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Hebb Repetition Effects in Complex and Simple Span Tasks Are Based on the Same Learning Mechanism

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The Hebb repetition effect shows improvement in serial recall of repeated lists compared to random nonrepeated lists. Previous research using simple span tasks found that the Hebb repetition effect is limited to constant uninterrupted lists, suggesting chunking as the mechanism of list learning. However, the Hebb repetition effect has been found in complex span tasks, which challenges the chunking explanation, as successive list items are separated by distractor processing, possibly interfering with the unified representations. We tested the possibility that Hebb repetition learning arises from chunking in simple span, but from position–item associations in complex span. In a series of five experiments, we found evidence that contradicts that hypothesis. Results show that (a) Hebb repetition learning in a complex span task can be transferred to a simple span task; (b) Hebb repetition learning from a complex span task cannot be transferred to a partially repeated simple span task; (c) partial repetition in a complex span task does not lead to learning; (d) Hebb repetition learning from a simple span task can be transferred to a complex span task; and (e) repeating the distractors in complex span has no impact on the Hebb repetition effect. These results suggest that the mechanism underlying the Hebb repetition effect in simple and complex span tasks is the same and points at the creation of chunks while excluding the distractors from the long-term memory representation.

Keywords: Hebb repetition learning, complex span tasks, simple span tasks, working memory, long-term memory

In an attempt to understand the sequence learning process, Hebb (1961) created an experimental paradigm in which the same sequence of digits was repeated every third trial in an immediate serial recall task. He found that the performance in the repeated sequence improved with each repetition, while the nonrepeated sequences performance remained stable. This increase in the recall accuracy on repeated lists is now known as the *Hebb repetition effect* (henceforth referred to as the Hebb effect); and the long-term learning that happens with the repetition is called *Hebb repetition learning* (Saito et al., 2020). The Hebb effect has been widely used as a tool for understanding the relationship between short-term and long-term memories (LTM), specifically in learning serial-order information. Hebb repetition learning is considered a laboratory analog of vocabulary and language acquisition (Mosse & Jarrold, 2008; Page & Norris, 2008, 2009; Page et al., 2013; St-Louis et al., 2019; Szmalec et al., 2009, 2012). Although it has been mostly studied using verbal materials, Hebb repetition learning has also been found with visual (Horton et al., 2008; Johnson & Miles, 2019; Johnson et al., 2017; Musfeld et al., 2023), spatial (Couture & Tremblay, 2006; Sukegawa et al., 2019), and visuospatial (Souza & Oberauer, 2022) materials, demonstrating the generalizability of the effect.

Using immediate serial recall tasks, the Hebb effect has been demonstrated to be robust as long as the entire sequence is repeated across

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The data are available at https://osf.io/asd2y/

The experimental materials are available at https://osf.io/asd2y/

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trials (N. Cumming et al., 2003; Hitch et al., 2005). Previous research has shown conditions in which the Hebb effect does not occur. For example, when at least the first two items at the start of the repeating list change with each repetition (Hitch et al., 2005; Schwartz & Bryden, 1971); and when only the odd or even positions of a list are repeated (Hitch et al., 2005), there is no repetition learning. Moreover, learning of a whole repeated sequence cannot be transferred to a list where only every second item was maintained in the same position (N. Cumming et al., 2003). These findings rule out the possibility that Hebb repetition learning rests on gradual learning of individual position–item associations because the partially repeated lists still included several items that repeatedly occurred in the same list position and were nevertheless not learned. Hebb repetition learning also does not occur when list items are repeated in a constant order but shifted and wrapped around (e.g., ABCDE is repeated as BCDEA; Hitch et al., 2005). This finding rules out the possibility that Hebb repetition learning rests on the acquisition of individual item-to-item associations because the relations between each item and the next are still mostly repeated across the shifted repetitions of the Hebb list, but they were not learned.

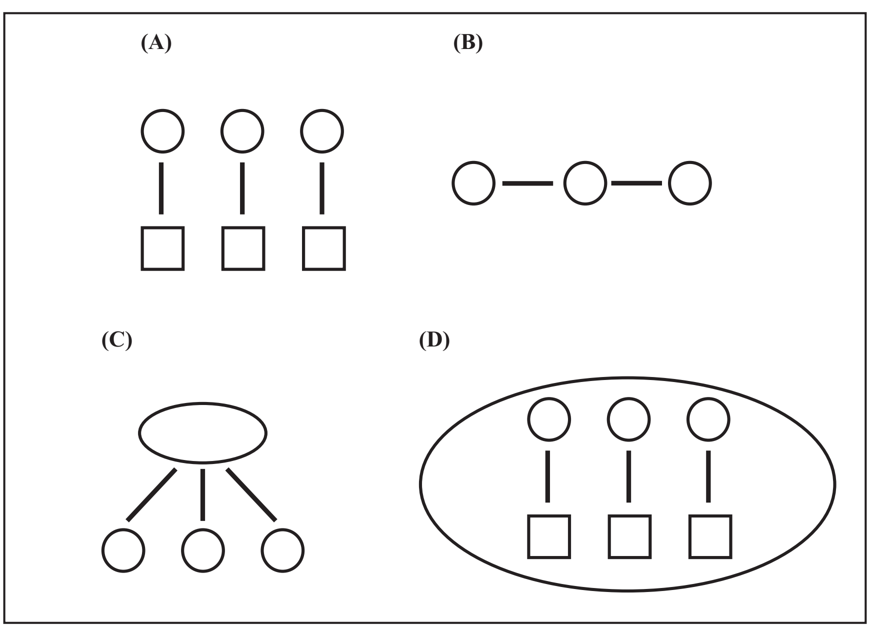
Together, these findings suggest that repetition of the sequence as a whole is necessary for the Hebb effect to occur. Hebb repetition learning does not arise from learning of individual, independent item–item associations, or individual position–item associations (see Figure 1 for a visual representation). Instead, the Hebb effect probably arises from the creation of a unified representation of the sequence, a process sometimes referred to as *chunking*.

The term chunking was first coined by Miller (1956) who stated that an important part of the learning process is the recoding of the to-be-remembered items in terms of known units or chunks. For instance, when a string of letters is recognized as a word or an acronym, it is encoded as one unit rather than as a sequence of individual letters. In a Hebb repetition experiment, a chunk representation of the repeated list as a single unit seems to be what is being learned (N. Cumming et al., 2003; Hitch et al., 2005). This means that the LTM representation of a list that underlies the Hebb effect is acquired as one unit, and retrieved as one unit, rather than as a collection of pair-wise associations of items that can be acquired and retrieved independently.

