervals. Lilienthal and colleagues interpreted these findings as follows: representations of the spatial locations get weaker over time as a result of time-based decay, but eye movements (or shifts of visuospatial attention) directed to the locations of the memorized dots could be used to reactivate their representations and prevent forgetting. The presence of the grid was assumed to facilitate the correct rehearsal of the spatial locations, which was considered to be faulty when the screen was blank.

This interpretation is in line with suggestions that overt (gaze-based) or covert shifts of visuospatial attention may serve as a rehearsal mechanism for spatial representations in WM (Awh et al., 2000, 2006; Awh & Jonides, 2001; Baddeley, 1986; Godijn & Theeuwes, 2012; Guérard et al., 2009; C. C. Morey et al., 2017; Theeuwes et al., 2009; Tremblay et al., 2006), and with correlational evidence suggesting that some patterns of eye-movements are associated with better recall from spatial WM (Czoschke, Henschke, & Lange, 2019; Godijn & Theeuwes, 2012; Guérard et al., 2009; C. C. Morey et al., 2017; Tremblay et al., 2006; but see Lange & Engbert, 2013; Martin, Tapper, Gonzalez, Leclerc, & Niechwiej-Szwedo, 2017).

Although consistent with a decay-rehearsal explanation, the data of Lilienthal and colleagues (2014, 2016) do not rule out alternative explanations in terms of interference. A large body of studies have shown that eye-movements or secondary tasks tapping spatial attention can interfere with the maintenance of spatial information in WM (Awh, Jonides, & Reuter-Lorenz, 1998; Golomb & Kanwisher, 2012; Guérard et al., 2009; Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Lange, Starzynski, & Engbert, 2012; Lawrence, Myerson, & Abrams, 2004; Lawrence, Myerson, Oonk, & Abrams, 2001; Pearson & Sahraie, 2003; Postle, Idzikowski, Sala, Logie, & Baddeley, 2006; Smyth & Scholey, 1994; Van der Stigchel, Merten, Meeter, & Theeuwes, 2007). At times, these data have been interpreted as evidence that gaze-based or attention-based rehearsal is needed to maintain information in visuospatial WM (Awh et al., 1998). But these data can also be easily interpreted with an interference-only framework in which eye-movements (Lange et al., 2012; Lawrence et al., 2001; Postle et al., 2006), or any sort of spatially guided movement such as pointing (Hale et al., 1996; Smyth & Scholey, 1994), arm movements (Lawrence et al., 2001), and finger tapping (Smyth, Pearson, & Pendleton, 1988) may lead to the encoding of irrelevant spatial representations to WM, which will then interfere with the retrieval of the memoranda. For instance, in the case of the irregular dot-grid task used by Lilienthal and colleagues, increases in the retention interval provides more opportunities for spontaneous eye movements to be carried out. In the absence of stimuli on the screen (aka blank condition), eye movements may be more often directed at distractor locations on the screen, leading to the encoding of these spatial locations, and increasing interference with the memoranda. This interference would accumulate during the retention interval because the passage of time is associated with more opportunities for eye-movements. When the grid is onscreen, participants have a template to look at, and they may strategically look at the locations that were occupied by the memoranda. In this scenario, this gaze-based rehearsal behavior serves to reduce the likelihood of irrelevant spatial representations being encoded to WM.

In sum, so far it is unclear which factors contribute to time-based forgetting of visuospatial representations and which processes can be used to counteract it. Accordingly, the main aim of the present study was to assess the roles of overt (gaze-based) and covert shifts of visuospatial attention as well as dual-task demands for the retention of visuospatial representations in WM. We choose to address these questions using the paradigm used by Lilienthal et al. (2014) for two reasons. First, substantial time-based forgetting was observed in this task over the course of a few seconds. This provides us with the opportunity to try to understand the causes of this forgetting. Second, the overall benefit offered by the presence of the grid during the retention interval as well as the protection it afforded against time-based forgetting allowed us to address hypotheses regarding rehearsal processes that might occur more efficiently with the grid than in its absence. We started with assessing the viability of two conjectures. First, could overt or covert shifts of visuospatial attention be implicated in the forgetting over time observed in the irregular grid task when the retention interval is blank? Second, if the grid facilitates rehearsal of the spatial representations, what are the relative contributions of overt (gaze-based) and covert shifts of visuospatial attention to these representations for their protection against time-based forgetting? In the last experiment, we were interested in uncovering whether a central processing bottleneck (i.e., response selection) is implicated in the protective effect of the grid against time-based forgetting.

Experiment 1

In this experiment, participants completed an adapted version of the irregular grid task used by Lilienthal and colleagues (2014, 2016). In every trial, participants had to retain in mind six spatial locations highlighted across an irregular (trial-unique) grid. Unlike the study by Lilienthal et al., the six highlighted locations were presented simultaneously onscreen for encoding, and memory load was constant throughout the trials. Memory array offset was followed by a brief retention interval, and a memory test in which the six highlighted locations had to be recalled. We manipulated the duration of the retention interval (1.5 s vs. 4.5 s), and whether the grid of possible spatial locations was visible throughout the retention interval or a blank screen appeared (grid vs. blank condition, respectively). Participants completed this task while we continuously monitored their eye position. Recording of eye-movements allowed us to assess the viability of two differential, nonmutually exclusive, conjectures: (a) irrelevant eye-movements may impair memory when the retention is blank, and (b) the grid facilitates gaze-based rehearsal of spatial representations.

Method

Participants. The minimum number of participants in each experiment was determined based on the requirement to fully counterbalance the order of conditions (which was 24 in most experiments). We increased sample-size when possible and desirable to increase the certainty in estimating the effects of interest in the data. Given that we used Bayesian statistics for our inferences, changes in sampling plan do not unduly inflate the chances of false positives compared to false negatives (Rouder, 2014; Schönbrodt, Wagenmakers, Zehetleitner, & Perugini, 2017).

For Experiment 1, 28 students (M = 24 years old, SD = 4.1) recruited via the website or mailing list of the Max Planck Institute for Empirical Aesthetics participated in a 1-hr session in exchange of financial reimbursement (15 Euros). One additional student took part on the experiment but the eye movement recording was unreliable, and therefore the data of this participant was excluded from the sample. All participants had normal or corrected-to-normal vision.

In all experiments reported here, participants signed an informed consent form in the beginning of the experiment. The experimental procedure in Experiments 1 and 2 were ethically approved by the Ethics Council of the Max Planck Society.

The data and analysis scripts of all experiments are available at the Open Science Framework (OSF) at https://osf.io/9qdkv.

Apparatus. Data collection took place in a sound attenuated booth, equipped with a 24-in. BenQ-XL 2420 Z Monitor (resolution 1,920 × 1,080, refresh rate 144 Hz, 32 color bit), and eye tracker (Eye Link 1000 from SR Research). The experimental task was programmed in Psychtoolbox 3 (Brainard, 1997; Pelli, 1997) implemented in Matlab. We tracked the right eye with a sampling rate of 1000 Hz. A chin- and head-rest supported the head of the participants, and was located 60 cm away from the monitor.

Procedure. Participants completed a spatial WM task adapted from the one reported by Lilienthal et al. (2014). For every participant and trial, 30 dot-locations (radius = 25 pixels) were randomly generated by selecting positions within a squared region (side = 560 pixels, 8.2° visual angle) centered on the middle of the screen. Given these specifications, the dots subtend a visual angle between 1.30–1.32° (farthest to closest to screen center). The dots locations had to be, at least, 50 pixels apart from each other and 40 pixels away from the center of the screen. The 30 locations were marked by hollow circles (hereafter referred to as the grid). From this set of 30 locations, six were selected as memory locations (hereafter targets) and the remaining ones served as distractors.

A standard 9-point calibration procedure of the Eyelink software was applied before the first trial to adjust the camera of the eye tracker. This procedure was repeated, at least, every 10 trials. Participants were asked to reduce blinking during the experimental trials. Furthermore, each trial started with a short one-point recalibration check in which participants were asked to look at a central white fixation cross. If the eye tracker was able to detect the fixation in the determined perimeter within a maximum interval of 2 s, the WM trial started. The recalibration check failed if the fixation was recorded at a distance larger than 21.5 pixels from the center (corresponding to 0.57° visual angle around the center of the screen). In this case, the 9-point calibration procedure was reinstated immediately.

Each trial of the WM task started with presentation of the grid in white (RGB 255 255 255) against a gray background (RGB 128 128 128) in which the six target locations were filled with blue color (RGB 0 0 255) for 1 s (see Figure 1). Participants were instructed to remember the locations of the blue dots. After re-

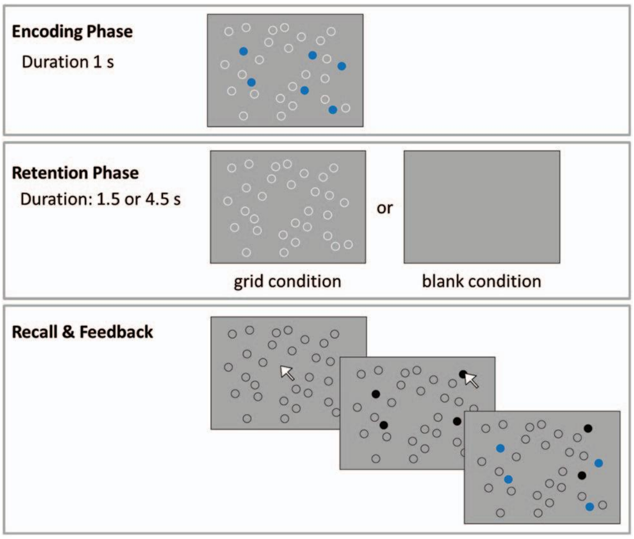

Figure 1. Illustration of the displays in each phase (i.e., encoding, retention, recall, and feedback) of the experimental trial. See the online article for the color version of this figure.

moval of the dots from the screen, a retention interval of 1.5 or 4.5 s followed (with these intervals varying in a block-wise fashion). During the retention interval, either the grid remained onscreen (grid condition) or a blank screen was shown (blank condition), with these conditions varying between blocks. At recall, the grid was shown in black color and the mouse cursor appeared at the center of the screen. Participants were instructed to indicate the locations of the six targets by clicking on their corresponding positions on the grid. When a location was clicked, it turned black. Participants could not change their response. After all six locations were selected, correctly recalled locations turned blue for 1 s (visual feedback). There was a minimum of 1.5 s separating every two trials plus the time to recalibrate the eye-tracker.

Participants completed four blocks of 30 trials. After every tenth trial participants were allowed to take a short self-paced break, and were encouraged to close and relax their eyes. The four experimental blocks differed regarding grid presence (grid vs. blank condition). These two conditions were completed in alternated fashion across the blocks (i.e., grid-blank-grid-blank or blank-grid-blank-grid, with the two orders counterbalanced across participants). Each block was further split into two subblocks in which the retention interval was either short (1.5 s) or long (4.5 s). All participants that started the experiment with the grid condition were exposed to the long-short alternation of retention intervals within a block, whereas all participants that started the experiment with the blank condition were exposed to the short-long alternations. In Experiment 2 the order of the two retention conditions within each block was fully counterbalanced across participants. Because memory performance accuracy was the same for Experiment 1 and 2, we do not think that order of retention condition and grid condition interact.

Eye movement data. Eye-movement data were categorized into saccades and fixational eye movements, using the velocity-based algorithm from Engbert and Mergenthaler (2006). Saccades with amplitudes shorter than 20 pixels (0.48° viewing angle), or with a duration less than 10 ms were ignored. Overall, the algorithm detected 89,136 saccades for all participants and trials. These saccades occurred in different time points during the experimental trial (e.g., encoding, retention, recall, feedback). However, only saccades recorded during the encoding and retention phases were of interest here. A total of 19,654 saccades were recorded during these two time-points, yielding ca. 700 saccades per participant on average. Of further interest for our analysis were the landing positions of the saccades. This led us to also exclude from the data-set 4 saccades that started during one of these periods but terminated in another phase of the trial (yielding a final set = 19,650 saccades).

We classified the landing position of the saccades as being on a target location, a distractor location, or the center of the screen by computing the smallest distance between the fixation and the locations of these elements on the screen. We excluded from the data-set 290 saccades (1.5% of all saccades) that landed at a location that was farther than 150 pixels from all locations of interest (center, targets, or distractors). The 150-pixel threshold allowed us to exclude from the categorization only saccades that occurred outside of the area of possible grid locations. Using a more stringent threshold led to a much larger rate of exclusion of saccades, but did not change the pattern of results reported here.[1] Figure 2 shows one example trial for each condition alongside the fixations recorded in these trials for a representative participant. This figure also illustrates the classifications applied to these fixations using the 150-pixel threshold.

