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Updating of working memory: Lingering bindings

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Three experiments investigated proactive interference and proactive facilitation in a memory-updating paradigm. Participants remembered several letters or spatial patterns, distinguished by their spatial positions, and updated them by new stimuli up to 20 times per trial. Self-paced updating times were shorter when an item previously remembered and then replaced reappeared in the same location than when it reappeared in a different location. This effect demonstrates residual memory for no-longer-relevant bindings of items to locations. The effect increased with the number of items to be remembered. With one exception, updating times did not increase, and recall of final values did not decrease, over successive updating steps, thus providing little evidence for proactive interference building up cumulatively.

Keywords: Working memory; Updating; Binding; Proactive interference.

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Mental activities such as language comprehension and reasoning require the construction and maintenance of relational representations in working memory. By relational representations we mean representations of new configurations of known objects or events, such as a new constellation of pieces on a chess board, a new network of causal relations between variables that we learn from a scientific text, or a new set of social relations that we pick up when listening to gossip. These representations are often referred to as mental models in reasoning (Goodwin & Johnson-Laird, 2005) or situation models in text comprehension (Morrow, Greenspan, & Bower, 1987). The composition of relational representations requires temporary bindings between representations of the components. Providing a mechanism for such bindings has been argued to be one of the main functions of working memory (Halford, Wilson, & Phillips, 1998; Oberauer, Süß, Wilhelm, & Sander, 2007; Waltz et al., 1999).

Thinking and language comprehension also involve the manipulation of relational representations, which implies that bindings must be updated quickly. Therefore, bindings in working memory must be established such that they can be established quickly but also disbanded quickly when the configuration of a relational representation is changed (Oberauer et al., 2007). For instance, reading a text about the movement of

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a woman through a house involves building a mental model of the room layout and binding a representation of the woman to her location (e.g., Rinck, Hähnel, Bower, & Glowalla, 1997). When the woman is said to move into another room, the binding to the previous room must be abolished and a binding to the new room established. If working memory cannot get rid of old bindings, the represented woman will be stuck in the previous room, making her either lag behind events as described in the text, or finding herself in multiple locations at the same time.

A failure to unbind when a relational representation is updated could create proactive interference on bindings. On the other hand, traces of outdated bindings could also lead to proactive facilitation when a previously discarded relation needs to be established again. If, for example, the woman is said to move from the kitchen to the living room and then back to the kitchen, remaining traces of bindings between her and the kitchen could be reused once she returns to the kitchen. The purpose of the present research is to search for evidence of proactive facilitation and proactive interference on bindings in a simple working-memory updating task.

Proactive interference and proactive facilitation in the memory-updating task

We used a simplified version of the memory-updating task (Oberauer, 2003). Participants were asked to remember a small set of items, distinguished by their locations on the screen. The initial items were to be updated several times by new items presented on the screen. Each updating step consisted of the presentation of one new item in one of the original locations, and participants had to replace the old item they remembered for that location by the new item. When ready, they pressed the space bar, upon which they saw the stimulus for the next updating step, or the request to recall all current items in their correct locations (see Figure 1).

Each updating step presented either a new item or an item that was presented before in the sequence (i.e., repeated items). Repeated items reappeared in the same or a different location

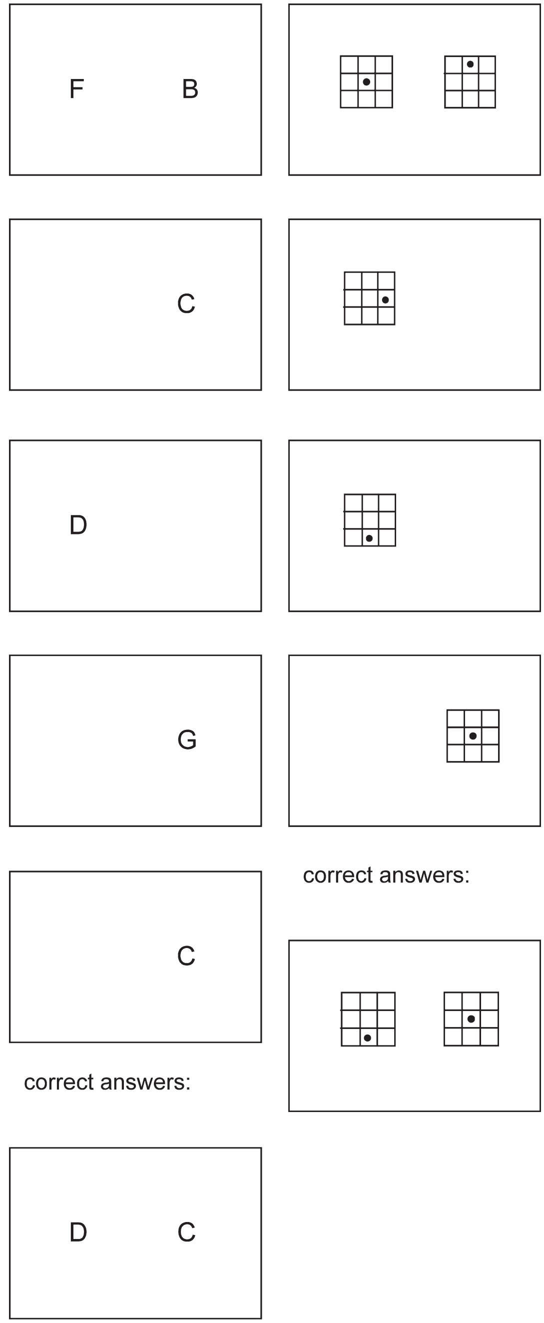

Figure 1. *Example sequence of events in a trial with consonants (left side) and one trial with spatial positions (right side). Successive screens are displayed from top to bottom. Correct answers to be produced are shown at the end.*

from before. Thus, we distinguish three basic conditions. *New items* have not been bound to any location in the present trial and therefore should not suffer from proactive interference or benefit from proactive facilitation. *Repeated items* that have been presented in a location, then have been replaced, and now reappear in the *same location* should benefit from residual bindings of the item to that location. *Repeated items* presented before in a *different location*, in contrast, should suffer from proactive interference on bindings if residual bindings to their previous locations still affect working memory. In addition, both kinds of repeated items could benefit, relative to new items, from repetition priming. Therefore, finding a benefit of repeating an item in the same location relative to new items is not sufficient evidence for lingering bindings in working memory; the critical evidence derives from contrasting repetitions in the same location to repetitions in new locations. A further variable to consider is the lag of a repetition—that is, how many updating steps intervene between discarding an item from a location and reencoding the same item again later in the sequence, either in the same or in a different location. We expect that traces of no-longer-relevant bindings should gradually vanish with increasing lag and therefore predict an interaction of any evidence for proactive interference or proactive facilitation with lag.

We used as the dependent variable the time people take for individual updating steps, which we assume to reflect the difficulty of consolidating a representation of the presented item, bound to its location. This measure has the advantage that it does not create ceiling effects even in tasks that do not exceed working-memory capacity and therefore are fairly easy. Thereby we could use small set sizes that do not exceed the capacity of working memory by any estimate, so that the task demand does not force people to draw on long-term memory. Two items is the minimum set size that requires bindings to keep the items separate, and Experiments 1a and 1b used this set size. Experiment 2 compares this minimal set size to larger set sizes that push working-memory capacity to its limits.

In addition to the local effects of specific prior item–location conjunctions on the encoding of the same or similar conjunctions in individual updating steps, we also investigate proactive interference on a more global level. Each trial consists of a varying number of updating events, each presenting a new item–location pairing to be encoded that replaces a previous, similar pairing. In this regard, each trial is analogous to a series of learning trials in a proactive-interference experiment. Moreover, in all present experiments we administered alternating trials with verbal and with visual–spatial material, thereby introducing an opportunity for release from proactive interference after each trial. Typical experiments on release from proactive interference in long-term memory (e.g., Gardiner, Craik, & Birtwistle, 1972) have shown that proactive interference gradually builds up over trials using similar material; switching to dissimilar material reverses the effect back to baseline. Classical interference theory (Crowder, 1976; Mensink & Raaijmakers, 1988) explains this effect by assuming that at retrieval the memory traces of previous trials compete with those of the current trial to the degree that they are similar.