Two computational models of Hebb repetition learning incorporate this idea. Burgess and Hitch (2006) proposed a model in which each list is represented through associations of items to positional contexts. Each list uses its own set of positional contexts, so that representations of each list are stored separately in LTM, each with its own context set. When a list is repeated, a matching representation can be retrieved from LTM and used to represent the new list as well. In this way, rather than creating a new representation of the repeated list, an old representation is strengthened. Across several repetitions, the LTM representation of the repeated list is strengthened more and more, thereby enabling better immediate recall.

For this mechanism to work, the decision whether to form a new representation of an incoming list, or to retrieve a matching representation from LTM and strengthen it, must be made early during the list presentation. In the Burgess and Hitch model, this is accomplished by a continuous process of cumulative matching: As a new sequence of events is experienced, it is compared to LTM representations of previous sequences, activating those that match the incoming sequence up to the current point. All active LTM representations are strengthened by learning. Once a certain degree of mismatch is detected between an active LTM representation and the incoming sequence, that LTM representation is deactivated, excluding it from further learning and from control of recall. This is why partially repeated lists do not lead to Hebb repetition learning, especially when the repeated lists differ in early list positions.

Figure 1
Illustration of Possible Mechanisms



Note. (A) Position-item associations. (B) Item-item associations. (C) Chunking (Page & Norris, 2009). (D) Chunking (Burgess & Hitch, 2006). Circles represent memory items; squares represent serial positions; and the oval represents a new unit including the repeated memory items.

The model of Page and Norris (2009) uses a similar mechanism to explain Hebb repetition learning. The model uses a primacy gradient of activation to represent the serial order of items in a list. A representation of that order in LTM is created by associating each list item to a single unit, with association strengths that match the primacy gradient (i.e., they decline from the first to the last item). This unit, which is dedicated to representing a memory list, is referred to as a chunk. When a list is repeated, a matching chunk is reactivated, and the given list is represented by strengthening the existing chunk, rather than creating a new one.

Both these models can explain why Hebb repetition learning is not found when only every second list item is repeated: as such partially repeated lists are compared to chunks of previous lists in LTM, and none of these chunks matches the incoming list sufficiently to be retrieved and used to influence recall.

A challenge for chunking as the mechanism of Hebb repetition learning comes from experiments with complex span tasks, in which the presentation of the list items is interrupted by the processing of distractors. There is strong evidence that Hebb repetition learning occurs in complex span tasks (Araya et al., 2022; Oberauer et al., 2015). The complex span task poses a problem for the acquisition of a chunk representing the Hebb lists (i.e., the repeated lists), as the memory items are separated by distractors. Thus, Hebb lists in complex span repeat only every second event—the list items—interleaved by not-repeated distractor episodes. As such, Hebb lists in complex span are similar to partially repeated Hebb lists in the experiments of Hitch et al. (2005) and N. Cumming et al. (2003), in which only every second item was repeated.

One possibility to circumvent this problem is to encode only the memory items into working memory, filtering out the distractors. However, there is compelling evidence that distractors that need to be processed in complex span tasks cannot be completely kept out of working memory (Oberauer & Lewandowsky, 2016, 2019; Oberauer et al., 2012). Another solution could be that the learning mechanism forms a chunk of the uninterrupted sequence of recall, rather than the presentation sequence. However, Hebb repetition learning has also been observed in variants of the complex span paradigm in which recall of the list items was interrupted by distractor processing (Oberauer et al., 2015), or in which both presentation and recall were interrupted by distractor processing (Araya et al., 2022). A third possibility for making a chunk learning mechanism work as an explanation for Hebb repetition learning in complex span is to assume that the distractors, although encoded into working memory as part of the list representation, are somehow excluded from the information encapsulated in the chunk that represents the memory list in LTM, and also excluded from the comparison of each new list with chunks of earlier lists in LTM.

In light of these challenges for a chunking explanation of Hebb repetition learning in complex span, we considered the possibility that Hebb repetition learning in the complex span paradigm might not rely on chunking but rather on the gradual learning of each item's ordinal list position. This position–item association hypothesis states that what strengthens with repetition is the association between the item and its position. Although this mechanism has been dismissed as underlying Hebb repetition learning (N. Cumming et al., 2003), more recent studies have shown that position–item associations can be learned through repetition across a series of trials of immediate list recall (Majerus & Oberauer, 2020; Nakayama & Saito, 2017; Nakayama et al., 2015). In complex span tasks, memory items might have stronger temporal distinctiveness due to the longer distance between items compared to items within a simple span task. Hence, it might be the case that positional information is more effectively used in complex span than in simple span. If this is true, then Hebb repetition learning would rely on different mechanisms in simple span tasks without distractors (i.e., chunking) and in complex span tasks (i.e., learning of position–item associations).

In an earlier study, we showed that the Hebb repetition learning that occurs in a complex span task can be transferred to a simple span task (Araya et al., 2022). This transfer appears to speak against different learning mechanisms. However, position–item associations learned in a complex span task could be transferred to simple span because these associations are still useful for maintaining the sequence of items. The reverse transfer—from chunks learned in simple span to a complex span task in which the presented sequence of events only partially matches the sequence represented by the chunk—would be expected to work less well.

The Present Study

The present study aimed to test the hypothesis that Hebb repetition learning in complex span relies on strengthening position–item associations rather than chunk learning. If this is the case, the following predictions should hold: (a) Hebb repetition learning in complex span should transfer to simple span even when only every second list item is repeated because position–item associations of individual items are independent of each other. By contrast, if people learn a chunk encapsulating the entire complex span list, transferring it to a partially repeated list should not work, because the chunk does not match the partially repeated list well enough (Page & Norris, 2009). We tested this prediction in Experiment 2. (b) In complex span—different from simple span—learning should also occur when only every second list item is repeated, because position–item associations can be learned separately for each item. This prediction is tested in Experiment 3. (c) Hebb repetition learning with a simple span task should not transfer to complex span, because in simple span, people acquire a chunk for the memory list, which does not match the sequence of events in the complex span task, where the repeated list is interleaved with distractors. We test this prediction in Experiment 4.

As all the present experiments were conducted online, we preceded these experiments by a conceptual replication of the Hebb effect in complex span, because most[1] previous experiments on it have been lab-based. In addition, Experiment 1 tested a new distractor task in which participants judged the case of letters. We chose this distractor task because it used the same stimulus class as the memoranda—letters—thereby maximizing the potential for confusion between memory items and distractors. At the same time, the case judgment task was easier than the letter–rhyme judgment task that we had used as distractor task in one of our previous experiments (Araya et al., 2022), where we observed rather poor performance on the distractor tasks.