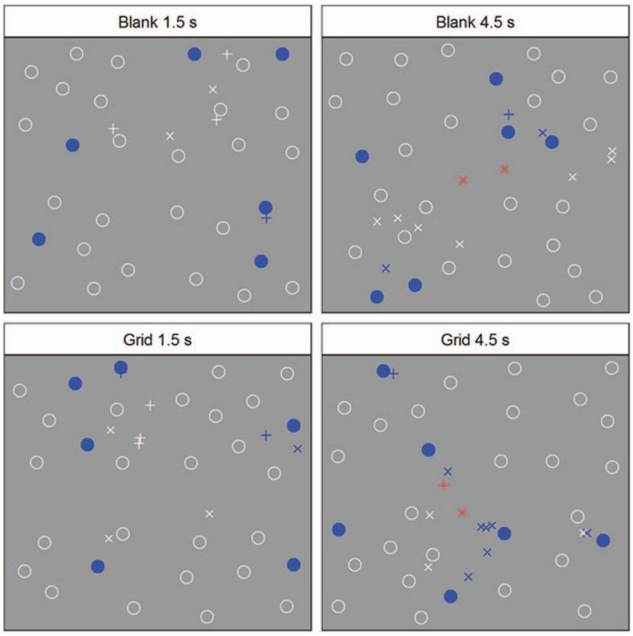

Figure 2. Example of the memory arrays and fixation positions displayed by one participant in one trial of each experimental condition. Distractors and targets are designated by unfilled circles and filled blue/dark grey dots, respectively (as in the experimental task). Fixations were differently depicted for the encoding (+) and retention (×) phases. The color of the symbols indicates the classification of the fixation location: red/light grey = center; white = distractor; blue/dark grey = target. See the online article for the color version of this figure.

Data analysis. Dependent variables were the recalled locations in each trial, and the number and location of fixations during the encoding and retention phases. We submitted our data to Bayesian Analysis of Variance (Rouder, Morey, Speckman, & Province, 2012; Rouder, Speckman, Sun, Morey, & Iverson, 2009) using the default settings of the Bayes Factor package (Morey & Rouder, 2015) implemented in R (R Core Team, 2017). The ANOVA provides the evidence (Bayes Factor, BF) for models including all possible combinations of the entered predictors against a model including only between-subjects variance (null model). The BF is the relative likelihood of the two models given the data. The BF provides a continuous index of the support for one model over the other. Here we will present the BF for the alternative hypothesis (H_1) over the null hypothesis (H_0), that is, BF_{10}.[2] The model with the highest BF_{10} is favored by the data, and this model will be referred to here as the best model. One can also compute the evidence for retaining a given predictor in the best model, or against the inclusion of a predictor in this model, by taking the ratio of the best model against other models that exclude or include the given predictor. When BFs are in the range of 0.33 to 3, they are usually regarded as providing inconclusive evidence. In line with previous suggestions (Jeffreys, 1961; Kass & Raftery, 1995; Wetzels & Wagenmakers, 2012), here we will describe BFs >3 as providing substantial support for the stated model (or indicated predictor) and BFs <0.33 as providing substantial support for the null hypothesis (or for exclusion of a given predictor). The reader is, however, cautioned to interpret the BF in a continuous fashion to update their belief in the stated model.

In Bayesian statistics the parameters describing the data under a given model are described as probability distributions. The probability distribution of a parameter reflects its likely values given the data (i.e., the posterior distribution of a parameter). Assessment of the posterior distribution of an effect indicates how confident we can be to observe an effect of a given size. Assessment of the posterior can be done by describing the interval covering 95% of the distribution (i.e., the highest density interval, HDI). Interpretation of the 95% HDI is straightforward: it reflects the range of credible intervals of the parameter, and we should expect that the true value of the parameter lies in this interval 95% of the time (Kruschke, 2011, 2013).

Results

Memory accuracy. Figure 3A shows that recall accuracy was higher in the grid than in the blank condition. The increase in the length of the retention interval led to a stronger reduction in accuracy in the blank condition compared to the grid condition. Accordingly, the best model of this data included the main effects of grid, retention, and their interaction (see Table 1).

[1] We assessed the effect of changing this threshold to either 100 or 50 pixels. This led to the exclusion of 3.7% and 45.6% of the fixations as out of the range for classification, respectively. These more stringent criteria led to exclusion of saccades landing within the area of grid locations, but had no effect on the pattern of fixations to targets, distractors, and screen-center as a function of grid presence and retention interval. The results of these additional analyses are available at the OSF.

[2] The evidence for the null over the alternative hypothesis (BF_{01}) can be derived by computing $1/BF_{10}$.

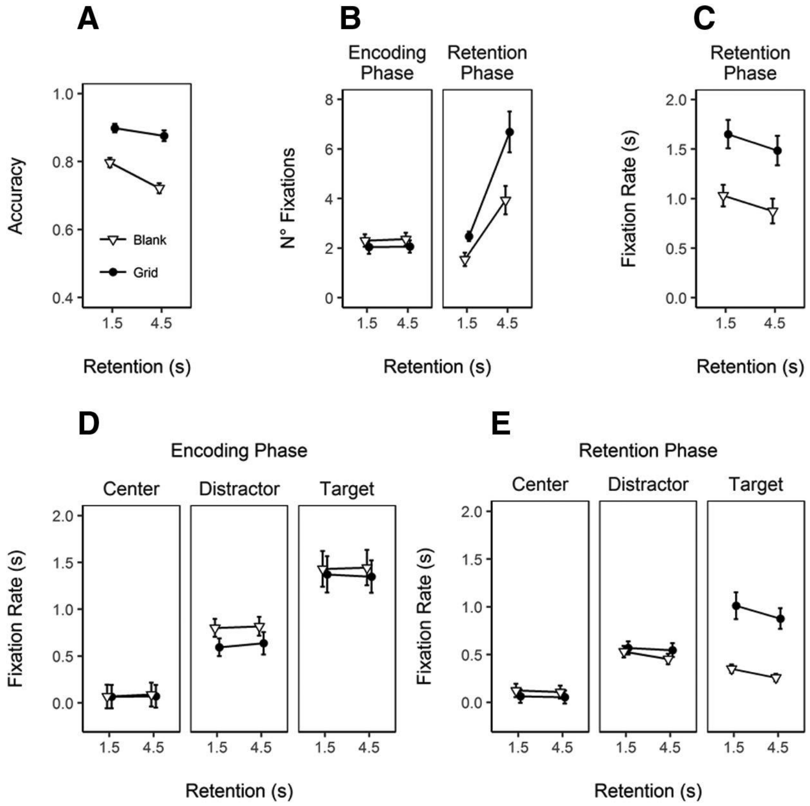

Figure 3. Results of Experiment 1. (A) Recall accuracy in each experimental condition. (B) Average number of fixations recorded during the encoding and retention phases as a function of retention interval duration and grid presence. (C) Fixation rate (fixations per second) in the retention phase. (D and E) Fixation classification in terms of their landing position: screen center, distractor, or target in the encoding and retention phases, respectively. Error bars depict 95% within-subjects confidence intervals.

Eye movements. Figure 3B shows the number of fixations recorded during the encoding and retention phases as a function of the duration of the retention interval and of grid presence. At encoding a slightly larger number of fixations were recorded in the blank than the grid condition, and the evidence for this effect was overwhelming (see Table 1). There was no evidence for an effect of retention duration or its interaction with grid presence. This finding indicates that participants were slightly more likely to explore the screen at encoding when they knew the grid would not remain onscreen during the following retention interval.

Regarding fixations during the retention phase, Figure 3B shows a clear increase in the number of fixations in the long compared to the short retention interval. This is expected given the threefold increase in time (and hence in opportunities for eye movements). Figure 3C shows fixation frequency normalized by the length of the retention interval (which gives the rate of fixation in the same scale as during encoding, i.e., fixations per second). This figure shows a clear effect of grid presence on the frequency of fixations, and also a slight tendency for a reduction in the rate of fixations as the length of the retention interval increases. When one analyzes the number of fixations across conditions, the best model includes the main effects of grid, retention duration, and their interaction (see Table 1). However, when the dependent variable is fixation rate, only the main effects of grid and retention duration are included in the best model. This shows that the interaction uncovered in the analyses of fixation frequency is mainly due to the proportional increase in fixation frequency in the grid condition given the length of the retention interval.

Next, we turn to the classifications of the landing positions of the fixations. About 54.5% of all fixations recorded were close to target locations, 38.4% were close to distractor locations, and only about 5.6% were close to the center of the screen (the remaining 1.5% were unclassified fixations that landed too far—more than 150 pixels away—from any relevant location). Figure 3D and 3E shows the rate of fixations per landing location in the encoding and retention phases, respectively, split per retention interval duration and grid presence. We analyzed the fixations in each phase separately entering grid, retention duration, and location as predictors. Given that 18 models are evaluated when a three-predictor analysis is performed, we will not present the BF of all models here.[3]

As shown in Figure 3D, at encoding fixations tended to land at a target location, followed by a distractor location, with the least preferred category being the screen center. The best model in the encoding phase included only the main effects of location and grid

[3] The interested reader can find the full pattern of evidence over models in the OSF.

Table 1
Bayesian ANOVA Results for Recall Accuracy and Number of Fixations in Experiment 1

Dependent variable	Model	Included predictors: Grid	RI	Grid × RI	BF_{10}
Accuracy	**1**	✓	✓	✓	**2.44×10^{28}**
	2	✓	✓		2.82×10^{26}
	3	✓			1.82×10^{20}
	4		✓		13.82
Number of fixations (encoding)	1	✓	✓	✓	6692.87
	2	✓	✓		23335.84
	3	✓			**87935.83**
	4		✓		.24
Number of fixations (retention)	**1**	✓	✓	✓	**9.05×10^{21}**
	2	✓	✓		1.59×10^{20}
	3	✓			374.21
	4		✓		1.74×10^{13}
Fixation rate (retention)	1	✓	✓	✓	7.37×10^{13}
	2	✓	✓		**2.68×10^{14}**
	3	✓			4.13×10^{13}
	4		✓		.90

Note. RI = retention interval. The best model is printed in boldface.

presence ($BF_{10} = 6.93 \times 10^{77}$). The evidence supporting the inclusion of the main effect of grid was, however, ambiguous ($BF_{10} = 1.56$). There was hardly any effect of any other manipulation, except perhaps for a slightly higher frequency of fixations in distractor locations in the blank condition, but this putative interaction was not supported by the data ($BF_{10} = 0.28$).

Figure 3E shows the classification applied to fixations occurring during the retention phase (normalized by length of the retention). As shown in this figure, the two grid conditions differ mainly on the rate of fixations at target locations. The best model of this data included the main effects of grid, retention duration, fixation location, and the interaction of grid and fixation location ($BF_{10} = 1.28 \times 10^{76}$). When looking at each fixation category separately, there was ambiguous evidence for a difference between the blank and grid conditions in the rate of fixations at distractor locations ($BF_{10} = 1.84$); however, they differed strongly on target fixations ($BF_{10} = 1.86 \times 10^{22}$). Critically, the interaction of grid and fixation category reflects the fact that in the blank condition more fixations landed at distractor locations than target locations, whereas in the grid condition the reverse was true: more fixations landed at target than distractor locations. To make the interaction clearer, Figure 4 shows the posterior of the ratio of target to distractor fixations across the two conditions. If fixations at targets and distractors occurred at the same proportion, the posterior would be at 1 (red vertical line). As shown in this graph, there was almost twice as much distractor fixations than target fixations in the blank condition, whereas the reverse was the case in the grid condition.

Recall versus fixations. What is the relation between eye-movements and recall? To assess for this relationship, we classified recalled items as having being fixated during the encoding phase, during encoding and the retention phase, during the retention phase only, or not fixated at all. Figure 5 presents the proportion of recalled items falling into one of these fixation categories separately for correctly (targets) and wrongly (distractors) recalled locations, the length of the retention interval (RI of 1.5 or 4.5 s), and grid presence (blank vs. grid). Figure 5 shows that most of the recalled items (irrespective of them being targets or distractors) were not fixated during the trial. There were more distractor recalls in the blank than in the grid condition, but this increase was not related to recall of distractor locations fixated during the encoding and/or retention phases. Not-fixated targets were recalled at the same rate in the blank and grid conditions, and this proportion decreased with the length of the retention interval. The larger number of correct recalls in the grid than the blank condition was due to additional recall of targets fixated during the retention phase (i.e., Enc + RI and RI categories, see Figure 5). In sum, these data suggest that the advantage yielded by the grid presence is attributable to the possibility to gaze at target locations during the retention phase, with these rehearsed positions being then recalled at test.