Experiments on proactive interference usually manipulated similarity between individual items; here we are concerned with proactive interference on bindings rather than on item memory, and therefore it is the similarity between successive item–location conjunctions encountered over successive updating events that potentially leads to gradual build-up of proactive interference. In this regard, our paradigm is analogous to the AB, ABr paradigm in long-term memory research, in which on successive learning occasions the same retrieval cues from Set A are paired with the same to-be-retrieved items from Set B, but recombined into new pairings. Proactive interference is known to be particularly strong in this form of pair-associate learning (Kliegl & Lindenberger, 1993). In our experiments, item–location pairings within a trial are similar because they involve the same locations and items from the same category (e.g., letters). Between successive trials, item–location pairings are less similar because they involve items from very different categories (e.g., letters vs. locations

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in matrices, see Figure 1). Therefore, if proactive interference in working memory gradually builds up in the same way as it does in long-term memory, it should be minimal at the beginning of each trial and gradually build up over successive updating events. As a consequence, the efficiency of updating should deteriorate over successive updating steps, and the ability to recall the final item–location conjunctions at the end of a trial should decline with the run length—that is, the number of updating steps in a trial.

To summarize, the experiments in this paper test for proactive interference and proactive facilitation on bindings in the memory-updating task on a local and a global level. On a local level we look for effects of previous, no-longer-relevant item–location bindings on the efficiency of building new item–location bindings, as a function of lag since the point where the old bindings became irrelevant. On a more global level we test for the gradual build-up of proactive interference over the course of a trial, as reflected in global performance measures. Experiment 1a involves updating of verbal contents (i.e., consonants), Experiment 1b involves updating of spatial contents, and Experiment 2 investigates the role of memory set size with both kinds of materials.

EXPERIMENT 1A

Method

Participants

The sample consisted of 22 adults from the university community at Potsdam, Germany (mean age = 24.18 years; *SD* = 2.87; ranging from 20 to 30 years; 17 females and 5 males). Three additional persons belonged to the initial sample, but they did not meet the criterion of at least 35% completely correct trials, and therefore their data were discarded. Participants received course credit or €6 for their participation in a one-hour session.

Material and procedure

This and the following experiments were conducted in a quiet room on a Macintosh G 3 desktop computer with a Mac OS 9 operating system, using the Matlab Psychophysics toolbox (Brainard, 1997). Participants were tested individually.

The consonants B, C, D, F, G, in capital letters formed the stimulus set. At the beginning of each trial, two consonants chosen at random without replacement were presented on a line centred on the screen, separated by 8 cm. The consonants were 4 cm tall and were displayed in Arial font, white on a black background. Participants had to remember these consonants until they were replaced by a new consonant presented on the same side. Every time participants pressed a key, one consonant appeared on one side of the screen, while the other side remained black. The consonant could be different or the same as the consonant presented before on the same side. Participants had to update their memory representation by the current consonant, while for the other side, the consonant presented there last still had to be remembered.

After each updating event the trial stopped with a probability of .1. To avoid overly long trials, the maximum number of updating events was set to 20. The resulting exponential distribution of numbers of updating steps served to ensure that participants could not anticipate the end of the trial. Each presented consonant had an equal probability of being the last one in the trial, and hence there was no incentive of paying different amounts of attention to consonants presented at different serial positions throughout a trial. In every updating event, the location of the consonant to be presented (left or right) was determined at random with an equal probability. At the end of a trial, participants were instructed to type the last consonant presented on the left side and the last consonant presented on the right side. The procedure is illustrated in Figure 1.

The whole experiment consisted of 32 trials; the first 4 of these were practice trials. The experiment was combined with another memory-updating experiment involving visual material (not reported here). The two experiments alternated on a trial-by-trial basis, thereby minimizing the potential for proactive interference between trials.

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Design and analysis

All updating events were categorized according to four variables: (a) *Location switch*: An updating event on the same side as the immediately preceding one is defined as a no-switch event, whereas updating on the other side is called a switch event. Switching between different items in working memory that are distinguished by their location is known to incur a cost that is often referred to as "object switch cost" (e.g., Oberauer, 2003). In the present paradigm, each updating step replaces the old "object" by a new one, and therefore we find it more appropriate to speak of a location switch. (b) *Repetition*: If the consonant presented in an event had been presented before in the same trial, it is classified as a repetition, otherwise it is classified as new. (c) *Repetition location*: Repetition events are categorized as same-location repetitions if the presented consonant had last been held in working memory on the same side and as other-location repetitions if it had last been held in working memory on the other side. (d) *Lag:* The lag of a repetition consonant is determined as the number of updating steps since the same consonant has last been held in working memory, on the same or the other side. The shortest lag category was lag 1, representing an event in which the presented consonant matches one currently held in working memory. All repetition events were classified into lag categories 1, 2, 3, or 4+, the latter including all higher lags, which occurred too infrequently to justify separate categories. Figure 2 illustrates the assignment of lag values.

		repetition location	lag category
B	**F**		
D	F	(new)	(new)
D	**D**	other	1
D	**F**	same	2
D	**F**	same	1
C	F	(new)	(new)
C	**D**	other	2
B	D	same	4+

Figure 2. *The assignment of the different lag categories. Successive pairs of letters represent successive updating episodes; the letters in each row are the letters currently to be held in working memory; the bold letter is the one actually presented, whereas the other letter is maintained from a previous episode. The first line contains the two consonants shown together at the beginning of a trial (B and F). In the first updating event, B on the left side has to be replaced by D, while F is still remembered for the right side. The values for repetition location and lag are displayed on the right side of the Figure; they always refer to the letter presented in the corresponding event. In the first updating event, the letter D presented on the left side is new. In the second updating event, D presented on the right side has lag = 1 and repetition location = other, because the presented D matches the D held in working memory on the other side during the immediately preceding event. In the third event, F is presented on the same side as where it has been held in working memory up to two events before, giving a value of lag = 2 and of repetition side = same.*

The design is not fully crossed, because new consonants have no values on the repetition location and the lag variable. Furthermore, in the case of a location switch, repetitions on the same side cannot occur with lag 2, and in the case of no location switch, repetitions on the other side cannot occur with lag 2.[1] With a purely random selection of consonants to be presented at each trial, the design cells would have been filled with very uneven frequencies. Therefore, we introduced constraints biasing the selection of each new consonant against selecting one that would fall into a design cell that was already filled frequently in the current trial. Table A1 in the Appendix presents the resulting frequencies of events used in the analyses broken down by the design factors.

[1] These constraints arise for the following reasons: A same-side repetition with lag 2 means that over three successive updating steps the objects A, B, A are held in the critical location. This sequence can come about only if the last two updating steps focus on that location, first replacing A by B, and then immediately replacing B by A. Therefore, the latter of these two updating steps cannot involve a location switch. An other-side repetition with lag 2 means that over three successive updating steps the two locations have the contents (AX), (BX), (XA), where the two letters in each pair of brackets represent the current contents of the two locations (left, right), and X can be any letter different from A and B. This sequence can come about only by an updating step on the left side, replacing A with B, followed by an updating step on the right side, replacing X with A. Therefore, the latter of these updating steps must involve a location switch.