To foreshadow, Experiments 2–4 led to a compelling rejection of the hypothesis that Hebb repetition learning in complex span relies on position–item associations. This renders chunking the most plausible alternative, and thereby raises the question of how people can

[1] Experiment 4 in Araya et al. (2022) was conducted online with a different procedure. The distractor task was rhyme judgment stimuli, included in both the encoding and recall phases.

form chunks of the repeated memory list without apparent disruption by the not-repeated distractors. This requires that distractors are excluded from the information represented in the chunk, and also from the comparison process between each new series of events in a trial and the chunks representing earlier trials. If that is the case, then Hebb repetition learning in complex span should be unaffected by whether or not the distractors are repeated across repetitions of the Hebb list. This prediction was tested in Experiment 5.

This study was approved by the institutional ethics committee for experimental psychology research of the Graduate School of Education, Kyoto University (approval numbers: CPE-395, CPE-431, CPE-485, and CPE-497).

Experiment 1

Experiment 1 replicated the Hebb repetition design in complex span tasks in an online setting with a new distractor task, in order to have a baseline of Hebb repetition learning for the following experiments. Previously, we had found that in complex span tasks with a semantic distractor task (i.e., size judgments on words) or a phonological distractor task (i.e., rhyme judgments on letter pairs), the Hebb effect did not differ from Hebb repetition learning in simple span tasks (Araya et al., 2022; Oberauer et al., 2015). However, one might argue that the size judgment task involved distractors that are very distinct from the memory items, which are letters, and therefore could easily be excluded from learning. The rhyme judgment task appeared to be considerably more difficult than other distractor tasks and led to poor performance in the distractor task. For that reason, we decided to replicate the experiment using an easier task, but still one that uses distractor stimuli that are highly similar to the memory items, thereby challenging the selective learning of the memory items while excluding the distractors. To that end, we used a letter case judgment task that used the same pool of letters as the memory items.

Method

Data, analysis scripts, and task scripts can be accessed on the Open Science Framework at https://doi.org/10.17605/OSF.IO/ASD2Y.

Participants

Sixty volunteers recruited via Prolific Academic (Prolific AC) took part in a single 30-min session in exchange for £7. Inclusion criteria for all of the experiments were as follows: (a) native English speaker; (b) nationality must be from the United Kingdom, the United States, Canada, Australia, or New Zealand; (c) approval rating of at least 90% on prior submissions at Prolific AC; (d) normal or corrected-to-normal vision; (e) no cognitive impairment or dementia; and (f) age between 18 and 30 years.

After excluding the participants with poor performance on the distractor task (i.e., lower than 80% of accuracy); outliers; and incomplete data files, the total sample was 56 participants (25 female and 31 male) with ages ranging from 18 to 30 years ($M = 23.55$). Participants gave informed consent prior to the experiment.

The sample sizes were primarily determined based on previous experiments (see Araya et al., 2022; Oberauer et al., 2015), which showed sufficient evidence in complex span Hebb repetition experiments with 25–30 participants. However, taking into account the potential limitations of an online environment, including that the experiment had to be shorter than in-person, we decided to double the sample size.

Materials

The experiments were programmed using the JavaScript jsPsych library (de Leeuw, 2015) Version 6.2.0. A list of all the consonants in the alphabet except *Q* and *Y* was used as memory items. The memory list for each trial was created by randomly selecting consonants without replacement. The list for the first repeated trial (i.e., Trial 3) was constructed in the same way and then held constant for every repetition (i.e., every third trial). The distractor task was a letter case judgment task. The same pool of letters used for the memory items was used, including both lower- and upper-case versions of each letter. Participants had to decide whether the letter presented was in lower or upper case. The distractor's letters were selected at random on every trial, including on the repetition trials.

Procedure

The task consisted of 18 trials. During the encoding phase, participants were required to remember a list of eight consonants, each interleaved by two distractor stimuli. Each trial started with a fixation cross that lasted 3 s, followed by the first consonant (memory item) displayed centered and in red for 1.5 s, immediately replaced by the first distractor letter. For example, the letter "r" was presented on the screen, and the participant had to respond to whether the letter is upper case or lower case, by pressing the "right arrow" or the "left arrow" key, respectively. Each distractor was presented until there had been a response or for a maximum of 2 s. After the complete memory list was presented, the recall phase began. A red question mark was shown on the screen, prompting participants to type the letters in the same order as presented. The entered letter was shown on the screen for 0.3 s, followed by a red question mark, and so on until the eight letters were recalled; omissions were not allowed. To begin the next trial, participants had to click on a "continue" button, giving opportunity to take a break if necessary. For the repeated lists, the same list of consonants was repeated every third trial, combined with a new random set of distractor stimuli. At the end of the main task (i.e., 18 trials), we included three trials (two random and one repeated) without the letter case judgment task, in order to measure learning transfer from a complex to a simple span task. We refer to this last cycle of three trials as Transfer cycle.

Data Analysis

The data from the main task were analyzed using the *lmBF* function in the BayesFactor package (Morey & Rouder, 2018; Rouder et al., 2012) for R (R Core Team, 2020). This function is used to estimate the Bayes factor (BF) of linear models. The BF reflects the relative strength of evidence for one of the two models compared to another (Dienes, 2014). Two given models can be compared indirectly by dividing their BFs from comparisons to the same reference model (usually a null model). The main hypothesis we tested is that serial recall performance increases over repetitions for the Hebb trials but not the filler trials. In complex span, Hebb repetition learning could also affect performance on the distractor task because when memory for the list is supported by knowledge in LTM, participants could devote more time or cognitive resources to the distractor task. Therefore, we tested the secondary hypothesis that speed and accuracy of the distractor task improved over repetitions for the Hebb but not the filler trials.

For each dependent variable, the models included two predictors—cycle and repetition. As a cycle, we define each set of three consecutive trials, including one repeated Hebb list and two nonrepeated filler lists; in total, there were six cycles per participant. Cycle was entered into the model as a continuous variable centered on its mean. Repetition refers to the comparison between the repeated list and the nonrepeated lists. We estimated four Bayesian linear regression models: M_c, containing only the main effect of cycle; M_r, with only the main effect of repetition; M_{add}, with the additive effects of cycle and repetition; and M_{full}, with both the additive effects and their interaction.

Although the Hebb effect has usually been tested through the interaction of repetition with cycle, the main effect of repetition is equally compelling evidence for learning of the repeated lists because there is no other possible explanation for better performance on repeated than on filler lists (Oberauer et al., 2015). Therefore, in this and the following experiments, we consider a main effect of repetition, an interaction of repetition with cycle, or a combination of both as sufficient evidence for Hebb repetition learning.