Discussion

Using a task in which the spatial locations were encoded simultaneously, Experiment 1 replicated the basic findings of Lilienthal et al. (2014, 2016): recall is higher in the presence of the grid, and the rate of forgetting over time is reduced in the grid compared to the blank condition. Eye-movement recordings allowed us to track the frequency and location of fixations across experimental conditions during both the encoding and retention phases. Our aim was to examine the viability of the propositions that (a) eye movements may more often land at distractor locations during the retention interval in the blank condition, leading to interference; and (b) the grid would more efficiently guide gaze toward target locations, allowing people to more efficiently rehearse these locations during the retention interval.

Our data indicate that both conjectures are viable. As the duration of the retention interval increases, participants have more opportunities to move their eyes around during the retention phase. Accordingly, the sheer number of intervening fixations increase, and so the putative interference yielded by these fixations. Al-

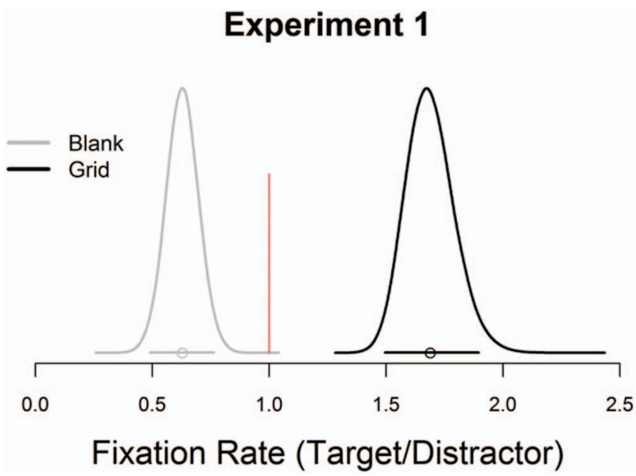

Figure 4. Posterior of the ratio of target to distractor fixations in the two grid conditions of Experiment 1. The posteriors were drawn from the best model of the data. The vertical (red) line indicates the value if fixations toward targets and distractor locations occurred at the same proportion. The bar underneath the curve shows the 95% HDI of the posterior, and the dot on the bar indicates the mean of the posterior. See the online article for the color version of this figure.

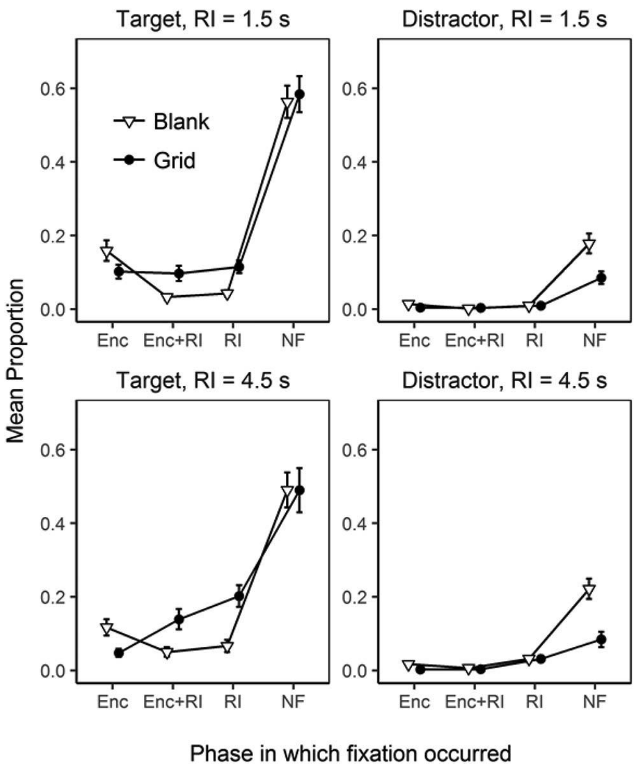

Figure 5. Classification of recalled items in Experiment 1 in relation to fixations directed at them during the encoding phase only (Enc), encoding and retention phases (Enc + RI), retention phase only (RI), or not fixated at all (NF). Error bars depict 95% within-subjects confidence intervals.

though the absolute number of distractor fixations during the retention phase was not larger in the blank than the grid condition, distractor fixations outnumbered target fixations in the blank condition (see Figure 4). This may blur the separation between the representations of target and distractor locations in WM. Previous research has shown that intervening fixations introduces interference of retinotopic locations (Golomb & Kanwisher, 2012; Golomb, L'Heureux, & Kanwisher, 2014; Henriques, Klier, Smith, Lowy, & Crawford, 1998). Hence the relative increase in distractor to target fixations may point to an increase in interference during the retention interval in the blank condition. The analysis of recall as a function of fixation status (see Figure 5), however, indicates that if this interference exists it is unspecific: the distractor locations recalled at the end of the trial were not the ones being fixated during the encoding or retention phases.

The presence of the grid during the retention interval changed the pattern of fixations. The total number of fixations increased and, critically, more fixations landed near target locations. The presence of the grid therefore does seem to guide gaze more efficiently toward target locations, in line with the proposition that the grid facilitates rehearsal. Figure 5 lends further support for this relationship: the higher rate of target recalls in the grid condition compared to the blank condition was related to an increase in recall of locations that were fixated during the retention phase. Experiment 1, however, did not include a manipulation of eye-movements, and hence we cannot draw any causal relations between eye-movements and memory performance. This was the goal of Experiment 2.

Experiment 2

Eye-tracking in Experiment 1 showed different patterns of fixations in the blank versus grid conditions. On the one hand, the blank retention interval led participants to fixate relatively more often at (empty) distractor locations than target locations. On the other hand, when the grid was onscreen, the number of fixations increased compared to the blank condition, particularly due to an increase in fixations toward target locations during the retention phase. Given that fixated distractor locations were not more likely to be recalled, these data are compatible with the hypothesis that forgetting may be induced by some unspecific interference caused by eye movements, and that forgetting is prevented by gaze-based rehearsal of target locations.

To assess for these possibilities, Experiment 2 implemented two eye-movement conditions. The *free viewing* condition was the same as in Experiment 1: participants were allowed to freely move their eyes during the retention interval. In the *fixate center* condition, participants were instructed to fixate the center of the screen during the whole retention interval. The fixate-center condition prevents participants from (a) performing potentially disruptive eye movements during the retention interval and (b) using eye movements to rehearse the target locations. If the forgetting over time observed in the blank condition is partially explained by the proportional increase of fixations at distractor compared to target locations, then fixating the screen center should reduce the rate of time-based forgetting observed in the blank condition. Furthermore, if the grid benefit is due to the increase in the frequency of fixations at target locations, then forcing people to fixate the center will prevent gaze-based rehearsal of the target locations, leading to the observation of increased forgetting over time in the grid condition.

Method

Thirty-two students (M = 24 years old, SD = 3.44) took part in two sessions lasting 1-hr at the Max Planck Institute for Empirical Aesthetics, Frankfurt, in exchange of 30 Euros. The equipment and experimental task were identical to the one described in Experiment 1 with three exceptions. First, a fixation cross was displayed in the middle of the screen throughout the retention phase. Second, we implemented a manipulation of eye-movement behavior during the retention interval. In one session, participants were instructed to keep their gaze at the fixation cross for the whole duration of the retention interval (fixate-center condition). In the other session, participants were instructed that they could freely move their eyes (free-viewing condition) during the retention interval and they should try to ignore the presence of the fixation cross. Noteworthy, during encoding participants were free to move their eyes as they wished in both conditions. To more easily distinguish between eye-movement behavior conditions, the fixation cross was associated with different colors (yellow, RGB 180 180 0; or green, RBG 0 180 0) in each viewing condition, and the association between color and condition (and the order of the two conditions over sessions) was counterbalanced between participants. Third, order of grid conditions (grid or blank) and retention intervals (1.5 s or 4.5 s) was fully counterbalanced across participants within each session.

As in Experiment 1, participants completed 120 trials per session, which were distributed across four blocks. Each block comprised either the grid or blank condition, and the duration of the retention interval was changed midway through the block. Before each experimental block, participants were fully instructed about the presence or not of the grid during the retention interval and of the fixation condition that would be in effect (fixate center or free viewing).

We applied the same analysis to the eye recordings as in Experiment 1. There were 124,872 fixations recorded during the experiment, but only about 1/3 of these fixations (40,974) occurred during the encoding and retention intervals and were further retained for analysis. We again classified fixations in terms of their landing position based on the closest location (max. 150 pixels away). Overall, 49.9% of the analyzed fixations were directed at target locations, 33% at distractors, 15.2% at the screen center, and 1.9% were unclassified (falling more than 150 pixels away from any relevant location).[4]

Results

Eye movements. The critical manipulation in Experiment 2 was regarding eye-movement constraints during the retention phase (hereafter the eye predictor): the free condition was similar to Experiment 1, whereas in the fixate condition participants were told to fixate the screen center during the retention phase. Figure 6A shows the fixation rate during the encoding phase in Experiment 2. There were more fixations in the blank than the grid condition, and there were also more fixations in the free condition than the fixate condition, indicating that the instruction to fixate the center during the retention phase already had some impact at eye-movements at encoding. Accordingly, the best model of this data included the effects of grid + eye ($BF_{10} = 6.18 \times 10^{12}$). Figure 6C shows fixation rate during the retention phase. In the free condition, there were a larger number of fixations in the grid than blank conditions. In the fixate condition, the number of fixations was reduced to similar levels in the blank and grid conditions. The best model of this data included the effects of grid, retention, eye, and a Grid × Eye interaction ($BF_{10} = 3.47 \times 10^{44}$). The interaction reflects the fact that the larger number of fixations observed in the grid than blank condition under the free viewing instruction was reduced under the fixate center instruction.

Figure 6B and 6D shows the classification of fixations in terms of their landing position in the encoding and retention phases, respectively. The data of the free condition mainly replicate the results of Experiment 1: At the encoding and retention phases, fixations were more often directed at target locations, followed by distractors, and less often to the screen center. The only exception to this pattern was during the retention phase in the blank condition in which distractor fixations were again slightly more frequent than target fixations. The instruction to fixate the screen center during the retention interval had an impact on eye-movements during encoding: participants fixated targets and distractors less often, whereas fixations toward the screen center increased. In line with the visual inspection of Figure 6B, the best model of the fixations during encoding included the main effects of fixation category (center, distractor, or target), grid, eye, and an Eye × Fixation Category interaction ($BF_{10} = 1.98 \times 10^{157}$).

As expected, the instruction to fixate the screen center during the retention phase reduced the number of fixations to distractors

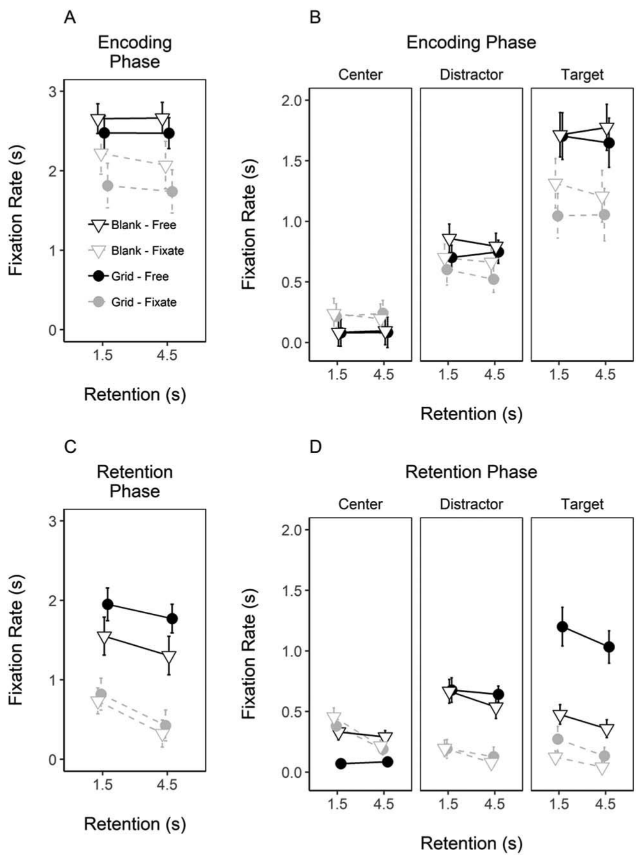

Figure 6. Results of Experiment 2. (A) Fixation rate (fixations/s) in the encoding phase. (B) Classification of fixations in the encoding phase. (C) Fixation rate (fixation/s) in the retention phase. (D) Fixation classification in the retention phase. Error bars depict 95% within-subjects confidence intervals.

and target locations during the retention interval (Figure 6D). There was, however, a slightly higher rate of target fixations in the grid than blank condition even in the fixate-center condition (Figure 6D, right subplot). In line with these effects, the best model of this data included the effects of fixation category, grid, retention, eye, and the interactions of Fixation Category × Grid, Fixation Category × Eye, Grid × Eye, and Fixation Category × Grid × Eye ($BF_{10} = 2.86 \times 10^{148}$).