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The incomplete design rendered analysis of variance a less than ideal tool for analysing the data. We therefore used multilevel regression to determine the impact of the four design variables on updating latencies. Data were analysed with linear mixed effects (LME) models (Pinheiro & Bates, 2000), assigning regression coefficients to predictor variables on the group level (i.e., fixed effects) and on the level of individual participants (i.e., random effects). Fixed effects represent the mean effect of a predictor variable for the whole sample, and random effects represent the deviation of individuals' effect sizes from that mean. Random effects are not estimated as separate regression coefficients for each individual; rather, LME estimates the variance of each regression coefficient, assuming a normal distribution of coefficients around the fixed effect estimate. Covariances of coefficients can also be estimated, but for the sake of simplicity, and because of the small sample sizes in the present experiments, we fixed all covariances between random effects to zero. In addition to the predictors the fixed and random effect of the intercept are always included in the model, adding two further free parameters; coefficients of the predictors are allowed to covary with the intercept. LME affords a very parsimonious representation of the linear relations between predictors and criterion variable on the group level and the individual level, with a maximum of three parameters (mean, variance, and its covariance with the intercept) for each predictor. All analyses were computed with the *lme* algorithm (Pinheiro, Bates, DebRoy, & Sarkar, 2005) implemented in *R* (R-Development-Core-Team, 2005).

We investigated a series of models using the four design variables and their interactions as predictors and the log-transformed latencies of individual updating events as criteria. Logarithmic transformation of latencies was used to move their distribution closer to normality, because LME is a maximum-likelihood-based procedure resting on the assumption of normality. The design variables were coded as follows: location switch: 0 for no switch and 1 for switch; repetition: 0 for new and 1 for repeated consonants; repetition location: −1 for same location, 1 for other location, and 0 for new consonants; lag: −1.5, −0.5, 0.5, and 1.5 for lags 1, 2, 3, and 4+, respectively, and 0 for new consonants. By this coding scheme repetition location and lag are orthogonal to each other and to the other two design variables, thereby removing the confounds from the incomplete design (e.g., if lag had been coded 1 to 4, it would have been confounded with repetition). Location switch and repetition were orthogonal by design; therefore there was no need to centre their codes on zero. For these variables we chose a coding scheme assigning 0 to the baseline and 1 to the experimental condition, so that the regression coefficients directly reflected the experimental effects.

A further variable entered as predictor was the serial position of an updating step within the trial (ranging from 1 to 20). Serial position could be confounded with some other predictors—for example, longer lags are more likely at later serial positions—and therefore it is important to ensure that the effects of the other variables uphold when serial position is entered in the equation. Furthermore, an increase of response times (RTs) with serial position would be expected if proactive interference gradually built up within a trial.

The analysis progressed through six steps. In the first step, a model with all four main effects as fixed and random effects was fitted to the data. In the second step, all meaningful two-way interactions were added, again with fixed and random effects. There are four meaningful interactions: Location Switch × Repetition, Location Switch × Repetition Location, Location Switch × Lag, Repetition Location × Lag. The interactions of repetition with repetition location and with lag are not meaningful because with one level of repetition (i.e., new consonants), the other variable does not vary. In the third step, the one meaningful three-way interaction (Location Switch × Repetition Location × Lag) was added. In each of the first three steps, those effects that led to an improvement in fit were retained. The best fitting model identified in this way was then submitted to attempts to increase parsimony. In Step 4 we removed the random effect associated with each fixed effect included in the model, and each random effect was retained in the model only

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if it increased the fit, relative to the model with that random effect removed. In Step 5 we did the same for all fixed effects. Finally, serial position is entered as a further predictor, and the significance of all other remaining predictors is tested again in its presence.

Model fit was evaluated by three criteria: the likelihood ratio (i.e., the ratio of the maximum likelihoods of two models under comparison), the Akaike Information Criterion (AIC), and the Bayesian Information Criterion (BIC). AIC and BIC are derived from a model's likelihood, incurring penalties for its number of free parameters. Because we treated each updating latency as a case, our analysis was based on a very large sample size, rendering significance tests for the likelihood ratio highly sensitive. Therefore, we adopted a conservative criterion for model comparisons, regarding a model as fitting better than another model if and only if the likelihood ratio for the comparison was significant, and the model with the higher likelihood had better (i.e., lower) values of AIC and BIC. Because BIC penalizes more for the number of parameters than does AIC, it turned out to be the most conservative criterion in all our model comparisons; thus, we effectively made all decisions on the basis of BIC. In addition, we also report the proportion of variance accounted for, adjusted for the number of free parameters:

$$R^2_{adj} = 1 - \frac{\sum_{i=1}^{n}\left(d_i - \hat{d}_i\right)^2/(n-k)}{\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2/(n-1)}.$$

Results

Participants reached an average of 89.6% completely correct trials, with a range from 75.0% to 96.4%. Only latencies from trials with completely correct answers were included in the analyses. Furthermore, latencies shorter than 200 ms and latencies exceeding an individual's mean by more than 3 standard deviations within each condition of the location switching variable were excluded from analyses. By these criteria, 2.1% of the data were excluded as outliers. The remaining latencies were log-transformed and were submitted to the LME analyses outlined above.

The final model reached after progressing through the six steps of comparative fitting outlined above had three fixed effects (location switch, repetition location, and lag) and one random effect (location switch), in addition to the fixed and random intercept. These three effects remained significant after entering serial position as further fixed effect; including serial position did not improve model fit and therefore was dropped again. The fit of the final model is summarized in the first line of Table 1. Table 2 shows the loss of fit associated with removing each fixed effect individually; in each case, removing an effect led to a significant and substantial loss of fit, showing that the effect was significant, and keeping it in the model was worth the loss in parsimony incurred by it. The data together with the model predictions are displayed in Figure 3. The predictions were generated by transforming the predicted log-RTs for each participant back to the original RT scale and then averaging across participants. Here and in all other experiments the predictions underestimate the observed RTs on the original scale. This effect arises from the shrinkage correction in LME, together with the fact that we applied LME to log-transformed RTs.[2]

The main effect of location switching means that participants took longer for an updating step when it involved a switch to the other side. This finding replicates previous reports of object-switch costs in memory-updating paradigms (Garavan, 1998; Oberauer, 2003) and extends them to a situation where the old object in working memory simply

[2] Shrinkage correction means that model predictions for individual participants vary less around the mean than observed data; the degree of shrinkage depends on the reliability of the data (Pinheiro & Bates, 2000). Therefore, the predicted log-RTs have smaller variance than the observed ones. Reducing the variance in a normal distribution translates into a reduced mean after exponentiation.

Table 1. *Fit indices of best fitting models*

Model	*N*	*n* (par)	*LogLik*	*AIC*	*BIC*	R^2_{adj}
Experiment 1A	3,591	7	−1,208	2,433	2,483	.571
Experiment 1B	3,523	12	−1,848	3,723	3,803	.607
Experiment 2, letters	16,935	22	−7,516.4	15,079	15,257	.744
Experiment 2, positions	14,620	23	−9,246	18,540	18,722	.622

Note: N = number of data points, n (par) = number of estimated parameters, LogLik = log likelihood. AIC = Akaike Information Criterion. BIC = Bayes Information Criterion.

Table 2. *Best fitting model for Experiment 1A*

		95% CI				
Parameter	*Estimate*	*Lower*	*Upper*	*L-Ratio*	*ΔAIC*	*ΔBIC*
Location switch	.161	.082	.241	453	448	429
Repetition location	.030	.017	.043	20	19	12
Lag	.034	.023	.044	39	37	31

Note: Estimates are unstandardized regression weights for fixed effects; they reflect the size of the effect on the log-RT scale (RT = response time). L-Ratio = likelihood ratio of complete model to model with effect removed (all ps < .001); ΔAIC and ΔBIC are changes in Akaike Information Criterion and Bayes Information Criterion, respectively, when removing effect (positive values mean decrease of fit).

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has to be replaced by a new one. The main effect of repetition location shows that repetitions on the same side were encoded faster than repetitions on the other side. In addition, repetitions were encoded faster with smaller lags.