We evaluated the strength of evidence for each effect by calculating the BF of a more comprehensive model relative to a model in which the effect in question is removed, starting with the full model and gradually removing individual effects (Rouder et al., 2016). That is, we estimated evidence for the interaction by BF(M_{full})/BF(M_{add}) and chose the better model, then compared that model to a derived model in which the main effect of interest was removed in order to assess that effect, that is, BF(M_{full})/BF($M_{full\text{-}cycle}$) and BF(M_{full})/BF($M_{full\text{-}repetition}$) or BF($M_{add}$)/BF($M_{add\text{-}cycle}$) and BF($M_{add}$)/BF($M_{add\text{-}repetition}$). BFs larger than 1 reflect evidence in favor of the model in the numerator, and BFs smaller than 1 reflect evidence in favor of the model in the denominator. The strength of evidence for the model in the denominator can be calculated by the reciprocal of the BF. For example, if BF(M_{full})/BF(M_{add}) = 0.5, then the BF in favor of the additive model is 2. According to Kass and Raftery (1995), BF between 1 and 3.2 show evidence "barely worth mentioning"; between 3.2 and 10 show "substantial evidence"; between 10 and 100 show "strong evidence"; and >100 show "decisive evidence."

The data from the transfer cycle were analyzed using the *ttestBF* function for paired-samples in the BayesFactor package (Morey & Rouder, 2018; Rouder et al., 2012) for R (R Core Team, 2020), which tests the null hypothesis that the mean difference between two samples is 0. We evaluated whether the cumulative learning from Hebb repetition in the main task can be transferred to a different task in a transfer cycle by comparing the accuracy in the repeated list versus the nonrepeated list.

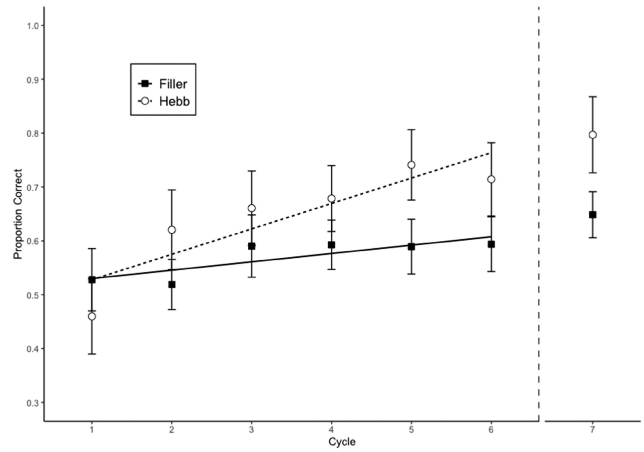
For all of the experiments, we analyzed the data before and after removing outliers with the percentile method (i.e., upper 97.5% to lower 2.5%). Even though the results did not yield any important difference, we decided to report the results excluding the outliers because these were participants who seemed to have responded at random or using some kind of aid. The online task gives the participants more space to respond in an inadequate way, and therefore the data should be treated with care for potential distortions by such responses.

Results

Memory Accuracy

Memory performance was scored as the proportion of letters recalled in their correct within-list position. Figure 2 shows the proportion of correct responses by cycle and repetition. Table 1 summarizes the BFs reflecting the strength of evidence for the main effects and the interaction. The analysis showed strong evidence for the interaction, as well as the main effects of cycle and repetition. Effect sizes were estimated by sampling from the posterior distribution, using the posterior function in the *BayesFactor* package (Morey & Rouder, 2018). The results give information about the posterior mean and the 95% credible interval of the effect, which is the range in which the true effect size lies with a posterior probability of .95 (see Table 2 for a visual comparison between experiments). In this case, the mean of the posterior effect of repetition was .07, with a 95% credible interval of .04–.10. Based on these results, we can say that the Hebb effect increases memory performance in a complex span task by 4–10 percentage points over six list repetitions. This finding replicates the results of our previous experiment using size judgment and rhyme judgment task as distractors (Araya et al., 2022).

Figure 2
Memory Accuracy in Experiment 1



Note. Error bars are 95% CIs for within-subject comparisons (Bakeman & Mcarthur, 1996). The CIs can be interpreted in terms of classical null-hypothesis tests for pair-wise comparisons between data points. Two means differ significantly ($p < .05$) when their CIs overlap by less than 50% of the interval between each mean and the corresponding CI boundary (G. Cumming & Finch, 2005). The straight lines are regression lines estimated from fitting a linear model (Cycles 1–6); Cycle 7 is the transfer cycle. CIs = confidence intervals.

Letter Case Judgment Performance

Failures to respond to a letter case judgment trial within the allotted 2 s were scored as errors. We analyzed data including only the response times (RTs) of correct responses. The Bayesian linear models were estimated with the same predictors as for memory accuracy. The BFs are shown in Table 1, and the proportion of correct answers and RTs are presented in Figure 3. There was no evidence for the interaction for either accuracy or RTs; therefore, the analysis was conducted with the additive model. As for the accuracy in the distractor task, there was no evidence for a main effect of neither cycle nor repetition variables. However, there was strong evidence for the main effect of both cycle and repetition on the RTs. The main effect of repetition shows that the list repetition had a beneficial

Table 1
Experiments 1–4: Bayes Factors for the Linear Models

Effects	Experiment 1	Experiment 2	Experiment 3	Experiment 4
	Memory accuracy		(odd/even)	(*a*/*b*)
Cycle	6.19×10^5	2.42×10^3	19.80/2.98	0.54/130.49
Repetition	88.18	1.06×10^5	0.31/0.24	$107.75/3.86 \times 10^4$
Cycle × Repetition	12.22	0.76	0.16/0.15	0.87/0.91
	Letter case judgment accuracy			
Cycle	0.08	9.54×10^3	—	—
Repetition	0.76	0.40	—	—
Cycle × Repetition	0.64	0.57	—	—
	Letter case judgment RT			
Cycle	1.45×10^{14}	7.97×10^{41}	—	—
Repetition	725.69	7.73	—	—
Cycle × Repetition	0.58	0.07	—	—

effect on the RTs. The main effect of the cycle shows that there was a progressive change in the RTs as the task moved forward.

Transfer Cycle Performance

Memory accuracy in the transfer trials was scored as the proportion of letters recalled in their correct within-list position. We tested the hypothesis that the cumulative learning from the Hebb effect in the complex span task can be transferred to a simple span task. Cycle 7 of Figure 2 shows the proportion of correct answers by repetition. A Bayesian paired-samples *t* test showed that the repeated list had a higher proportion of correct responses than the filler lists, $BF_{10} = 16.54$ (means: Filler = .64 and Hebb = .79).