Memory accuracy. Figure 7A shows recall accuracy across conditions. As in Experiment 1, memory was better in the grid than the blank condition, and increasing the length of the retention interval led to more forgetting in the blank than the grid condition. Performance was worse when participants had to fixate the center of the screen, and this effect was larger in the grid than the blank condition. The best model of the data included the effects of grid + retention + grid × retention + eye + eye × grid ($BF_{10} = 6.92 \times 10^{62}$). Although unexpected, there was strong support for the

[4] Changing the threshold to 100 or 50 pixels led to the exclusion of 3.98% and 40.26% of the fixations. As in Experiment 1, these additional fixations fell within the area of grid locations, and hence in order to retain as many fixations as possible, we used the more lenient threshold.

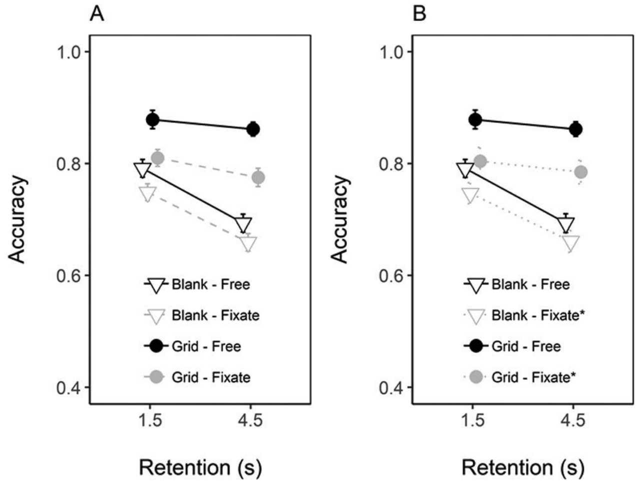

Figure 7. (A) Recall in Experiment 2. (B) Recall in Experiment 2 considering only trials in the fixate condition in which fixation was maintained at the screen center for the whole duration of the retention phase. Error bars depict 95% within-subjects confidence intervals.

Grid × Eye interaction (BF_{10} = 72.57). This result indicates that requiring participants to fixate the screen center was somewhat more impairing when the grid was visible onscreen. The rate of forgetting over time was, however, relatively unaffected by this manipulation: There was some evidence against including an Eye × Retention interaction in the best model (BF_{10} = 4.8), and against including the three-way interaction (BF_{10} = 2.13). Furthermore, both eye-movement conditions showed the same pattern of grid, retention, Grid × Retention effects, with this being the best model in each eye movement condition when analyzed in isolation.

Figure 7B shows the data of the fixate condition when we removed any trials (ca. 1/3 of all trials) in which participants failed to fixate the screen center for the whole duration of the retention interval (i.e., a filtered data-set). Again, the results show a clear pattern of forgetting over time in the blank condition, and reduced rate of forgetting in the grid condition regardless of eye-movement instruction (best model: grid + retention + eye + grid × eye, $BF_{10} = 1.46 \times 10^{39}$).

Figure 8 shows the posterior of the effect of retention interval on memory accuracy for the blank and grid conditions under the free-viewing and fixate-center conditions when we consider the full data-set (panels A) and the filtered data (panels B). It is clear from this figure that there is substantial forgetting over time in the blank condition, and the rate of forgetting is not affected by the eye-movement condition. For the grid condition, the rate of forgetting is close to zero, with this value being well within the likely parameters of the posterior (i.e., the range of 95% credible values of the effect, aka the HDI). The lack of an effect of the eye-movement instruction on rate of forgetting is even clearer in the filtered data, in which we are sure participants did not move their eyes away from the screen center.

Recall versus fixations. Lastly, we looked at the relation between recall and eye-movements (see Figure 9). Replicating Experiment 1, the largest proportion of the recalled items was not fixated at all during the trial in all conditions. Under the free-

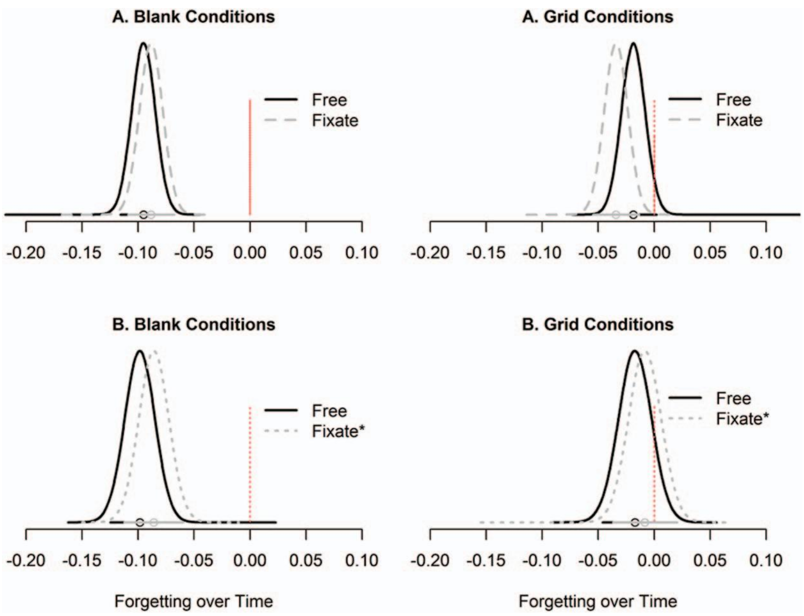

Figure 8. Posterior of the effect of the length of retention interval on memory accuracy (aka forgetting over time) for the blank conditions (left panels) and grid conditions (right panels) estimated from the full model including the effects of all predictors (i.e., grid, retention, and eye) and their interactions. (A) Full data set in Experiment 2. (B) Filtered data-set in Experiment 2. The vertical (red) line indicates the value expected under the null hypothesis of no forgetting over time. The bar underneath the curve shows the HDI, and the dot indicates the mean of the posterior. See the online article for the color version of this figure.

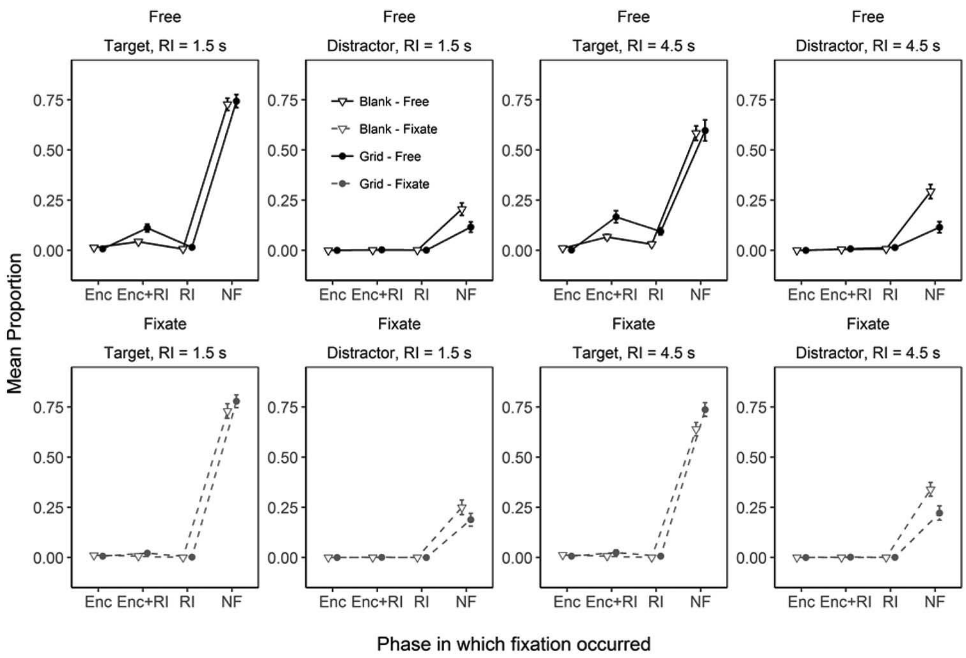

Figure 9. Classification of recalled items in relation to fixations directed at them during the encoding phase only (Enc), encoding and retention phases (Enc + RI), retention phase only (RI), or not fixated at all (NF) in Experiment 2. Error bars depict 95% within-subjects confidence intervals.

viewing instruction, the additional correct recalls observed in the grid condition were again associated with recall of targets that were fixated during the retention phase (Enc + RI and RI categories) similarly to Experiment 1. Under the fixate-center instruction, however, preventing participants from rehearsing the locations via eye-movements removed the benefit associated with the recall of targets rehearsed during the retention phase. Importantly, preventing eye-movements did not completely eliminate the grid benefit and now the grid and blank conditions started to differ on the number of targets recalled that were not fixated at all. In sum, these results suggest that part of the grid benefit is associated with rehearsal of the items during the retention phase, but this does not fully explain the grid benefit nor the protection the grid offers from time-based forgetting.

Discussion

Asking participants to fixate the screen center was associated with a memory cost compared with the free-viewing condition, and this cost was larger in the presence of the grid. Nevertheless, this manipulation did not change the pattern of forgetting over time observed in these conditions. Together with the results of Experiment 1, this finding indicates that irrelevant eye-movements performed during the retention interval cannot explain the rate of forgetting over time observed in the blank condition, lending no support for the eye-movement interference hypothesis.

Furthermore, fixating the center yielded a cost to the grid condition, but it did not induce more time-based forgetting. Our analysis of the relation between recall and eye-movements (see Figure 9) suggests that the overall cost is related to the lack of gaze-based rehearsal of targets during the retention interval. Nevertheless, the grid benefit remained even under this condition and Figure 9 reveals that this was due to better recall of targets that were not fixated at all but maintained without fixating. Hence, the protection from time-based forgetting afforded by grid presence is not fully attributable to the use of gaze-based rehearsal strategies.

One may wonder whether the general costs associated with the fixate-center condition are due to the inhibition of saccades at encoding. To assess for this possibility, we correlated the total number of fixations at encoding and the accuracy score across eye-movement conditions on a trial-by-trial basis: The correlation was close to zero (r = .033, BF_{10} = 0.14). We also assessed whether target fixations at encoding would be a better predictor of recall accuracy, but again the correlation was close to zero and the null hypothesis was favored (r = .069, BF_{10} = 0.15). Hence, there is no evidence that the differences in fixation patterns at encoding were predictive of recall from visuospatial WM, and that they could explain the costs we observed. This is line with recent evidence provided by Czoschke et al. (2019) that high or low rates of fixations at encoding in a visuospatial WM task are not related to recall. Instead, our results point to a stronger role of fixations at the maintenance phase as being more functional for recall from visuospatial WM.

In sum, Experiment 2 indicates that eye-movements are unlikely to be the cause of the time-based forgetting observed in the blank condition, and that gaze-based rehearsal explains part of the grid-benefit. Nevertheless, a substantial part of the grid benefit still remained in the absence of gaze-based rehearsal (i.e., under the fixate instruction), and the grid still protected WM against time-based forgetting.

Experiment 3

In Experiment 2 participants were required to fixate the screen center, and we monitored compliance with the eye tracker. Visuospatial attention, however, can be directed to memory locations covertly in the absence of overt eye-movements (Posner, 1980). Rehearsal in spatial WM has been assumed to be carried out by overt (gaze-based) or covert shifts of visuospatial attention to the locations previously occupied by the memoranda (Awh & Jonides, 2001; Awh et al., 1998; Baddeley, 1986; Godijn & Theeuwes, 2012; Guérard et al., 2009; Theeuwes et al., 2009).

The goal of Experiment 3 was, therefore, to assess the impact of covert shifts of visuospatial attention as a spatial maintenance mechanism. To do so, we applied a dual-task condition, requiring participants to keep their visuospatial attention on the screen center. In the dual-task conditions of Experiment 3, participants had to monitor the fixation cross for a low-salient change in brightness occurring during the retention interval (Souza & Oberauer, 2017; Tal & Yuval-Greenberg, 2018; Williams, Pouget, Boucher, & Woodman, 2013). This task binds visuospatial attention to the fixation cross, leading to a lower processing rate of other visual objects (Poth, Petersen, Bundesen, & Schneider, 2014). This task has also been found to inhibit the occurrence of saccades toward the sudden-onset of a parafoveal stimulus, leading to costs to its processing (Tal & Yuval-Greenberg, 2018). Furthermore, combining this task with a multiple-object tracking task which requires rapid shifts of visuospatial attention across different locations on the screen to track the whereabouts of moving targets leads to costs for the processing of both tasks (Souza & Oberauer, 2017). Accordingly, we reasoned that imposing this secondary task would allow us to assess whether reducing the likelihood or efficiency of shifts of visuospatial attention would affect the rate of forgetting in the blank versus grid condition.