Although repetition location did not interact with lag, we consider the possibility that the repetition location effect arose only from the lag 1 trials, in which a repetition on the same side requires no updating of working memory at all, whereas a repetition on the other side involves an updating step, after which the same letter is held on both sides. To rule out this trivial explanation, we ran the model-based analysis again, excluding lag 1 trials. The best fitting model had just one fixed effect, repetition location; removing it led to a loss of fit on all three fit indices. The repetition location effect was .035, even larger than in the model including lag 1 trials.

We analysed accuracy of recall of the final letters as a function of run length to test whether proactive interference builds up over successive updating events. Gradual build-up of proactive interference should lead to worse recall with longer runs of updating events. We classified trials into four categories of run length according to the number of updating events (2–5, 6–10, 11–15, 16–20). The linear contrast over these four levels was significant, $F(1, 21) = 24.4$, partial $\eta^2 = .54$, $p < .001$. The effect, however, went in the opposite direction of what would be expected from proactive interference; mean accuracy increased with run length, averaging .89, .97, .98, and .99 for successive levels of run length.

EXPERIMENT 1B

This experiment is a replication of the design of Experiment 1A, using visual–spatial material.

Method

Participants

Participants of Experiment 1B were 16 women and 4 men with a mean age of 23.5 years ($SD = 2.69$;

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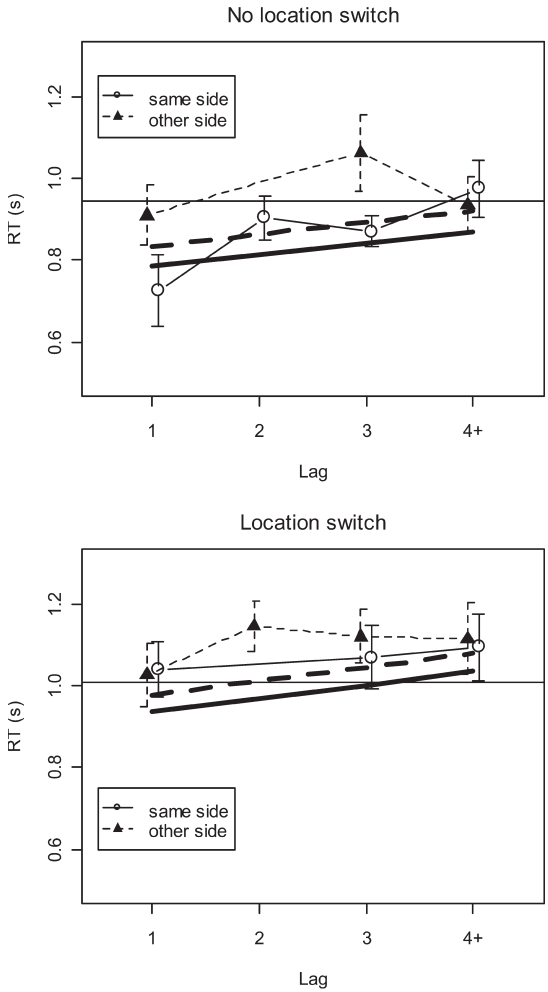

Figure 3. *Mean updating latencies in Experiment 1A (2 letters), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new letters. Top: no-switch condition; bottom: switch condition. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

ranging from 20 to 29 years). Two further participants were tested but were excluded from analysis because they had accuracies below 35% correct.

Material and procedure

The material consisted of 3 × 3 matrices in which one cell was filled by a dot (see Figure 1). For each trial, five of the nine possible stimuli were randomly selected, and only these five stimuli were presented in that trial. Thereby, the number of different stimuli per trial was the same as that in Experiment 1A. In all other regards, the procedure was the same as that for Experiment 1A. Table A1 in the Appendix shows the frequencies of cases per design cell that were generated by the constrained algorithm for producing trials; with one exception (location switch, same-location repetition with lag 4+) there were sufficient cases for analysis in all design cells. Trials of Experiment 1B alternated with trials of an unrelated experiment using a verbal memory-updating task to minimize proactive interference between trials.

Results

Participants achieved on average 73.9% completely correct trials (range 57.1 to 82.1). The latency data were analysed in the same way as those of Experiment 1A. The best fitting model had six fixed effects (main effects of location switch, repetition, repetition location, and lag, as well as the interactions of location switch with repetition, and location switch with lag) and three random effects (location switch, repetition location, and lag), in addition to fixed and random effects of the intercept. The fit indices are given in Table 2, and the results of testing each individual fixed effect are summarized in Table 3. Again, each effect was significant and substantial. Adding serial position as a further fixed effect improved the model fit, but once the random effect of serial position was included as well, the fixed effect could be removed without loss of fit as indexed by BIC.

As shown in Figure 4, updating latencies were slower following a location switch than following no switch. Repeated stimuli were encoded faster than new stimuli. Among repeated stimuli, those repeated on the same side were encoded faster than those repeated on the other side. Repetitions with shorter lags resulted in faster updating. The interactions mean that the repetition effect and the lag effect were both smaller following a location switch than following no

Table 3. *Best fitting model for Experiment 1B*

Parameter	*Estimate*	*95% CI* *Lower*	*Upper*	*L-Ratio*	*ΔAIC*	*ΔBIC*
Location switch	.104	.028	.181	84	79	60
Repetition	− .305	− .355	− .254	150	146	134
Repetition location	.090	.060	.119	21	19	13
Lag	.145	.110	.179	40	36	24
Location Switch × Repetition	.187	.117	.257	27	26	20
Location Switch × Lag	− .055	− .085	− .026	13	12	6

Note: Estimates are unstandardized regression weights for fixed effects; they reflect the size of the effect on the log-RT scale (RT = response time). L-Ratio = likelihood ratio of complete model to model with effect removed (all ps $< .001$); ΔAIC and ΔBIC are changes in Akaike Information Criterion and Bayes Information Criterion, respectively, when removing effect (positive values mean decrease of fit). Removing main effects also involves removing their interaction.

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switch. We again reran the model-fitting procedure with lag 1 trials excluded. This resulted in a model with four fixed effects (location switch, repetition, repetition location, and the Location Switch × Repetition Location interaction). The repetition location effect was larger than that in the model with lag 1 trials included (.104 compared to .086). Therefore, the repetition location effect cannot be due solely to the lag 1 trials.

The analysis of accuracy of final recall by run length revealed a similar pattern to that with the letters in Experiment 1A: Accuracy increased from the first to the second category of run length and then slightly declined (means .75, .94, .94, .91 for successive run length categories). The upward linear trend was significant, $F(1, 19) = 35.8$, partial $\eta^2 = .65$, $p < .001$. The slight downward slope over run lengths in the range from 6 to 20 (Categories 2 to 4) was not significant, $F = 2.1$, $p = .17$.

Discussion

In both experiments we found a positive effect of repetition location, showing that working memory can be updated faster when the new information must be bound to the same spatial location to which it had been bound before than when it must be bound to a new location, even when the old information had been discarded in between the first and the second time of its encoding. This result demonstrates that after disbanding the binding of a letter or a pattern to a spatial position, some residual trace of that binding still remains in working memory. Although statistically significant in both experiments, the effect in Experiment 1A was small in size, amounting to no more than 40 ms. This documents that, although not perfect, removing no-longer-relevant bindings of letters to spatial locations is highly efficient. The effect was considerably larger in Experiment 1B (about 240 ms), suggesting that bindings of visuo-spatial patterns to spatial locations are more persistent after they become outdated.

The main effect of lag and its lack of interaction with repetition location show that stimuli are encoded faster when they have been held in working memory recently, regardless of the location in which they were held. This effect is best interpreted as repetition priming arising from residual activation of the repeated letter or pattern, independent of its binding. The main effect of repetition in Experiment 1B can be understood in the same way.

The main effect of repetition location shows that previous bindings affect the time for establishing new bindings of the same stimulus, but it is difficult to determine whether this reflects proactive facilitation for same-location repetitions or proactive interference for other-location repetitions.