Discussion

Experiment 1 effectively replicated the results of our previous experiments in which we found evidence of the Hebb effect in complex span tasks. In our previous series of experiments, we found a comparable Hebb effect size between in-person experiments with university students using size judgment tasks as distractors; and an online experiment with a sample not restricted to university students, that used rhyme judgment tasks as distractors. The present results add to the evidence of generalizability, robustness, and reliability of the Hebb effect in complex span tasks. Therefore, we can safely continue using letter case judgment tasks as distractors for the following experiments, without the task being too distinctive from the memory items (i.e., size judgment) or too difficult (i.e., rhyme judgment). Having obtained this confirmation, Experiment 2 aimed to tackle directly the underlying mechanism issue.

Table 2
Means and 95% Credible Intervals for the Hebb Effect

Experiment	*M*	95% credible interval
1	.07	[.04, .10]
2	.06	[.04, .09]
3: Odd	.02	[−.07, .06]
3: Even	.02	[−.01, .07]
4a	.06	[.03, .10]
4b	.08	[.05, .11]
5: Item-repetition	.10	[.06, .13]
5: Item-distractor-repetition	.07	[.04, .11]
5: Distractor-repetition	−.01	[−.05, .02]

Experiment 2

We tested the assumption that in complex span, Hebb repetition learning relies primarily on position–item associations. If that is the case, Hebb repetition learning from a complex span list should be transferred to a partially repeated simple span list (i.e., only odd or even positions repeated) because the position–item associations created can be used for recall of each list item independent of other items. Therefore, Experiment 2 tested the prediction that transfer to partially repeated lists is possible when the list was learned in the context of a complex span task.

Method

Participants

120 volunteers (divided into two equal groups) recruited via Prolific AC took part in a single 45-min session in exchange for £10. The inclusion criteria were the same as in Experiment 1. The sample analyzed was 43 subjects (23 female and 20 male) with ages ranging between 18 and 30 years old ($M = 27.51$) for the odd-transfer group and 40 (21 female and 19 male) with ages ranging between 18 and 30 years old ($M = 25.15$) for the even-transfer group. Participants gave informed consent prior to the experiment.

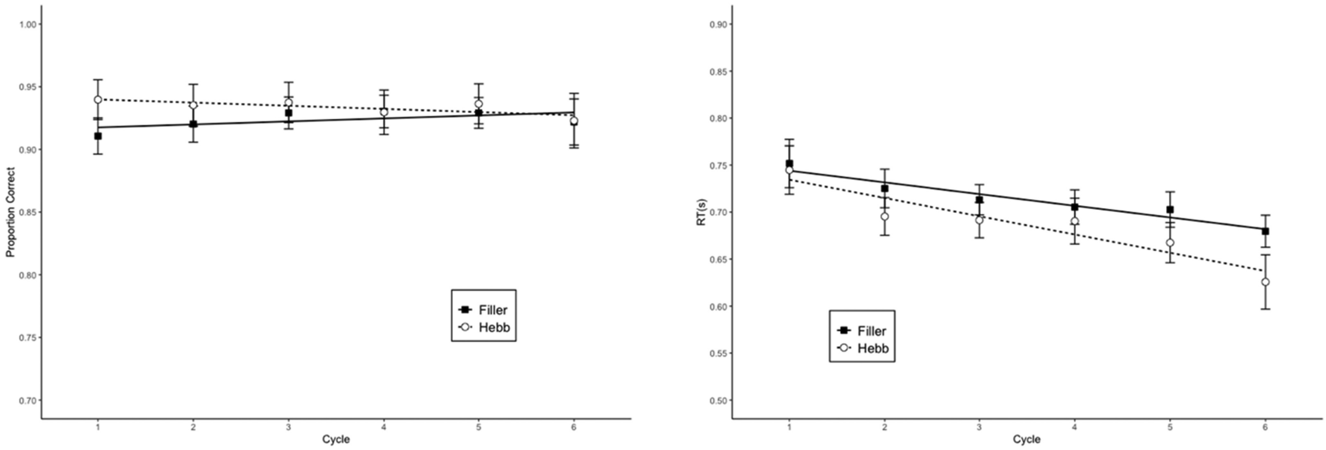
Materials

The same materials as in Experiment 1 were used.

Procedure

The same task procedure as in Experiment 1 was followed. The main task was the same as in Experiment 1, but a modification was made on the transfer cycle. The sample was divided into two groups, for one, only the odd positions (i.e., 1–3–5–7) of the repeated list were repeated, and for the other group, only the even positions (i.e., 2–4–6–8) were repeated in order to measure learning transfer from a complex span task to a partially repeated simple span task.

Figure 3
Performance in the Letter Case Judgement Task in Experiment 1

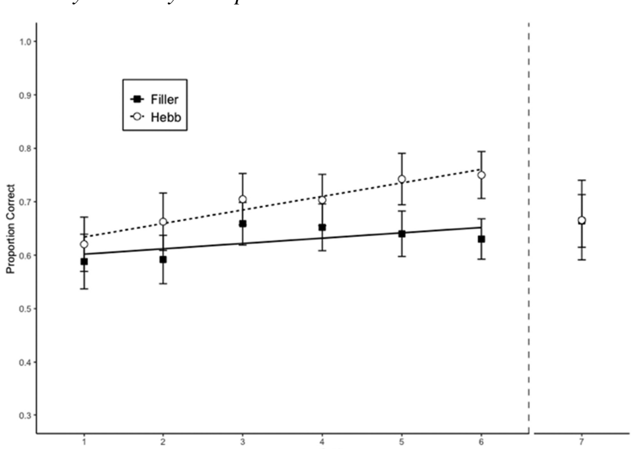


Note. Left: Accuracy. Right: Response time. Error bars are 95% CIs for within-subject comparisons. The straight lines are regression lines estimated from fitting a linear model. CIs = confidence intervals.

Data Analysis

We analyzed the data as in Experiment 1. Although the sample was divided in two, the main task was identical for both groups. Therefore, we combined the two groups. For the transfer cycle, we obtained the average of the accuracy only from the repeated list positions. The total sample was 83 subjects (44 female and 39 male) with ages ranging between 18 and 30 years old ($M =$ 26.37).

Figure 4
Memory Accuracy in Experiment 2



Note. Error bars are 95% CIs for within-subject comparisons (Bakeman & Mcarthur, 1996). The CIs can be interpreted in terms of classical null-hypothesis tests for pair-wise comparisons between data points: Two means differ significantly ($p < .05$) when their CIs overlap by less than 50% of the interval between each mean and the corresponding CI boundary (G. Cumming & Finch, 2005). The straight lines are regression lines estimated from fitting a linear model (Cycles 1–6); Cycle 7 corresponds to the transfer cycle. CIs = confidence intervals.