Method

Participants. Twenty-four students (M = 23 years old; SD = 3.93) from the University of Zurich took part in one experimental session lasting 1-hr in exchange for 15 CHF or partial course credit. One participant did not respond to the secondary visual task, and was therefore excluded from the final analysis. The study protocol was in accordance with the guidelines of the Institutional Review Board of the Psychology Department of the University of Zurich.

Procedure. Participants completed the same spatial WM task as described in Experiments 1 and 2 in which both the duration of the retention interval (1.5 s or 4.5 s) and grid presence (grid vs. blank condition) were manipulated across blocks of trials. Experiment 3 implemented six changes in the task set-up. First, eye-movements were not recorded. Second, a white fixation cross was continuously visible in the center of the screen during the encoding and retention phases of all conditions. Third, the empty grid was presented 500 ms before the target locations were highlighted onscreen. Fourth, in half of the experimental blocks, participants had to complete a visuospatial distractor task (which is described below) during the retention interval of the spatial WM task, hereafter referred to as the dual-tasking conditions. Fifth, the intertrial interval was set to be of the same length as the duration of the retention interval (i.e., if the retention interval = 1.5 s, the intertrial interval was also 1.5 s). Sixth, participants completed a total of 160 trials which were divided into four blocks. Each block consisted of a combination of grid (grid or blank) and task (single-task or dual-task) condition, whose order was counterbalanced using a full permutation of the four combinations. Half-way through the block, the duration of the retention interval was changed from short to long, or from long to short (order counterbalanced across participants). Hence, in total there were 20 trials with each combination of retention, grid, and dual-task condition.

Visuospatial distractor task. The visuospatial distractor task comprised the monitoring of the fixation cross for a potential change in brightness (from white to light gray; RGB 166 166 166) for a very brief interval (100 ms). The change only occurred in 25% of the trials. If a change was schedule to occur in a given trial, the timing of the change varied randomly with the constraints that it could not occur immediately after array offset (min. separation was 100 ms) and it had to occur at least 700 ms before the onset of the test to allow sufficient time for responding. Participants had to press the spacebar in case a brightness change was detected, but do nothing otherwise (i.e., simple reaction time (RT) task). The task only required a simple reaction (pressing of the spacebar in case of a change), hence not requiring response selection (Pashler, 1994) which reduces demands on other forms of attention than visuospatial attention (Frith & Done, 1986).

Arguably, this task inhibits shifts of gaze and visuospatial attention away from the screen center, while at the same time not introducing any sort of stimulus-based interference (the fixation cross was visible in all conditions). To further rule out any contributions of response execution, we only analyzed trials in which no-change occurred (i.e., the remaining 75% of the trials) and in which participants made no false alarms (no keypress).

Results

Visuospatial distractor task. Detection performance (computed as hits − false alarms) in the brightness change task was comparable across the two retention intervals (1.5-s retention, M = 83.1%, SD = 18%; 4.5-s retention, M = 86.5%, SD = 11.9%; BF_{10} = 0.31).

Memory accuracy. We removed from analysis all trials in which participants pressed the spacebar (to detect a brightness change), and all trials in which a brightness change occurred (13% of the available trials). Figure 10 shows recall accuracy as a function of experimental condition. The single task conditions showed better memory in the grid than the blank condition, coupled with more forgetting over time in the latter (replicating Experiments 1 and 2). The same pattern of results was observed in the dual-task conditions, with the only difference being that overall levels of performance were lower. Accordingly, the best model of the data included the main effects of grid, retention, and dual-tasking, and a Grid × Retention interaction ($BF_{10} = 1.56 \times 10^{34}$). There was some evidence against including the interactions between Dual-Tasking × Grid (BF_{10} = 0.46), Dual-Tasking × Retention (BF_{10} = 0.27), and the three-way interaction (BF_{10} = 0.34).

We also fitted the full model including all predictors and their interactions to the data, and sampled from the posterior distribution of the effects to compare the rate of forgetting across conditions. The posterior of the forgetting rate is plotted in Figure 11: forgetting was substantially larger than zero in the blank conditions with

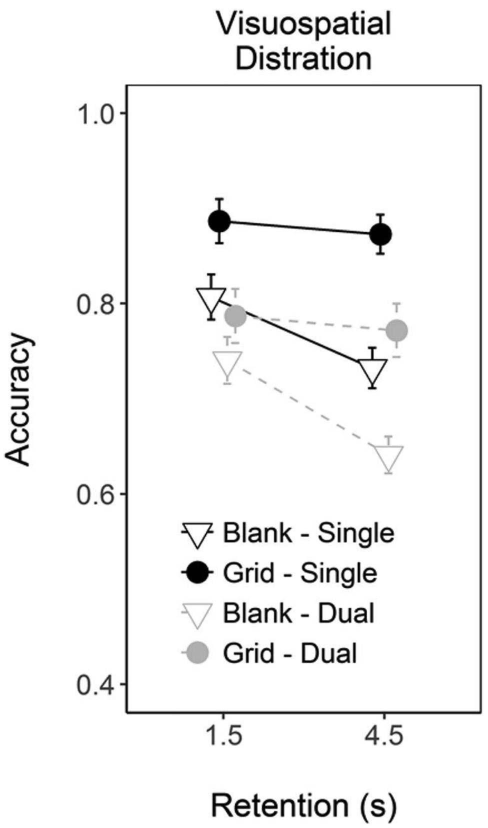

Figure 10. Accuracy in the experimental conditions implemented in Experiment 3. Error bars depict 95% within-subjects confidence intervals.

or without the visuospatial distractor tasks (i.e., single or dual-task). The 95% HDI of the distribution did not include 0, and the distributions of the single-task versus dual-task conditions substantially overlap. For the grid conditions, forgetting was not credibly different from 0 (zero is within the HDI), and the forgetting rate in the conditions with and without visuospatial distraction overlapped.

Discussion

Similarly to Experiment 2, imposing a dual-task binding visuospatial attention to the screen center impaired performance overall, but it did not change the pattern of forgetting over time observed in the blank and grid conditions. These results suggest that reducing the probability or efficiency of shifts of visuospatial attention had no impact on the relation between retention interval and grid presence. These results are in line with the hypothesis that the increased rate of forgetting in the blank compared to the grid condition is unlikely attributable to participants covertly shifting visuospatial attention to distractor locations on the screen (interference), and the grid protection from forgetting is also unlikely due to participants covertly shifting visuospatial attention to the to-be-maintained spatial locations (attention- but not gazed-based rehearsal).

There are two caveats though. The first one is that Experiment 3 did not include eye-tracking, and hence we could not assert that the visuospatial distraction task indeed inhibited shifts of gaze back to the locations of the memoranda. We reasoned that this was very likely because: (a) results of Experiment 3 were similar to the ones obtained for the central-fixation condition of Experiment 2 in which eye-tracking was conducted, and (b) Tal and Yuval-Greenberg (2018) demonstrated that a similar task inhibited saccades to a sudden onset target and also reduced the accuracy of reporting the target's feature. The second caveat is that our implementation of the visuospatial distractor task was low demanding: changes in brightness occurred relatively infrequently and only once during the retention interval. It is possible that with this low demand, participants were still shifting their visuospatial attention to target locations allowing them to prevent representations from undergoing time-base forgetting, particularly in the grid condition. Given that Experiment 3 did not include eye-tracking, we decided to run an additional experiment using the visuospatial distractor task (now with more demanding response requirements) and with eye-tracking.

Experiment 4

The results of Experiment 3 suggest that shifts of visuospatial attention are not the cause of the shallow rate of forgetting observed in the grid condition. Experiment 4 was designed to replicate this finding and at the same time extend it regarding three aspects. First, we included eye-tracking to assess the degree in which the brightness task requires participants to keep their gaze at the center of the screen. Second, we included single task blocks assessing not only spatial WM performance but brightness detection as well. This allowed us to assess any sort of trade-offs between allocation of visuospatial attention to the main memory task or to the distractor task. Third, we varied the number of brightness changes from 0–4 in an unpredictable fashion. In a previous study (Souza & Oberauer, 2017), we observed that increasing the number of changes makes this task harder, as reflected in a decrease in the accuracy of brightness-change detection. Accordingly, this should increase the demand to engage visuospatial attention to the screen center.

Method

Participants. Twenty-four students (M = 24 years old; SD = 3.84) from the University of Zurich took part in two sessions, each lasting 1.5-hr in exchange of 45 CHF or partial course credit. Two participants did not respond to the secondary visual task in a substantial proportion of the trials, and were therefore excluded from the final analysis. Eye-tracking data of one additional participant were lost, and hence this participant was excluded from eye-tracking analyses. The study protocol was in accordance with the guidelines of the Institutional Review Board of the Psychology Department of the University of Zurich.

Apparatus. Data collection took place in a room equipped with a 22-in. Monitor (resolution 1600 × 900, refresh rate 60 Hz), and an eye tracker (SMI Red500) in a dual computer setting. The participant and the experimenter were seated in the same room, side-by-side, separated by a divider. The experimenter monitored the data collection and eye tracking online. We tracked both eyes with a sampling rate of 500 Hz. Nevertheless, for comparison with the previous experiments, we only analyzed data of the right eye.

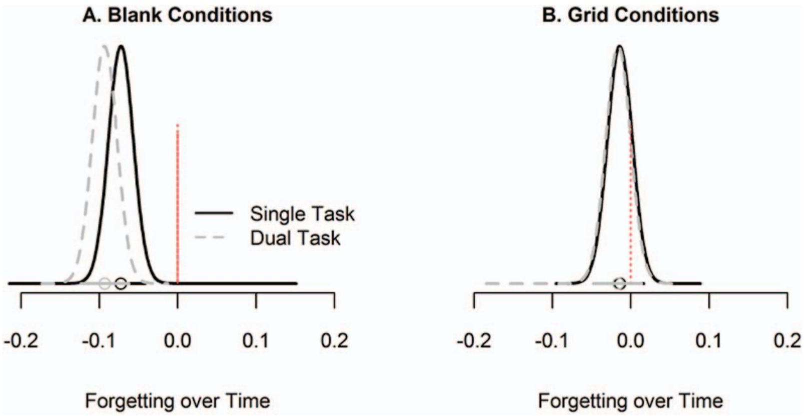

Figure 11. Posterior of the difference in memory accuracy across retention intervals in the blank (A) and grid conditions (B) with and without the visuospatial distractor task in Experiment 3. Posterior was sampled from the full model. The vertical (red) line indicates the null hypothesis of no forgetting over time. The bar underneath the distribution indicates the 95% HDI, and the dot indicates the mean of the posterior. See the online article for the color version of this figure.

A chin- and head-rest supported the head of the participants and was located 70 cm away from the monitor. Participants underwent a 9-point calibration of the eye-tracker in the beginning of the experiment. The calibration procedure was repeated at least every 10 trials. As before, participants were instructed to reduce blinking during calibration and trials.

Procedure. At the beginning of each trial, participants were asked to fixate a black dot for a 1-point fixation check. We used a small black dot to avoid confusions with the white fixation cross used in the visuospatial distractor task. The one-point calibration procedure required that participants fixate the screen center within a 3-s time window. If this fixation-check failed, a 9-point calibration procedure was reinstated immediately. If the fixation-check was successful, the trial started.

Participants completed two sessions with the spatial WM task and the visuospatial distractor task of Experiment 3. The presence of the grid during the retention interval was manipulated between-sessions, and the order of the sessions was fully counterbalanced across participants. Within each session, participants completed three task conditions: (a) a single-task condition with only the visuospatial distractor task (Visual condition; see Figure 12A); (b) a single-task condition with only the spatial WM task (Memory condition; Figure 12B); and (c) a dual-task condition in which participants completed both the spatial WM and the visuospatial distractor task (Dual condition; Figure 12C). The order of these conditions was fully counterbalanced across participants.

All trials started with a 1-point fixation-check, followed by presentation of the memory array (as in previous experiments).