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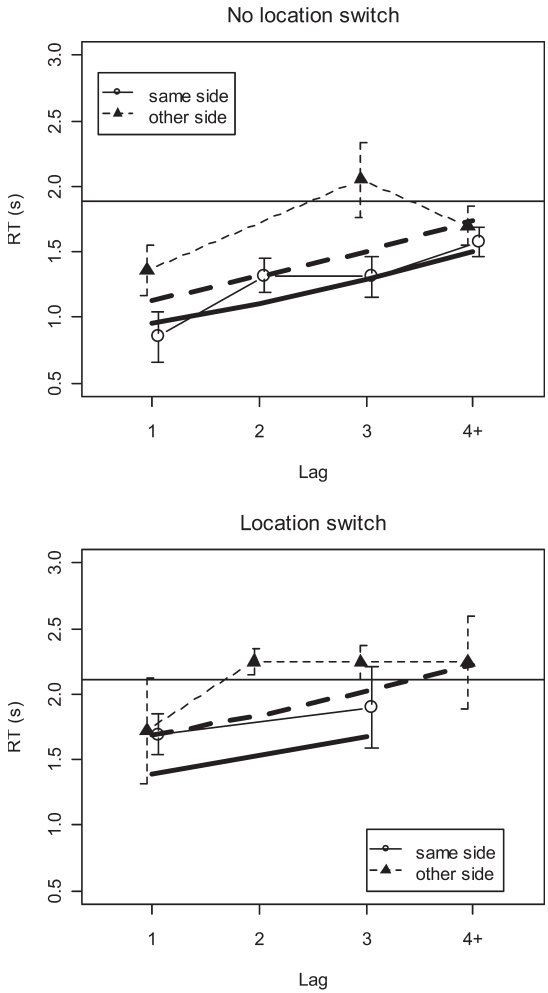

Figure 4. *Mean updating latencies in Experiment 1B (2 spatial positions), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new spatial positions. Top: No-switch condition; bottom: switch condition. Data from design cell location switch, lag 4+, same-location repetition are not plotted because there were too few trials. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

Compared to new stimuli, repetitions on the same side were faster, but repetitions to the other side were hardly slower. The comparison to new stimuli as baseline, however, is problematic because repeated stimuli could have a general benefit over new stimuli because of repetition priming. Repetition priming for items would speed up encoding of repeated items relative to new items and therefore could mask proactive interference and exaggerate proactive facilitation.

The findings regarding the more global effect of proactive interference, however, speak against a substantial interfering effect of residual bindings: Our design mirrors experiments on the build-up of and release from proactive interference, and therefore we should expect evidence for proactive interference gradually building up over successive updating events in a trial. This should have led to successive slowing of RTs over successive updating events and to worse recall after longer runs of updating events. Contrary to this prediction, there was no significant fixed effect of serial position on RTs, and no negative effect of run length on recall accuracy, in both experiments.

It could be argued that we found no evidence for build-up of proactive interference because it was counteracted by the facilitating effect of same-side repetitions. The presence of same-side repetitions, however, does not diminish the net amount of proactive interference that would be expected to build up over a trial, according to classical interference theory, for the following reason. The hypothesis of gradual build-up of proactive interference rests on the assumption that memory traces of all item–location bindings formed during a trial compete for retrieval. Longer runs of updating events imply more different traces in that competition, thus leading to more proactive interference. Each trace would enter the competition according to its strength. Traces of item–location conjunctions that were repeated during the trial are assumed to be stronger; this strengthening applies equally to the correct traces (i.e., those that should be retrieved) and to the incorrect competitors. Memory traces strengthened by repetition are not more likely to be the correct ones at final recall than are traces of nonrepeated conjunctions. Therefore, same-side repetitions would not be expected to create facilitation on global performance measures such as final recall. (The same argument applies to RTs across serial position as a global performance measure.)

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Finally, we briefly comment on the two underadditive interactions in Experiment 1B. We refrain from giving a substantive interpretation of these effects because underadditive interactions in log-transformed data could easily translate into additive effects in the original RT scale. Therefore, the results might simply reflect an additive effect of location switching costs and repetition priming on RTs, which is converted into an interaction by the logarithmic compression of RTs in the slowest condition.

EXPERIMENT 2

The purpose of Experiment 2 was to replicate and extend the previous results. The extension consists of investigating how increasing the load on working memory affects the updating of bindings. We considered two hypotheses. One is that residual traces of no-longer-needed bindings were held in working memory in the previous two experiments because the cognitive system could afford doing so. Holding two elements in working memory arguably does not exhaust the system's capacity—for instance, Cowan (2001) estimates the capacity of working memory to about four chunks. With capacity to spare, the system might find it useful to hold on to outdated bindings because they might be useful later, especially since the experimental design involved many repetitions of stimuli in the same location, which required reestablishing the very same bindings that have been discarded just seconds before. If this reasoning is correct, increasing the load on working memory should reduce the effects of previous bindings—that is, the main effect of repetition location.

Alternatively, the effect of no-longer-relevant bindings on the time for establishing new bindings could become more pronounced with increasing load on working memory. This expectation follows naturally from the binding hypothesis of working-memory capacity (Oberauer, 2005; Oberauer et al., 2007), which assumes that the capacity of working memory is essentially the capacity to build and maintain bindings. A higher load means that more bindings are already to be maintained, and this should make establishing an additional binding between a new stimulus and its location more difficult. Therefore, being able to draw on traces of previous bindings should be more helpful in conditions with higher load. The same hypothesis could also be motivated in two other ways. First, one could postulate that removing old bindings is a process that requires working-memory capacity, and therefore old bindings are removed less efficiently under higher load. Second, one could argue that the selective removal of one specific binding becomes more difficult the more other, to-be-maintained bindings are held at the same time. All three lines of argument lead to the same prediction: The repetition location effect should increase with higher load.

The experiment involved updating of both letters and spatial patterns. Memory load was varied through set size—that is, the number of elements to be held in working memory at any time, distinguished through their spatial locations on the screen. For letters we used set sizes 2 and 5, and for spatial patterns, set sizes 2 and 3. Pilot testing had shown that the updating task is about equally difficult with five letters and with three spatial patterns.

Method

Participants

Participants were 12 undergraduates from the University of Potsdam; their mean age was 23.7 years ($SD = 3.1$, range from 20 to 29 years); 10 of them were female and 2 male. They participated in six sessions on different days and received €6 for each 1-hour session. Two other persons took part in a first session but did not complete the whole experiment, so that their data had to be excluded.

Material and procedure

The material consisted of the letters B, C, D, F, G, H, J, K, L and the nine possible spatial patterns created by placing a dot in one cell of a 3 × 3 grid, as illustrated in Figure 1. Each trial used a random subset of five of the nine stimuli of one category. In the smaller set size conditions stimuli were

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displayed as in the previous experiments; in the conditions with larger set sizes, the stimuli were displayed in five (letters) or three (patterns) locations arranged equidistantly on an imaginary circle around the centre of the screen.

Every session consisted of 32 trials; half of the trials used verbal material, the other half spatial material. The kind of material was changed from trial to trial to minimize proactive interference between trials. Set size of each trial was determined randomly with the constraint that trials with high set size occurred as often as trials with low set size for both kinds of material. The first four trials of the first session—one trial for each combination of material with set size—were practice trials. As in the previous experiments, trials were constructed through an algorithm constrained to balance the frequencies in the design cells as much as possible. Tables A2 and A3 in the Appendix summarize the resulting frequencies for the design cells.

Results

Participants reached on average 96.7% completely correct trials for updating of two letters (range 92.9 to 100), 71.7% for five letters (range 47.6 to 91.7), 94.6% for two spatial patterns (82.1 to 98.8), and 70.8% for three spatial patterns (35.7 to 95.2).