Results

Memory Accuracy

Figure 4 shows the proportion of correct responses by cycle and repetition. Table 1 summarizes the BFs reflecting the strength of evidence for the main effects and the interaction. The analysis showed ambiguous evidence for the interaction and strong evidence for both main effects of repetition and cycle. As explained in the context of Experiment 1, the main effect of repetition is sufficient evidence for Hebb repetition learning. The mean of the posterior effect of repetition was .06 with a 95% credible interval of .04–.09. Based on these results, we can say that the Hebb effect increases memory performance in a complex span task by 4–9 percentage points over six list repetitions.

Letter Case Judgment Performance

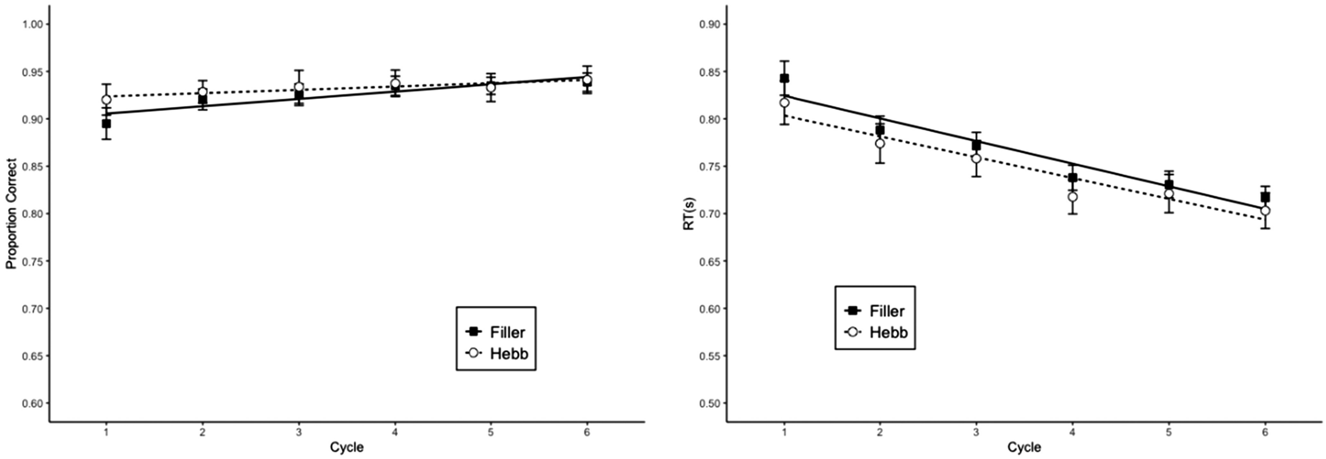
The BFs are shown in Table 1, and the proportion of correct answers and RTs are presented in Figure 5. There was strong evidence for the main effect of cycle on the accuracy and RTs; and substantial evidence for the main effect of repetition on the RTs.

Transfer Trials Performance

Memory accuracy in the transfer trials was scored as the proportion of letters recalled in their correct within-list position. In this case, only the repeated positions were taken into account for the analysis, that is, odd positions for the odd-transfer group and even positions for the even-transfer group. We tested the hypothesis that the cumulative learning from the Hebb effect in the complex span task can be transferred to a partially repeated simple span task. Cycle 7 of Figure 4 shows the proportion of correct answers by repetition. A Bayesian paired-samples t test showed weak evidence in favor of the null hypothesis that there is no difference between the Hebb and the filler lists, $BF_{10} = 0.34$ (means: Filler = .66 and Hebb =.66).

Figure 5

Performance in the Letter Case Judgement Task in Experiment 2



Note. Left: Accuracy. Right: Response time. Error bars are 95% CIs for within-subject comparisons. The straight lines are regression lines estimated from fitting a linear model. CIs = confidence intervals.

Discussion

The results of the present experiment show that Hebb repetition learning that occurs in complex span tasks cannot be transferred to a simple span task where only every other item is repeated, in both odd and even position repetitions. Those results are against the hypothesis that the Hebb effect in complex tasks arises mainly from learning of individual position–item associations, which can transfer to a simple span task (see Experiments 2–4 of Araya et al., 2022). Such position–item associations should be transferable individually to a partially repeated simple span task. The results indicate that the representation learned during the complex span task is not useful when the list is only partially repeated in a simple span task, similar to an experiment by N. Cumming et al. (2003) where they could not find a transfer effect from a fully repeated list to one were only the odd or even positions remained the same. Finding strong evidence for the Hebb effect and weak evidence against an effect of repetition in the transfer cycle suggest that the learning mechanism behind the Hebb effect in complex span tasks is not the strengthening of individual position–item associations. Still, so far this conclusion rests on only one experiment with one transfer cycle, with weak evidence. Further experiments are necessary to draw stronger conclusions.

Experiment 3

The results from Experiment 2 revealed no learning transfer from a complex span task to a partially repeated simple span task, which indicates that individual position–item association might not be the dominant mechanism underlying the Hebb effect in complex span tasks. In order to confirm those findings, we developed an experiment where the main task was a partially repeated complex span task with a transfer cycle to a partially repeated simple span task. That way both tasks would have the same partial-repetition structure.

If Hebb repetition learning in complex span relied on learning individual position–item associations, learning should occur, leading to an increase in recall performance on the repeated items versus the filler items. On the contrary, if there is no evidence of repetition learning, it would point to a different learning mechanism, perhaps chunking.

Method

Participants

One hundred twenty volunteers (divided into two equal groups) recruited via Prolific AC took part in a single 40-min session in exchange for £8. The inclusion criteria were the same as in Experiment 1. The total sample was 43 participants (23 female and 20 male) between 18 and 30 years old ($M = 23.90$) for the odd group; and 38 participants (17 female and 21 male) between 18 and 30 years old ($M = 25.34$) for the even group. Participants gave informed consent prior to the experiment.

Materials

The same materials as in Experiment 1 were used.