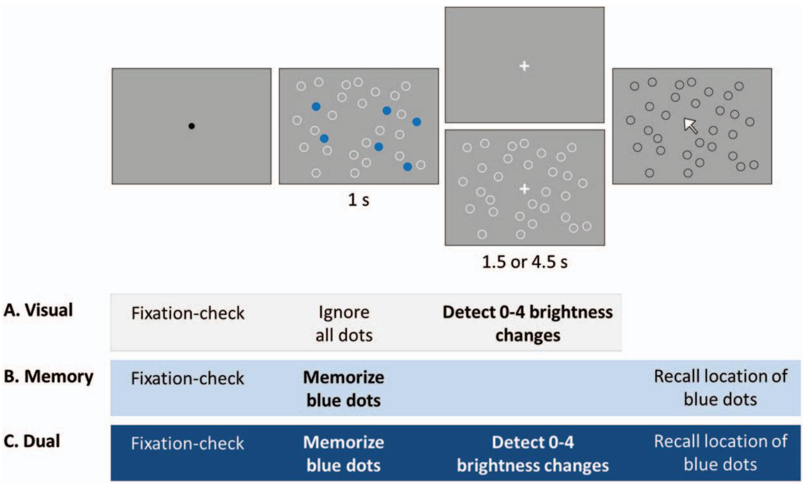

Figure 12. Flow of events in the three task conditions of Experiment 4. Panel A presents the single-task condition with the visuospatial distraction task. Panel B presents the single-task condition with the spatial WM task. Panel C illustrates the dual-task condition combining the memory task and the visuospatial distraction task. The blue dots appear as dark grey dots in black and white printing. See the online article for the color version of this figure.

The offset of the memory array coincided with the onset of the white fixation cross in the middle of the screen. The fixation cross remained onscreen for 1.5 s or 4.5 s (retention phase). These events were common to all conditions. Only if the task involved memorizing the location of the blue dots, the end of the 1.5- or 4.5-s interval was followed by a recall test (as in the previous experiments).

In the Visual condition, participants were instructed that their sole task was to detect an unpredictable number of brightness changes (0–4) of the fixation cross. The fixation cross could be alone onscreen (blank conditions) or the grid could be visible concurrently (grid conditions). Participants were instructed that any dots appearing onscreen were irrelevant to the task and should be ignored. This task remained in effect for 1.5 s or 4.5 s. When the interval was 1.5 s, we scheduled the occurrence of 0–2 brightness changes. When the interval was 4.5 s, we scheduled the occurrence of 0–4 brightness changes. Change times were selected such that (a) the first change had to occur at least 400 ms after memory array offset, (b) two sequential changes in brightness had a minimum of 400 ms separation to allow time for responding, and (c) the last change occurred at least 400 ms before the end of the retention interval. Participants were instructed to press any mouse-button whenever they detected a change in brightness (simple RT task). The number of changes was evenly and unpredictably spread across the number of trials in each condition.

In the Memory condition, participants were instructed that their sole task was to memorize the positions of the blue dots within the grid. The fixation cross was visible throughout the retention interval, but no brightness changes occurred, and participants received no instructions regarding it.

In the Dual condition, participants were instructed to complete both tasks: they were told to memorize the locations of the blue dots, and to detect the brightness changes (0–4) of the fixation cross during the retention phase.

Participants completed 30 trials of the single-task conditions (Visual or Memory) and 60 trials of the dual-task condition in each session. Half of the trials comprised short and the other half long retention intervals presented in a block fashion whose order was counterbalanced across participants, as in the previous experiments. Before the start of the experiment, participants completed six practice trials with the visuospatial distractor task alone, and six trials with the spatial WM task alone, which were excluded from the final analysis. Participants received feedback regarding their performance of the visuospatial distractor task in the practice block. Participants received feedback regarding which dots were recalled correctly in all trials (as in the previous experiments). Participants were allowed a short break every 10 trials, and they were instructed to try to relax their eyes during these breaks.

We analyzed eye recordings using the BeGaze software to classify eye movements into fixations, saccades, and blinks. There were 185,367 fixations recorded during the experiment, and 33.1% of these fixations (61,371) occurred during the encoding and retention intervals for the final sample ($n = 21$) and were further retained for analysis. We again classified fixations in terms of their landing position based on the closest location (i.e., falling no more than 150 pixels away from a relevant location). Overall, 24.5% of the analyzed fixations were directed at target locations, 39.7% at distractors, 35.6% at the screen center, and 0.19% were unclassified.

Results

Eye movements. Figures 13A and 13B present the fixation rates to the screen-center, distractor, and target locations recorded during the encoding and retention phases, respectively. Note that there was no encoding or retention phase in the Visual condition, but the displays were the same as in the memory tasks and therefore comparable in terms of visual stimulation, and hence we will use the same terminology for all three conditions. During the encoding phase (Figure 13A), fixations were more frequent at the screen-center when the only task to perform was the visuospatial distractor task (Visual condition), followed by distractor locations, and lastly target locations. For conditions requiring encoding of the blue dots (Memory and Dual), fixations were more frequently directed to target locations, followed by distractor locations, with the screen center being the least favorite category.

During the retention phase (Figure 13B), fixations patterns in the Dual condition became more similar to the ones observed in the Visual condition than the Memory condition. For example, center fixations were higher in both the Visual and Dual conditions compared with the Memory condition. Fixations at distractor and target locations were lowest in the Visual condition, but fixations directed at target locations were reduced in the Dual compared with the Memory condition indicating that the brightness task reduced the likelihood that participants would rehearse target locations during the retention phase. Critically, imposing the dual-tasking also reduced the disparity in fixation patterns between the grid and blank conditions observed when participants were free to move their eyes as they wish (e.g., Memory condition).

Visuospatial distractor task. Figure 14A presents accuracy in the visuospatial distractor task as a function of the number of changes (0–4), dual-tasking (Visual vs. Dual), grid presence, and retention interval. Detection decreased as the number of brightness changes increased, particularly in the short retention interval. This is probably because participants had less time, in average, to respond in the short retention interval as the number of changes increased (ca. 550 ms per change when two changes were scheduled) compared with the long retention interval (ca. 1 s per change when four changes were scheduled). Overall, detection was somewhat worse in the dual-task condition (Dual: $M = 0.88$, $SD = 0.29$) than the single-task condition (Visual: $M = 0.95$, $SD = 0.19$), and worse when the retention interval was short ($M = 0.90$, $SD = 0.29$) compared to long ($M = 0.94$, $SD = 0.19$). Performance was, however, similar in the grid ($M = 0.92$, $SD = 0.25$) and blank ($M = 0.92$, $SD = 0.24$) conditions. Accordingly, the best model of this data included the main effects of dual-tasking, retention, and number of changes, and an interaction between number of changes and retention interval ($BF_{10} = 4.65 \times 10^{70}$).

Memory accuracy. To make sure that the visuospatial task was taxing participants visuospatial attention, we only analyzed memory performance in dual-tasking trials in which all brightness changes were correctly detected.[5] Figure 14B presents memory performance as a function of retention interval, grid presence, and dual-tasking (Memory vs. Dual). In the single-task conditions, the

[5] The results were similar to that obtained when all trials were included in the analysis.

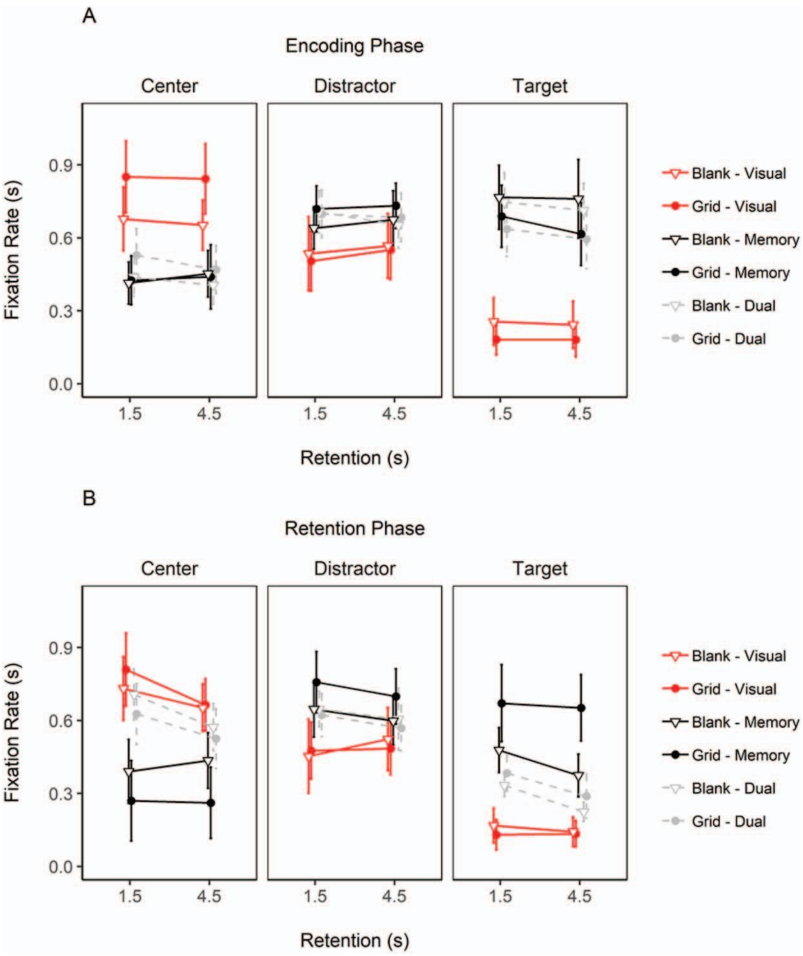

Figure 13. Eye-tracking results of Experiment 4. Panel A shows fixation rate (fixations/s) at the center, distractor, and target locations in the encoding phase, and Panel B shows fixation rate (fixations/s) at these locations during the retention phase. Error bars depict 95% within-subjects confidence intervals. See the online article for the color version of this figure.

results were similar to the ones obtained in the previous experiments: (a) worse performance in the blank than the grid and (b) more forgetting over time in the blank than the grid. In the dual-task conditions, performance was overall poorer than in the single-task conditions. Furthermore, dual-tasking tended to increase the rate of forgetting irrespective of grid presence. The Bayesian ANOVA indicated that the best model of this data included the effects of grid presence, length of the retention interval, dual-tasking, and an interaction between rehearsal and retention ($BF_{10} = 2.45 \times 10^{35}$). The best model did not include an interaction between dual-tasking and retention interval, but the evidence against the inclusion of this term was ambiguous ($BF_{10} = 1.9$).

Visual inspection of the data, however, suggests an increase in the rate of forgetting under dual-tasking. To assess whether there was support for this, we plotted the posteriors of the forgetting over time in the single-task and dual-task conditions (see Figure 15). In the single task conditions, there was credible forgetting over time (i.e., the 95% HDI of the posterior did not include 0) in the blank (panel A) but not in the grid condition (panel B). In the dual-task conditions, there was credible forgetting in the blank (panel C) and grid conditions (panel D).

One may wonder whether the difference between the grid and blank conditions would be reduced if trials in which target locations were still fixated during the retention interval were excluded from the analysis. We created a filtered data-set in which dual-task trials with target fixations during the retention interval were excluded. Performance was similar to when all trials were included: better performance in the grid (RI 1.5 s, $M = 0.81$, $SD = 0.19$; RI 4.5 s, $M = 0.77$, $SD = 0.19$) than in the blank condition (RI 1.5 s, $M = 0.71$, $SD = 0.21$; RI 4.5 s, $M = 0.63$, $SD = 0.25$) and with the rate of forgetting being ca. 4% in the grid condition and 8% in the blank condition.

Recall versus fixations. Lastly, we looked at the relation between recall and fixation status. Figure 16 shows that in the Memory condition, the grid and blank conditions differ in the proportion of targets recalled that were fixated during the retention phase replicating the previous experiments. During the Dual condition, the grid and blank conditions differ mainly in the rate of targets recalled that were not fixated during the retention phase.

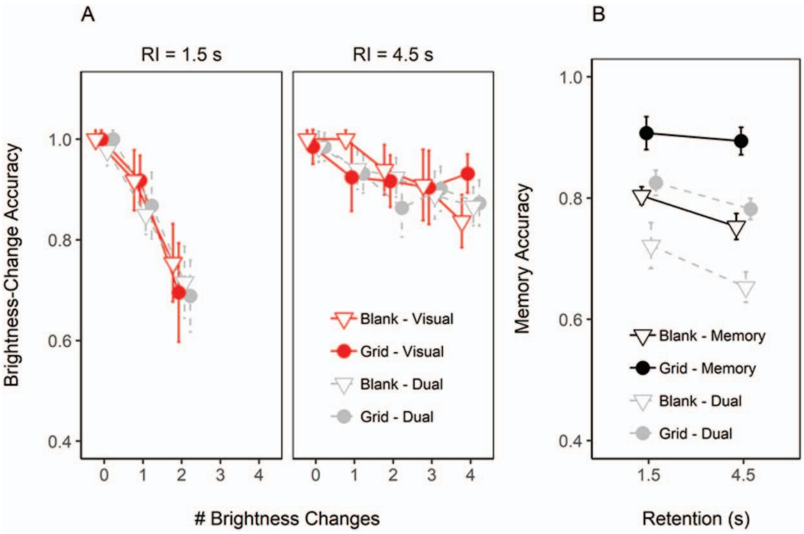

Figure 14. Panel A shows accuracy in the visuospatial distraction task as a function of the number of changes that occurred within the trial. Panel B shows accuracy in the memory task. Error bars depict 95% within-subjects confidence intervals. See the online article for the color version of this figure.