The log-transformed latency data of completely correct trials were analysed through two series of LME models, one for letter updating and one for spatial pattern updating, using the six-step procedure described in the context of Experiment 1A. Set size was added as a predictor, coding the smaller set size as 0 and the larger set size as 1; by coding the smaller set size as 0, the set size factor is neutralized for the conditions that correspond to Experiments 1A and 1B, so that the effects of all other variables can be compared across experiments; the amount by which these effects increase as set size is increased can be directly gleaned from the interaction terms of set size with those effects.

Letter updating

The fit indices of the best fitting models are summarized in Table 1. The best fitting model for letters had 12 fixed effects, listed in Table 4. In addition there were nine random effects (set size, location switch, repetition, repetition location, lag, Set Size × Location Switch, Set Size × Repetition Location, Set Size × Lag,

Table 4. *Best fitting model for letters in Experiment 2*

		95% CI				
Parameter	*Estimate*	*Lower*	*Upper*	*L-Ratio*	*ΔAIC*	*ΔBIC*
Set size	1.101	.893	1.309	15,232	15,211	15,134
Location switch	.385	.295	.476	3,878	3,868	3,829
Repetition	.047	.028	.066	113	109	93
Repetition location	.048	.034	.061	434	412	374
Lag	.028	.017	.040	587	570	508
Set Size × Location Switch	.085	0	.170	101	97	81
Set Size × Repetition	− .200	− .236	− .162	112	110	102
Set Size × Repetition Location	.087	.048	.127	386	379	356
Set Size × Lag	.055	.031	.079	184	178	155
Location Switch × Lag	− .030	− .043	− .016	19	17	9
Repetition Location × Lag	− .013	− .029	.004	233	227	204
Set Size × Repetition Location × Lag	− .058	− .072	− .045	70	68	60

Note: Estimates are unstandardized regression weights for fixed effects; they reflect the size of the effect on the log-RT scale (RT = response time). L-Ratio = likelihood ratio of complete model to model with effect removed (all ps $< .001$); ΔAIC and ΔBIC are changes in Akaike Information Criterion and Bayes Information Criterion, respectively, when removing effect (positive values mean decrease of fit). Removing main effects also involves removing their interactions.

Repetition Location × Lag). Figure 5 displays the data and predictions for set size 2, and Figure 6 for set size 5.

Looking first at the effects not involving set size, which directly reflect what happened in the condition with set size 2, we find the three main effects observed in Experiment 1A (location switch, repetition location, and lag) replicated here with comparable effect sizes. In addition, there was a positive effect of repetition, implying that repeated letters took longer to encode than new letters in the set size 2 condition. The interaction of location switch with lag reflects the fact that, in this experiment, the effect of lag was

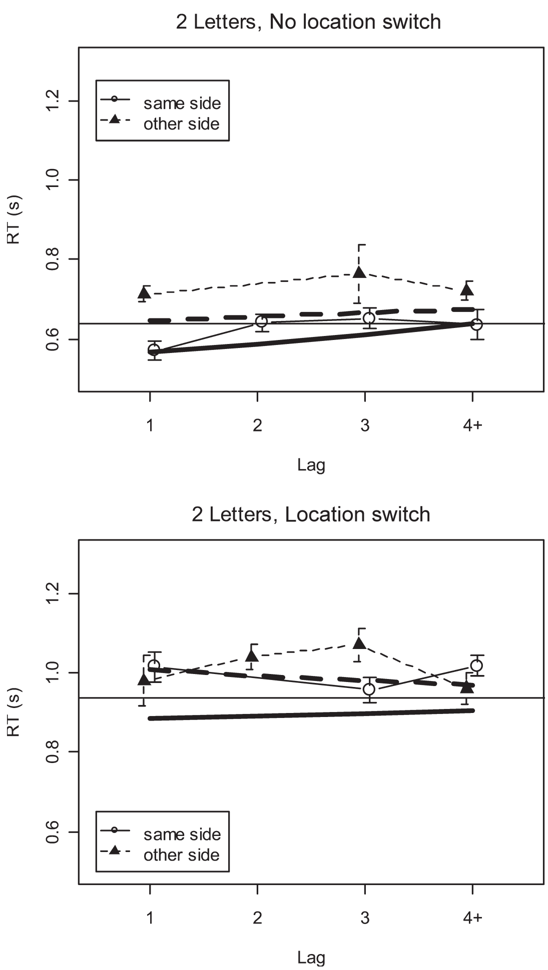

Figure 5. *Mean updating latencies in Experiment 2 (2 letters), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new letters. Top: no-switch condition; bottom: switch condition. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

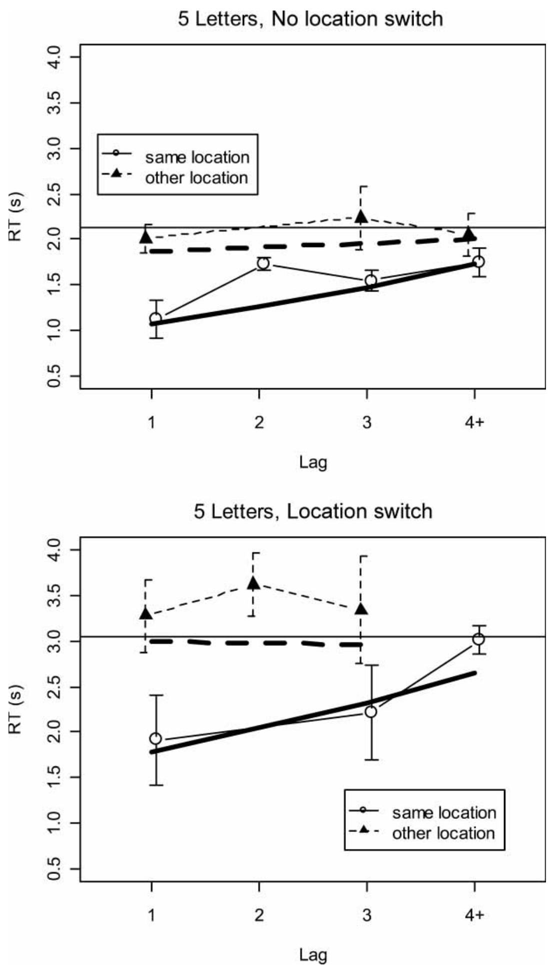

Figure 6. *Mean updating latencies in Experiment 2 (5 letters), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new letters. Top: no-switch condition; bottom: switch condition. Data from design cell location switch, lag 4+, other-location repetition are not plotted because there were too few trials. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

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limited to the no-switch condition. Of more interest in the present context is the interaction of repetition location and lag, because it suggests that the advantage for same-location over other-location repetitions decreased with increasing lag of the repetition, as would be expected if the residual traces of previous bindings became weaker with lag. The confidence intervals of the Repetition Location × Lag interaction, however, include zero, showing that this interaction by itself is not significant—it is part of the model only because LME automatically includes all lower order effects when a higher order interaction is part of the model, in this case a significant three-way interaction with set size, to be discussed below.

Unsurprisingly, set size had a large main effect on updating latencies. Set size modulated the main effects of the other four variables and the repetition location by lag interaction. The positive interaction of set size and location switch shows that location switch costs were larger with the larger set size, a finding that replicates previous observations on object switch costs (Oberauer, 2003). The negative interaction of set size with repetition indicates that, with set size 5, repetition no longer slows down processing but rather leads to faster latencies than with new letters. The interactions of set size with repetition location and with lag mean that the effects of repetition location and lag were inflated with higher set size. Finally, there was an interaction of repetition location and lag at the higher set size: At set size 5, but not set size 2, the repetition location effect diminished with increasing lag.