Procedure

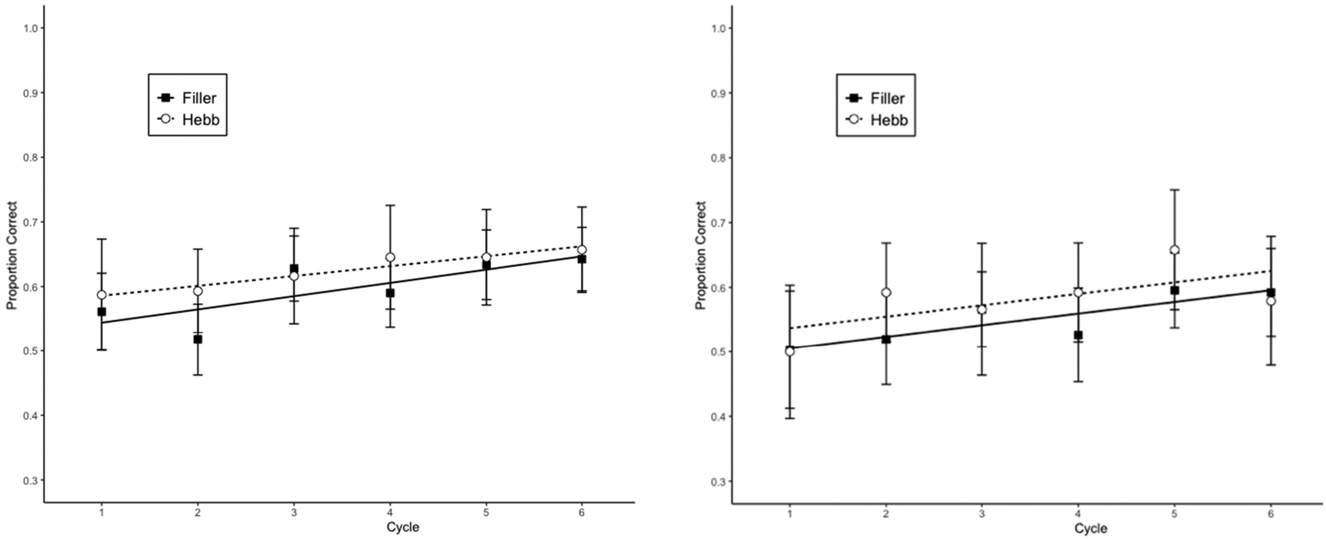
The same task procedure as in Experiment 1 was followed, with a modification on both the main task and the transfer cycle. The sample was divided into two groups, each with a type of partial repetition. For one group (odd repetition group), only the odd positions (i.e., 1–3–5–7), instead of the full list, were repeated every third trial, and for the other group (even repetition group), the repetition comprised only the even positions (i.e., 2–4–6–8). This extended to the transfer cycle as well, except without the distractor task in between each memory item. The data were analyzed in the same way as in Experiment 1, taking into account only the repeated positions.

Results

Memory Accuracy

Figure 6 shows the proportion of correct responses by cycle and repetition for the odd and even repetition groups. Table 1

Figure 6
Memory Accuracy in Experiment 3 Odd (Left) and Even (Right)



Note. Error bars are 95% CIs for within-subject comparisons (Bakeman & Mcarthur, 1996). The CIs can be interpreted in terms of classical null-hypothesis tests for pair-wise comparisons between data points: Two means differ significantly ($p < .05$) when their CIs overlap by less than 50% of the interval between each mean and the corresponding CI boundary (G. Cumming & Finch, 2005). The straight lines are regression lines estimated from fitting a linear model (Cycles 1–6). CIs = confidence intervals.

summarizes the BFs reflecting the strength of evidence for the main effects and the interaction. The analysis showed no interaction and no main effect of repetition for either group, implying that the Hebb effect did not occur in this experimental condition. There was a strong main effect of cycle for the odd group and a weak effect of cycle for the even group, which indicates a change in the memory accuracy across cycles; however, that change is not due to the repetition of some position–item associations. The means of the posterior effect of repetition were .02 for both groups, with a 95% credible interval of −.07 to .06 for the odd group and −.01 to .07 for the even group. Based on these results, we can say that there is no effect of partial list repetition over memory performance across six trials of a complex span task.

Given that the results showed strong evidence of the absence of Hebb effect, the distractors and transfer cycle analysis will not provide any relevant information; therefore, we do not include those results here.

Discussion

In Experiment 3, there was no evidence of learning when only the items in odd or even positions were repeated. The results confirmed that the Hebb effect cannot occur when the list is only partially repeated in a complex span task, similar to what Hitch et al. (2005) found in an immediate serial recall task.

Experiments 2 and 3 are the first concrete evidence of the underlying mechanism in complex span tasks being the same as in simple span tasks. It seems like the distractor tasks are not affecting the Hebb effect whatsoever. If that is the case, the Hebb effect should be transferable from a simple to a complex span task because the representation should be the same in both cases. Experiments 4a and 4b were designed to pursue that hypothesis.

Experiments 4a and 4b

Based on the assumption that the Hebb effect rests on chunking in simple span, but on position–item associations in complex span, we predicted an asymmetry in the transfer effect. The position–item associations obtained through complex span Hebb repetition learning could be useful also in a simple span task, as immediate serial order memory is supported by position–item associations (see, Saito et al., 2020). By contrast, the chunks learned in a simple span task could not be used in a complex span task because the sequence is interrupted by the distractors. However, having found no transfer from a complex span to a partial simple span task (Experiment 2) and no evidence of Hebb repetition learning in a partial complex span task (Experiment 3), it appears that the learning mechanism in complex span might not be position–item associations. Rather, the same learning mechanism is likely to operate in the two paradigms. If that is the case, transfer from simple span to complex span would be possible.

Experiments 4a and 4b had as an objective to gather evidence to confirm or refute that hypothesis with the use of two different distractor tasks. The letter case judgment task is less demanding than the rhyme judgment task. If the strength with which the distractors are encoded into working memory depends on the amount of cognitive work to be carried out on the distractors—and with it, the time spent on processing the distractors—then the rhyme judgment task would make it more challenging for the participants to remove the distractors from working memory (Oberauer et al., 2012), and more generally, to exclude them from the formation and retrieval of chunks in LTM. Therefore, a harder distractor task that demands longer cognitive engagement might make a transfer from simple span to complex span more challenging. We, therefore, ran the experiment with both distractor tasks for generality. Finding the same results with both types of tasks would make a more compelling case.

Method

Participants

Sixty volunteers recruited in each Experiments 4a and 4b via Prolific AC took part in a single 40-min session in exchange for £8; the inclusion criteria were the same as in Experiment 1. The total sample was 52 participants (25 female and 27 male) with ages between 18 and 30 years ($M = 24.48$) for Experiment 4a; and 53 participants (27 female and 26 male) with ages ranging between 18 and 30 years old ($M = 25.13$) for Experiment 4b. Participants gave informed consent prior to the experiment.

Materials

The memory list for Experiments 4a and 4b was constructed using the same materials as in Experiment 1. The distractor task used for the transfer cycles in Experiment 4a was letter case judgment, as in Experiment 1. In Experiment 4b, we used a rhyme judgment task, following Jarrold et al. (2010) procedure: Letter pairs were created from the following 12 letters (always presented in uppercase): A, C, D, E, G, I, J, K, P, T, V, Y. The pairs could rhyme (i.e., C–D) or not rhyme (i.e., A–P) and were selected at random on every trial.