Discussion

Experiment 4 imposed a more demanding visuospatial distractor task. Dual-tasking inhibited gaze toward memorized locations during the retention phase, and an overall reduction in performance was observed. Critically, the grid benefit remained. These results were similar to the ones observed in Experiments 2 and 3. Surprisingly, the more demanding visuospatial distractor task tended to increase the rate of forgetting irrespective of grid presence.

Altogether, the results of Experiments 2, 3, and 4 indicate that the grid benefit is maintained (albeit sometimes a bit reduced) under conditions in which gaze-based rehearsal and visuospatial attention-based rehearsal are inhibited. The analysis of the relation between recalled locations and fixated locations suggest that some part of the grid benefit might occur because of retention-based rehearsal, but in conditions in which this is prevented there is still better recall of nonfixated targets in the grid condition. This indicates that the grid benefit cannot be fully explained by rehearsal processes.

One intriguing finding of Experiment 4 was the observation of a tendency for higher forgetting rates in the dual-task condition, with or without grid (see Figure 15). This is the first manipulation in our experimental series that affected the forgetting rates, whereas restricting the gaze (Experiment 2) or restricting visuospatial attention (Experiment 3) did not. One difference between Experiments 3 and 4 is that the response demands increased. We therefore decided to test whether a well-controlled increase of response demands affects the rate of forgetting: We included response selection in a dual-task in Experiment 5. Response selection is a process that taps central cognitive processing. Central processing is assumed to be transmodal and limited in capacity because two central processes cannot be carried out simultaneously (Frith & Done, 1986; Pashler, 1991, 1994; Tombu & Jolicœur, 2003). In contrast to central attention, visuospatial attention only limits the processing of stimuli in the visual field (Johnston, McCann, & Remington, 1995).

Previous research has shown that the requirement to process a visual stimulus delays the onset of stimulus-driven saccades to a second target, whereas processing of an auditory stimulus (tone classification) does not interfere with saccade execution (Carbone & Schneider, 2010). Hence, in contrast to increased demands on visuospatial attention, higher demands on response selection per se should not impair gaze-based rehearsal. Why would response selection induce more forgetting then? Rehearsal of visuospatial representation may depend not solely on the allocation of visuospatial attention but also on memory retrieval. Memory retrieval is known to require central processing, and competition for the use of this limited resource may increase forgetting. A large body of WM research has shown that WM recall is reduced when participants have to process a secondary task requiring response selection during the retention interval, even if the two tasks come from different modalities (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, De Paepe, & Langerock, 2012; Vergauwe, Barrouillet, & Camos, 2010). This finding has been interpreted as evidence that maintenance of information in WM also depends on central attention.

If central processing is involved in the rehearsal of spatial representation and their protection from forgetting, we should expect increases in the rate of forgetting in dual-task conditions requiring response selection. Experiment 5 tested this hypothesis.

Experiment 5

Experiment 5 aimed at assessing whether a dual-task condition demanding central attention would affect the rate of forgetting in the grid and blank conditions in line with the assumption that protection from forgetting in this task requires central attention.

Method

Participants. Thirty-six students (M = 24 years, SD = 3.12) from the University of Zurich took part in one experimental

Figure 15. Posterior of the difference in memory accuracy across retention intervals in the blank single-task condition (A), grid single-task condition (B), blank dual-task condition (C), and grid dual-task condition (D) in Experiment 4. Posteriors were sampled from the full model. The vertical (red) line indicates the null hypothesis of no forgetting over time. The bar underneath the distribution indicates the 95% HDI, and the dot indicates the mean of the posterior. See the online article for the color version of this figure.

session lasting 1-hr in exchange of 15 CHF or partial course credit. Three participants did not respond to the central attention dual-task with sufficient accuracy (either they ignored the task or responded randomly) and their data was excluded from final analysis (final $n = 33$).

Procedure. The general procedure was the same as described for Experiment 3, with two exceptions. First, the visuospatial distraction task was replaced by a central distraction task (described below). Second, the long retention interval was reduced to 4 s instead of 4.5 s, in order to better match the conditions regarding the time to process the central distraction task.

Central distraction task. The task was to classify tones (100 ms duration) regarding pitch (high or low, 1000 Hz vs. 300 Hz, resp.) by pressing the up or down arrow keys in the keyboard. The first tone was presented 250 ms after the offset of the memory array. When the retention interval was short (1.5 s), participants responded to one tone (response window 1250 ms). When the retention interval was long (4 s), a sequence of three tones were presented, each separated by 1,250 ms (hence the response window was still 1,250 ms per tone). The goal was to fill the retention interval with a series of processing operations such that participants would had reduced opportunities to refresh the memoranda, thereby allowing us to observe forgetting over time in case central attention contributes to performance in this task. The tone task, however, did not prevent participants from freely moving their eyes around. The tones were presented through a headset. Participants were informed in the beginning of the block regarding the requirement to put on the headsets in the following block.

Participants completed eight blocks of 20 trials each in the memory task (160 trials in total) and 8 practice trials. Blocks differed regarding the presence of the grid (blank vs. grid), retention interval (1.5 or 4 s), and dual-tasking (single-task or dual-task). The order of the conditions was counterbalanced across participants.

Results

Central distraction task. Accuracy in the tone-classification task was overall high ($M = 91.7\%$, $SD = 24.8\%$), and it did not substantially vary with grid presence or retention interval (blank 1.5 s = 91%; blank 4.0 s = 91.9%; grid 1.5 s = 89.5%; grid 4.0 s = 94.5%). There was no evidence for an effect of grid presence ($BF_{10} = 0.19$), and ambiguous evidence for an increase in accuracy in the long retention interval compared to the short one ($BF_{10} = 1.76$).

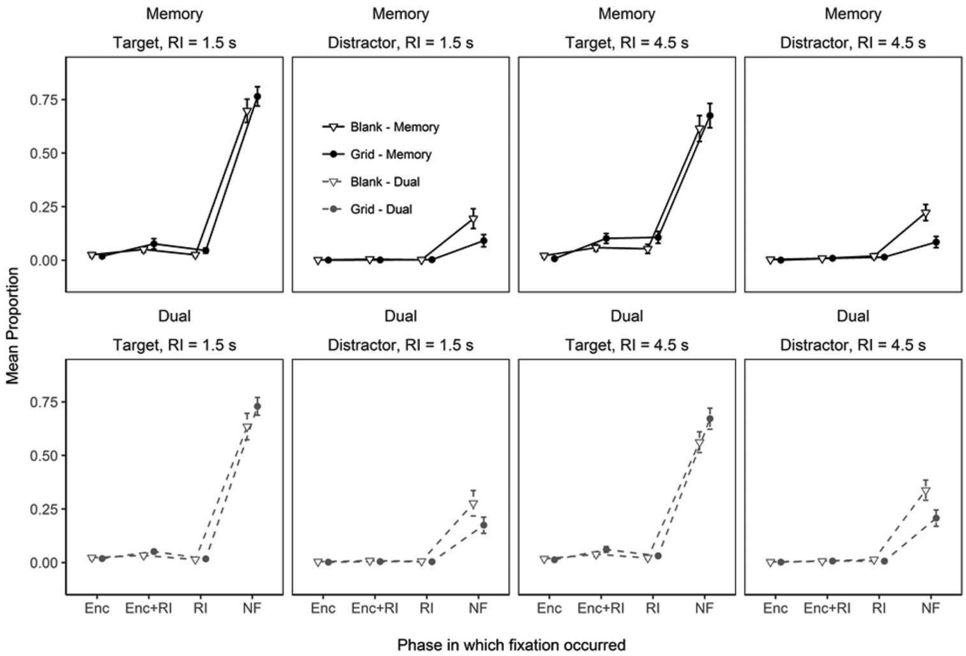

Figure 16. Classification of recalled items in relation to fixations directed at them during the encoding phase only (Enc), encoding and retention phases (Enc + RI), retention phase only (RI), or not fixated at all (NF) in Experiment 4. Error bars depict 95% within-subjects confidence intervals.

Memory accuracy. Figure 17 presents memory accuracy across conditions in Experiment 5. The single-task conditions show the same pattern as in Experiments 1–3: better memory in the grid versus blank condition, and reduced rate of forgetting over time in the grid than blank. Critically, dual-tasking impaired performance overall, but it also interacted with grid presence (being more detrimental for the blank than grid condition) and with retention interval (inducing a higher rate of forgetting). The best model of the data included the effects of: grid + retention + grid × retention + dual-tasking + dual-tasking × grid + dual-tasking × retention (BF_{10} = 4.92 × 10^{52}). The Dual-Tasking × Retention interaction was supported by a BF_{10} = 7.28. The Dual-Tasking × Grid interaction received somewhat ambiguous support (BF_{10} = 2.22).

Figure 18 presents the posterior of the forgetting rate in the blank and grid conditions with and without central distraction. As can be seen in this figure, dual-tasking increased the rate of forgetting in both conditions, and this effect was somewhat larger in the blank condition.

Discussion

In Experiment 5, we observed that the rate of forgetting over time increased when a task requiring central attention was imposed during the retention interval. This result is in line with the assumption that blocking the use of central attention prevents participants from protecting spatial representations from forgetting.

In the study of Lilienthal et al. (2014), the effects of different tasks tapping central attention were examined on memory in the irregular grid task. For example, in one task participants had to judge the accuracy of arithmetic problems (e.g., 8 + 4 = 12?; aka verbal distraction task), whereas in another task they judged the spatial distance between a line and two dots (visuospatial distraction task). These distractor tasks were presented during the blank interstimulus intervals in the irregular grid task. They observed that these dual-task conditions reduced spatial memory span compared to the single-task blank condition, and this reduction was more accentuated when the distractor task was visuospatial. These results suggest that central attention (and interference) is implicated in the maintenance of the visuospatial representations over time in the blank condition. Lilienthal et al. (2014), however, did not investigate whether central attention would also be involved in the grid protection against forgetting. Experiment 5 strongly indicates that blocking the use of central attention leads to more forgetting over time irrespective of grid presence.

How is central attention involved in protecting representations from forgetting? Several studies have proposed that central attention limits the availability of a refreshing mechanism that reactivates representations thereby preventing them from getting lost (Barrouillet et al., 2012; Camos et al., 2018) or that refreshing boosts the accessibility of WM representations above baseline (Souza & Oberauer, 2017; Souza, Rerko, & Oberauer, 2015). Results from the blank condition in all experiments, show that spatial representations are getting lost throughout the retention interval in a way that refreshing cannot fully counteract. In the presence of the grid, however, refreshing seems to be highly efficient, and the rate of forgetting is drastically reduced compared to the blank condition. Importantly, by inhibiting refreshing with a central distraction task, we were able to observe increased forgetting over time in the grid and the blank conditions. This corroborates the assumption that refreshing is highly involved in the grid

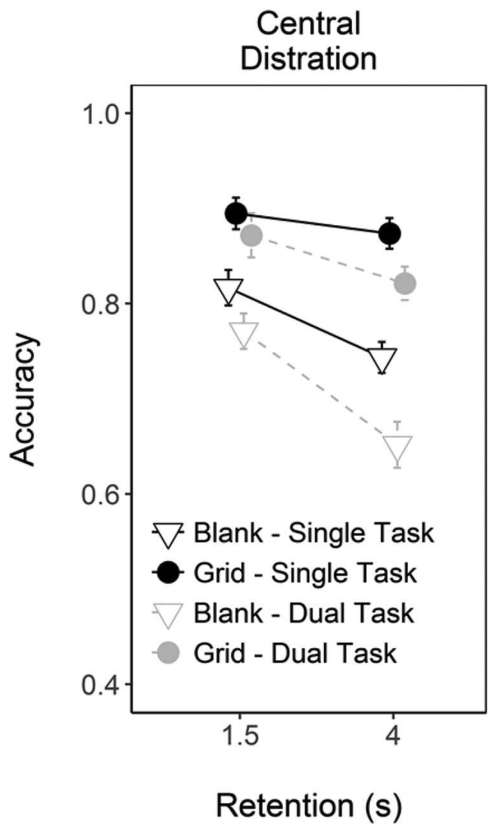

Figure 17. Accuracy in the experimental conditions implemented in Experiment 5. Error bars depict 95% within-subjects confidence intervals.

condition as well as the blank condition (Lilienthal et al., 2014), but it is less efficient in the latter. By blocking the use of refreshing, some inexorable forgetting of the spatial representations occurs that cannot be fully counteracted, even in the presence of the grid.