Spatial updating

Turning to updating of spatial patterns, the six effects found in Experiment 1B were all replicated here (see Table 5): Latencies were larger following a location switch, repeated patterns were encoded faster than new patterns, repetitions in the same location were faster than repetitions in another location, and latencies increased with lag (see Figures 7 and 8). The repetition and lag effects were reduced in the location-switch condition. Four additional effects were obtained that did not involve set size. The first was a main effect

Table 5. *Best fitting model for spatial patterns, Experiment 2*

Parameter	*Estimate*	*95% CI Lower*	*95% CI Upper*	*L-Ratio*	*ΔAIC*	*ΔBIC*
Set size	.465	.332	.599	3,785	3,775	3,737
Location switch	.445	.313	.577	3,282	3,268	3,215
Repetition	− .152	− .209	− .096	161	156	133
Repetition location	.074	.054	.093	891	875	814
Lag	.122	.079	.164	1,328	1,310	1,242
Serial position	− .004	− .005	− .002	20	18	11
Set Size × Repetition Location	.046	.025	.066	91	88	73
Set Size × Lag	.007	− .010	.024	NA	NA	NA
Location Switch × Repetition	.098	.055	.141	20	18	11
Location Switch × Repetition Location	.003	− .021	.027	38	34	19
Location Switch × Lag	− .065	− .105	− .025	105	100	77
Repetition Location × Lag	− .031	− .052	− .011	163	156	125
Set Size × Repetition Location × Lag	− .047	− .065	− .030	28	26	19
Location Switch × Repetition Location × Lag	.059	.039	.080	32	30	23

Note: Estimates are unstandardized regression weights for fixed effects; they reflect the size of the effect on the log-RT scale (RT = response time). L-Ratio = likelihood ratio of complete model to model with effect removed (all *p*s < .001); ΔAIC and ΔBIC are changes in Akaike Information Criterion and Bayes Information Criterion, respectively, when removing effect (positive values mean decrease of fit). Removing main effects also involves removing their interaction. NA = not available because the model with removal of Set Size × Lag interaction did not converge.

of serial position. Contrary to what would be expected from a gradual build-up of proactive interference, updating became faster with successive events in a trial. The other three new effects consisted of the three-way interaction of location switch, repetition location, and lag, and the two-way interactions included in it (Location Switch × Repetition Location, and Repetition Location × Lag). The two-way interaction of location switch and repetition location had an estimated effect of virtually zero; it was part of the model only because it was included in the three-way interaction. The interaction of repetition location and lag reflects the fact that the advantage

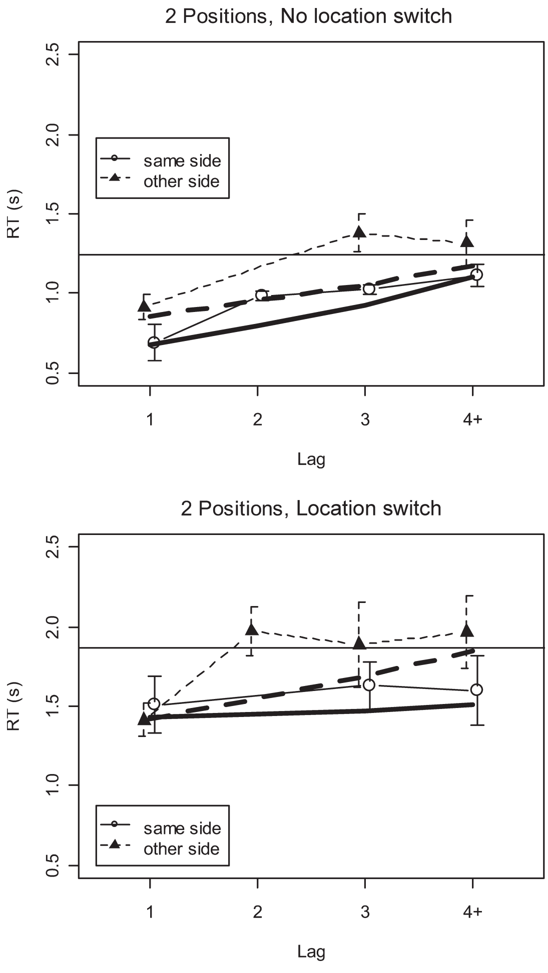

Figure 7. *Mean updating latencies in Experiment 2 (2 spatial positions), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new spatial positions. Top: no-switch condition; bottom: switch condition. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

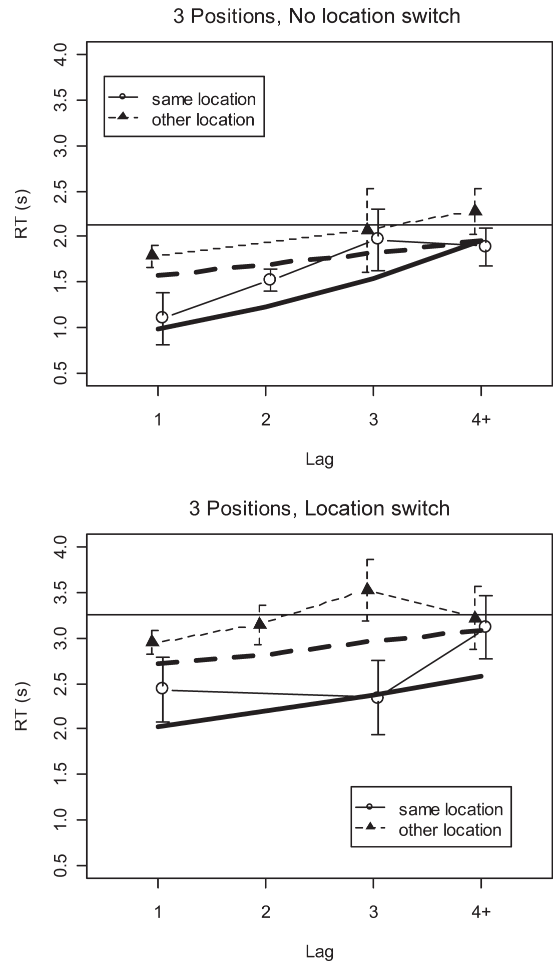

Figure 8. *Mean updating latencies in Experiment 2 (3 spatial positions), with predictions based on fixed effects in the regression models (bold continuous lines for same-side repetitions, bold broken lines for other-side repetitions). The thin horizontal line represents mean latencies for new spatial positions. Top: no-switch condition; bottom: switch condition. Error bars represent 95% confidence intervals for within-subject comparisons (Bakeman & McArthur, 1996).*

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for same-location repetitions decreased with the lag of repetition. This was true only for the no-switch conditions, as shown by the three-way interaction.

Set size had a large effect also on spatial updating latencies, and it modulated two other effects. Most important in the present context, the effect of repetition location was larger with set size 3 than with set size 2. Moreover, the repetition location by lag interaction was more pronounced with a larger set size.

Accuracy of final recall

Accuracies of final report were analysed by an analysis of variance (ANOVA) with material (numbers vs. positions), set size (small vs. large), session (1 to 6), and run length (2–5, 6–10, 11–15, and 16–20) as variables. We focus on the effects of interest for evaluating the effect of run length to test for the build-up of proactive interference; run length was again coded as the linear contrast over the four categories of updating steps. The main effect of that linear contrast was just significant, $F(1, 9) = 7.8$, $p = .049$, partial $\eta^2 = .66$. None of the interactions of run length with any other factor was significant, largest $F = 3.2$, $p = .15$. Inspection of the data, however, suggests that the decline of accuracy over run length was limited to the larger set size. Averaged across materials and sessions, accuracy for the four levels of run length with small set sizes was .97, .98, .98, and .96. With large set sizes, the means were .89, .86, .87, and .83, for successive levels of run length.

Discussion

Experiment 2 accomplished its two goals. First, all effects observed in the previous two experiments were replicated here with the corresponding kind of material. Some additional effects not involving set size were observed as well; these effects were small and not consistent across materials, and we do not see any obvious explanation for them, so we are inclined to regard them as less important. The second goal was to investigate how updating of bindings was modulated by set size. For both kinds of material, the repetition location effect increased with set size, showing that old bindings have a stronger effect on the speed of establishing new bindings when working-memory load is high. This observation rules out the spare-capacity explanation of the impact of outdated bindings. One possible explanation for our finding is that establishing new bindings is more difficult under high load and therefore benefits more from support from residuals of old bindings. Alternatively, it could be that under high load old bindings are removed less efficiently because removing bindings requires working-memory capacity itself, or because selective unbinding is more difficult when there are more bindings to select from. Against the latter hypothesis stands the three-way interaction of set size, repetition location, and lag: With larger set sizes, the effect of repetition location declined more steeply with lag, showing that the effect of outdated bindings diminished more quickly when set sizes were large. If high working-memory load made removing old bindings difficult, we should expect the opposite pattern.

Different from Experiments 1A and 1B, we found at least some evidence for proactive interference building up over the course of a trial. With the larger set sizes, accuracies declined over increasing run length. This suggests that proactive interference builds up when working-memory capacity is stretched to its limits, or beyond (Cowan, Johnson, & Saults, 2005). The run length effect, however, was barely significant, and it must be interpreted in light of the speed-up of RTs over successive steps of updating spatial patterns (i.e., the main effect of serial position), which goes contrary to the hypothesis of proactive interference build-up. Therefore, these data provide weak evidence at best for the build-up of proactive interference in working memory.

GENERAL DISCUSSION

We used a memory-updating paradigm to investigate whether bindings between spatial locations

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and their contents are maintained after they become outdated. The answer is yes. If a letter or spatial pattern has been bound to a location earlier in a trial but is then discarded and replaced by a new content, binding the same letter or pattern to the same location is easier afterwards than it is to bind them to another location. This relative facilitation cannot be explained as repetition priming for the letter or pattern itself, because it arises not from the repetition of a content element but from the repetition of a specific content–location conjunction. Memory for these conjunctions must be formed by ad hoc bindings of their components (i.e., the content item and the location), and therefore it must be traces of these bindings that produce a facilitating or interfering effect when the same content element is later bound again to the same or to a different location, respectively.

Compared to the time for encoding new items, encoding repeated items in the same location was often facilitated, and encoding repeated items in a different location was occasionally slowed. Whereas the benefit of repeating an item in the same location could be due to repetition priming of the item, the cost associated with repeating the item in a different location is unambiguous evidence for interference from outdated bindings. The beneficial effect of repeating an object in the same location is easy to understand—new bindings can build on the traces of old bindings and therefore can be established faster. It is less obvious why repeating an object in a different location should result in a cost, relative to new objects. Classical interference theory predicts interference when more content elements are associated to the same retrieval cue, but not when the same content element is associated to several retrieval cues. If we regard the location as the retrieval cue for the content element—as in the final recall phase—then binding the same content element to a new location should not create interference. Different from the recall phase, however, during the updating steps both the content element to be encoded and its location are presented. Therefore, each component of the content–location conjunction can serve as a retrieval cue for the other. When a content element is repeated in a different location, it could involuntarily cue its old location via its residual bindings to that old location, and cueing the old, now irrelevant, location could interfere with the requirement to focus on the new location and bind the given item exclusively to the new location.[3]

Perhaps surprisingly, the lingering traces of outdated bindings did not drag down the updating process appreciably. With the possible exception of the large set size conditions of Experiment 2, there was no evidence that proactive interference builds up over successive updating steps in a trial. The lack of evidence for cumulative proactive interference, at least with set sizes that unambiguously fall within the range that can be handled by working memory without assistance from long-term memory, converges with previous findings showing that working memory is immune from proactive interference (Cowan et al., 2005; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Halford, Maybery, & Bain, 1988; Wickens, Born, & Allen, 1963). Whereas previous research focused primarily on memory for contents, manipulating proactive interference through similarity of items, we investigated proactive effects on bindings. Nonetheless, we found little build-up of proactive interference on recombined conjunctions of contents and locations in working memory.

Despite the apparent immunity of working memory against cumulative effects of proactive interference, the fine-grained analysis of step-by-step updating times revealed that previous, no-longer-relevant bindings are not completely eradicated or screened off immediately. Where they can be reused, they lead to facilitation of updating, and

[3] The time cost incurred by repeating an old item in a new location might thus be an instance of the fan effect, in which the recognition of a relation between two elements is slowed if either element is related to other competing elements in memory. Different from the fan paradigm, however, the updating steps in the present experiments did not require recognition of old content–location relations. Rather, we must assume that recognition of old content–location bindings occurred involuntarily.

where an old content has to be relocated to a new spatial position, they lead to costs, relative to binding a new item to a location. The effect, however, is subtle and does not appear to accumulate over several updating steps, suggesting that the little bit of extra time that participants take when they have to relocate an old letter or spatial position is sufficient to completely overcome the difficulty.

One possibility that needs to be considered is that bindings in working memory vanish immediately upon being rendered irrelevant, and the residual effect of bindings that are no longer relevant arise from weak but persistent associations in long-term memory, which are built automatically even when the memory load is well within the capacity of working memory. This hypothesis could explain why the repetition side effect increased substantially with set size: When memory load exceeds the capacity of working memory, the system arguably relies more heavily on associations in long-term memory, making it more susceptible to proactive facilitation and interference. The hypothesis could also explain why we did not find a consistent decline of the repetition side effect with lag: Long-term memory associations should be expected to outlast lags of four or more updating events. We did, however, find a decrease of the repetition side effect with lag in particular in the conditions with high set size—that is, just in those conditions where reliance on long-term memory must be assumed to be largest. Therefore, the assumption that all residual effects of outdated bindings arise from long-term memory does not fit the data in all regards. A more definite answer as to the source of residual bindings in working memory or long-term memory could be given by brain-imaging studies using the present paradigm. If residual traces of outdated bindings are held in long-term memory, the contrast of repetitions versus new items, and possibly the contrast between same-side and other-side repetitions, should be reflected in differential activity of the hippocampus.

To conclude, we obtained evidence for an effect of bindings lingering on after being rendered obsolete by memory updating. The effect can be beneficial when the same content–location bindings were needed again, but also interfering when the old content has to be bound to a new location. The interfering effect does not cumulate over successive updating events and therefore remains benign, either because it can be overcome easily by taking some additional time for updating, or because it dissipates quickly over successive updating events. The overall picture emerging from these findings is of a working-memory system that, although not entirely free from proactive effects of old information, can be updated very efficiently.

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APPENDIX

Table A1. *Frequencies of valid latencies per design cell, Experiments 1A and B*

		Experiment 1A			*Experiment 1B*		
Switch condition	*Lag*	*New*	*Same-side repetition*	*Other-side repetition*	*New*	*Same-side repetition*	*Other-side repetition*
No switch	0	315			331		
	1		260	281		366	135
	2		200			298	
	3		66	106		190	108
	4		106	160		103	97
Location switch	0	513			544		
	1		296	327		266	319
	2			243			419
	3		92	116		97	109
	4		140	145		6	107

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Table A2. *Frequencies of valid latencies per design cell, Experiment 2, letters*

		Set size 2			*Set size 5*		
Switch condition	*Lag*	*New*	*Same-side repetition*	*Other-side repetition*	*New*	*Same-side repetition*	*Other-side repetition*
No switch	0	1,544			342		
	1		1,285	681		693	1,360
	2		1,752			558	
	3		1,336	97		334	56
	4		755	254		199	187
Location switch	0	402			308		
	1		448	183		298	603
	2			775			459
	3		253	294		42	221
	4		250	113		106	7

Table A3. *Frequencies of valid latencies per design cell, Experiment 2, spatial patterns*

		Set size 2			*Set size 5*		
Switch condition	*Lag*	*New*	*Same-side repetition*	*Other-side repetition*	*New*	*Same-side repetition*	*Other-side repetition*
No switch	0	833			644		
	1		1,287	1,284		791	626
	2		1,220			910	
	3		1,135	104		393	34
	4		563	217		168	159
Location switch	0	593			421		
	1		289	135		244	230
	2			405			528
	3		66	172		108	217
	4		101	49		86	58