General Discussion

The goals of the present study were twofold. First, we examined whether overt (gaze-based) or covert shifts of visuospatial attention to irrelevant spatial locations could explain the time-based forgetting in a spatial WM task. Second, we examined the hypothesis that the presence of the irregular grid onscreen during the retention phase facilitates the rehearsal of the spatial locations, and the putative mechanisms that may allow this rehearsal to take place: overt eye-movements, covert shifts of visuospatial attention, or memory retrieval constrained by a central processing bottleneck.

Time-Based Forgetting of Spatial Representations

It is still an unsolved issue whether and how rehearsal processes contribute to the maintenance of spatial representations in WM. Here we used an experimental task in which different processes contributing to forgetting could be dissociated (Lilienthal et al., 2014, 2016). We showed that the retention of spatial locations gets poorer over time in the absence of the spatial context in which these representations were learned. Lilienthal et al. (2014, 2016) interpreted this forgetting over time as best explained by decay. Here, we assessed the plausibility of an alternative interference explanation. Our first aim was to assess for the possibility that time-based forgetting occurs because of overt or covert shifts of visuospatial attention to locations away from the memoranda (eye-movement interference hypothesis). If participants are fixating or attending to distractor locations during the retention phase, these spatial locations might be encoded to WM wherein they will interfere with retrieval of the memoranda. In line with this possibility, observation of eye-movement patterns (Experiments 1, 2, and 3) showed that as the retention interval increased, the total number of fixations increased, and most of these fixations were directed to distractor locations. Given that distractor fixations outnumbered target fixations, it was possible that this lead to interference. If fixated locations were confused with target locations, one would expect that fixated distractor locations would be recalled more often than nonfixated distractor locations. Our analysis of the relation between recall and fixation did not lend support to this proposition, as fixated distractor locations did not increase in the likelihood of being recalled. This finding rules out an explanation of interference in terms of confusion between fixated target and distractor locations. If eye-movements would be interfering with the memory representations, this interference ought to be unspecific.

Observing a relation between the duration of the retention interval, an increase in distractor fixations, and reduced memory performance only could provide correlational support for an interference explanation. Hence in Experiments 2 to 4, we tested for a causal relation between overt and covert shifts of visuospatial attention and the rate of forgetting in the blank condition. In stand contrast to the interference hypothesis, preventing participants from moving their eyes (Experiment 2) and their visuospatial attention to distractor locations (Experiments 3 and 4) did not reduce the rate of forgetting over time in the blank condition; if anything it increased forgetting. Our results therefore indicate that overt or covert shifts of visuospatial attention toward distractor locations are unlikely to explain the forgetting over time observed in the blank condition, lending no support for an eye-movement or attention-based interference explanation.

We considered next whether the rate of forgetting over time is related to the availability of central attention (Experiment 5). Our results showed that a dual-task condition demanding central attention enlarged the rate of forgetting over time when the screen was blank. This result is line with the hypothesis that maintenance of visuospatial information benefits from recruiting central attention to maintain these representations, but this process is faulty (less efficient or error prone) when the screen is blank.

Rehearsal in Spatial WM and the Grid Benefit

Memory for spatial location was better and time-based forgetting was substantially reduced when the array of possible spatial locations of the memoranda remained visible during the retention phase compared to when the screen was blank. This grid benefit has been interpreted as reflecting the role of environmental support for spatial rehearsal (Lilienthal et al., 2014, 2016). Here we were concerned with understanding which type of rehearsal the grid

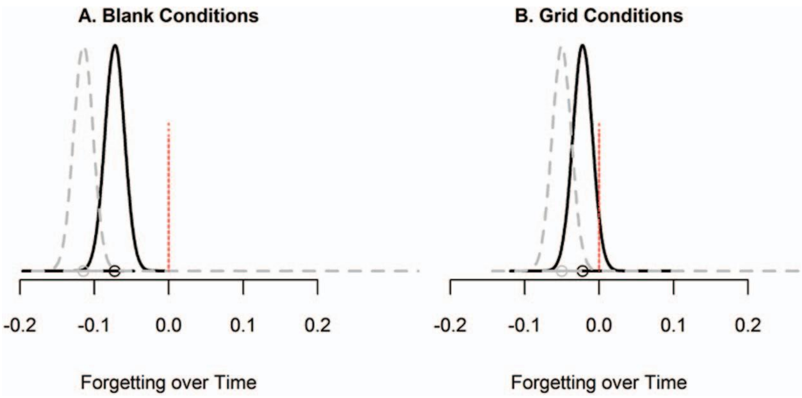

Figure 18. Posterior of the difference in memory accuracy across retention intervals in the blank (A) and grid conditions (B) with and without the central distractor task in Experiment 5. Posterior was sampled from the full model including all possible interactions between grid, retention, and central distraction variables. The vertical (red) line indicates the null hypothesis of no forgetting over time. The bar underneath the distribution indicates the 95% HDI of the distribution, and the dot indicates the mean of the posterior. See the online article for the color version of this figure.

supports. Experiments 1 and 2 showed that the presence of the grid is associated with a larger number of fixations during the retention interval compared to the blank condition. Critically, this increase in fixations was mainly attributable to participants looking back to the memorized locations. This supports the notion that the eye-movement system was activated to rehearse the memoranda (Laeng & Teodorescu, 2002; Tremblay et al., 2006). However, there is large overlap between the eye movement system and visuospatial attention (Chelazzi et al., 1995; Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986), and looking back to memorized location might have been motivated by the need to shift visuospatial attention with eye movements as an epiphenomenon. Shifts of visuospatial attention have been proposed as one key maintenance process in visuospatial WM (Awh & Jonides, 2001; Awh et al., 1998; Godijn & Theeuwes, 2012; Theeuwes et al., 2009).

Inhibiting eye-movements (Experiment 2) or shifts of visuospatial attention (Experiment 3) yielded overall costs to performance, but it did not eliminate the grid benefit nor did it induce more forgetting in the presence of the grid. The similarity in the costs yielded by Experiments 2 and 3 are in line with the hypothesis that eye-movements toward target locations (and not simply shifts of visuospatial attention) served a functional role for the rehearsal of spatial information in WM. If visuospatial attention had a larger role in the rehearsal of spatial representations, costs associated with inhibiting visuospatial attention should have been larger than that of only inhibiting eye-movements.

Notwithstanding the role of target fixations for part of the grid benefit, none of our manipulations was able to eliminate this benefit altogether. Our results therefore challenge the conclusion that the sole reason why the grid is beneficial is because it allows for better rehearsal. The presence of the grid during the retention interval is beneficial over and above rehearsal.

Further work will be required to fully understand the WM benefits associated with maintaining the same spatial layout throughout the retention phase. One hypothesis to consider in the future is that the presence of the trial-unique grid during the retention phase might allow participants to move from egocentric representations—namely, spatial representations that are centered on an individual's body parts—to more allocentric representations—that is, spatial representations that are centered in relation to the external environment (Burgess, 2006; Klatzky, 1998). There is evidence that egocentric representations became poorer over time. For example, Chieffi, Allport, and Woodin (1999) asked participants to maintain in WM the location of a single target for a later pointing movement which occurred 3 or 30 s after encoding. They varied the starting location of the hand (close or far from body), and pointing movements were made with the eyes closed. Pointing errors were consistent with the coding of the target location being centered on hand-position and these errors increased with delay. Furthermore, comparison of performance over time in conditions with egocentric versus allocentric frames of reference indicate that the error in pointing to target locations in egocentric conditions increase over time, but it remains constant in allocentric conditions (Chen, Byrne, & Crawford, 2011; Hay & Redon, 2006).

Another important finding was that the rate of forgetting in the presence of the grid was only increased when the visuospatial task demanded more responses (i.e., in Experiment 4, but the evidence in support of this increase was ambiguous) and when a two-choice reaction task was used as distraction (Experiment 5). We interpreted this finding as indication that the protection against time-based forgetting afforded by the grid was related to the availability of central attention. In line with recent findings in the WM literature, we suggest that this attentional-based mechanism might be attentional refreshing (Camos et al., 2018). Evidence for the role of refreshing in WM has been obtained by manipulating which WM representation participants attend to in which moment in time using attentional cues (Johnson, Reeder, Raye, & Mitchell, 2002; Souza et al., 2015). Guiding attention to the WM representations of colors (Souza & Oberauer, 2017; Souza et al., 2015), spatial locations, and even words (Souza, Vergauwe, & Oberauer, 2018) has been associated with better recall of these materials from WM, and this effect depends on how often information is attended to during the retention interval. Results of the present study suggest that the presence of the grid aids refreshing of the memoranda. Refreshing may be more accurate or faster in the presence of the grid than in its absence. Changes in any of these parameters would likely allow refreshing to protect more representations from forgetting. The use of central attention may not require a very precise visuospatial focus toward the memorized locations such that even distributed visuospatial attention toward the grid might be sufficient to allow refreshing to take place, and the efficiency of refreshing may increase when representations are allocentric compared to egocentric.

Another possibility to consider in the future is whether the grid may allow participants to use grouping strategies more efficiently, and whether the usage of these strategies may depend on the availability of central attention. Grouping by spatial proximity has been found to improve spatial WM (e.g., De Lillo & Lesk, 2010). Future studies could systematically create displays that are more or less suitable for grouping to independently assess whether these grouping strategies are more easily employed in the presence of the grid than the blank, and the role of central attention for employing such strategies.

The Role of Eye-Movements for Spatial Maintenance

We started our investigation asking whether (a) eye-movements to irrelevant locations (even in the absence of any object) interfere with the memoranda, and (b) eye-movements play a functional role for spatial WM maintenance. Our results are somewhat mixed. In the blank condition, there was relatively more fixations directed toward distractor locations than target locations, but importantly this was not related to erroneously recall of those locations. Furthermore, preventing distractor fixations (Experiment 2) or shifts of visuospatial attention to these locations (Experiments 3 and 4) did not reduce time-based forgetting in the blank condition. All in all, we did not observe support for an eye-movement interference explanation of time-based forgetting in visuospatial WM in our studies.

Our study provides quite some positive evidence for the functional role of eye-movements during maintenance. First, we demonstrated that recall in the grid condition was related to an increased proportion of fixations toward target locations during the retention phase, and that targets fixated during the retention phase tended to be recalled later in the grid condition. Second, we tested the role of eye-movements during the retention phase by requiring participants to fixate the screen-center (Experiment 2) or by using dual-tasks that inhibited fixations and shifts of visuospatial attention toward target locations (Experiments 3 and 4). These studies showed general costs to the maintenance of spatial representations when free viewing was constrained, and no additional costs of further binding visuospatial attention to the screen center. These results are in line with the proposition that eye-movements contributed to the maintenance of spatial representations corroborating studies proposing a large overlap between the eye-movement system and visuospatial WM (Ball, Pearson, & Smith, 2013; Ikkai & Curtis, 2011; Pearson, Ball, & Smith, 2014; Postle et al., 2006; Theeuwes, Olivers, & Chizk, 2005; Theeuwes, Van der Stigchel, & Olivers, 2006).

Importantly, our conclusions regarding the role of eye-movements do not transfer to protection from time-based forgetting. The assumption that oculomotor activity is related to the protection of time-based forgetting in the grid condition (through gaze-based reactivation of decaying traces of the targets) is inconsistent with our results. The pattern of overall costs of inhibiting eye-movements in the grid condition with no change in forgetting rates suggests that inhibiting gaze toward target locations leads to some suppression of these representations. One may wonder why this inhibition does not entail more forgetting over time (i.e., requiring more gaze suppression when the retention interval is longer). The suppression may be required only once, being thereafter sustained over time. This would produce an overall cost, but no additional time-based forgetting. In sum, our results suggest that eye-movements together with visuospatial attention allocation permits more information to be stored in WM overall, but these processes do not contribute to the maintenance of this information over time.

Conclusions

Spatial representations in WM get weaker over time when people retain this information in the absence of the spatial layout in which they were encoded. We tested whether this forgetting was attributable to interference induced by eye-movements or shifts of visuospatial attention to distractor locations, and found both explanations lacking. When the spatial layout is visible during the retention phase, WM performance improves and little time-based forgetting is observed. This benefit has been interpreted as evidence of the use of efficient rehearsal processes that allow information to be protected from time-based forgetting. Our studies show only partial support for this hypothesis. Preventing gaze-based or visuospatial-attention rehearsal reduced the spatial-layout benefit. Protection from time-based forgetting remained though. An increase in time-based forgetting was only observed when central attention was occupied in the processing of another task. Together these results point to different roles of gaze-based and visuospatial-attention rehearsal on the one hand, and central attention on the other hand, for visuospatial WM maintenance: gaze-based rehearsal provides additional WM storage, but a central process is responsible for keeping these representations intact over time in WM.

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