Procedure

The task consisted of 18 trials. The encoding phase followed a typical simple span procedure; participants were required to remember a list of eight consonants. Each trial started with a fixation cross that lasted 3 s, followed by the first consonant (memory item) displayed centered and in red for 1.5 s, immediately replaced by the following memory item until eight had been presented. The recall phase began with a red question mark prompting participants to type the letters in the same order as presented. The entered letter was shown on the screen for 0.3 s, followed by a red question mark and so on until the eight letters were recalled; omissions were not allowed. To begin the next trial, participants had to click on a "continue" button, giving opportunity to take a break if necessary. The same list of consonants was repeated every third trial. To measure learning transfer from a simple span to a complex span task, the transfer cycle for this experiment was a complex span task. The procedure was the same as in the main task except that each memory item was interleaved by two distractors stimuli, following the procedure explained in Experiment 1. Letter case judgment stimuli were used in Experiment 4a and rhyme judgment stimuli in Experiment 4b. Considering that the transfer cycles would start immediately after the main task, the participants had the chance to familiarize themselves with the complex span task before starting the experiment, in a practice phase with six complex span trials each with a list length of four items.

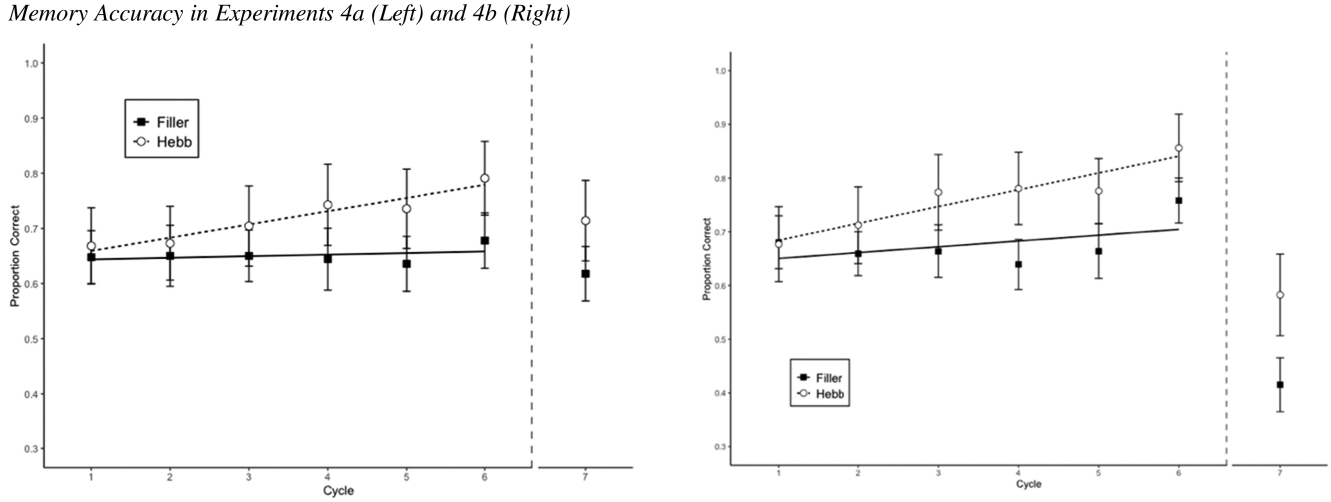
The data were analyzed following the same procedure as in Experiment 1.

Results

Memory Accuracy

Figure 7 shows the proportion of correct responses by cycle and repetition for Experiments 4a and 4b, respectively. Table 1 summarizes the BFs reflecting the strength of evidence for the main effects and the interaction. For both experiments, the interaction between cycle and repetition was not supported. Experiment 4a showed a strong main effect of repetition but not cycle. Experiment 4b showed a strong main effect of cycle and repetition. The mean of the posterior effect of repetition was as follows: Experiment 4a, 0.06 with a 95% credible interval of 0.03–0.10; Experiment 4b, 0.08 with a 95% credible interval of 0.05–0.11. Hence, Hebb repetition learning increases memory performance in a simple span task by 3–11 percentage points over six list repetitions.

Figure 7
Memory Accuracy in Experiments 4a (Left) and 4b (Right)



Note. Error bars are 95% CIs for within-subject comparisons (Bakeman & Mcarthur, 1996). The CIs can be interpreted in terms of classical null-hypothesis tests for pair-wise comparisons between data points: Two means differ significantly ($p < .05$) when their CIs overlap by less than 50% of the interval between each mean and the corresponding CI boundary (G. Cumming & Finch, 2005). The straight lines are regression lines estimated from fitting a linear model (Cycles 1–6); Cycle 7 corresponds to the transfer cycle. CIs = confidence intervals.

Transfer Trials Performance

Memory accuracy in the transfer trials was scored as the proportion of letters recalled in their correct within-list position. We tested the hypothesis that the cumulative learning from the Hebb effect in a simple span task can be transferred to a complex span task. Cycle 7 of Figure 7 shows the proportion of correct answers by repetition. A Bayesian paired-samples *t* test showed strong evidence for a difference between the means of the repeated and the filler lists, 4a: $BF_{10} = 15.08$ (means: Filler = .61 and Hebb = .71); 4b: $BF_{10} = 275.06$ (means: Filler = .41 and Hebb = .58).

Discussion

We found evidence of learning transfer from a simple span to a complex span task in both experimental conditions. Experiments 4a and 4b are the first ones to provide evidence of this type of learning transfer. These results suggest that the chunk representation created along the simple span task is still useful when facing a complex span task with either semantic or phonological distractor tasks. The results contrast with those of N. Cumming et al. (2003), who found that Hebb repetition learning did not transfer to a list in which only every second item was repeated. When we transfer from simple to complex span, only every second event in the complex span sequence (i.e., every item) is repeated. We conclude that the not-repeated distractors in a complex span task are functionally different from interleaved not-repeated list items. They appear to be excluded when learning a repeated list (Experiments 1 and 2, and Araya et al., 2022) and to be ignored when already acquired knowledge of a repeated list is applied to another repetition of that list (Experiments 4a and 4b). In Experiment 5, we investigate the role of distractors in Hebb repetition learning directly.

Experiment 5

Experiments 1–4 left us with an unanswered question: How are distractors in a complex span task being processed? Therefore, the objective of this experiment was to understand the role of the distractors in Hebb repetition learning in a complex span task. It appears that they are being processed differently from nonrepeated items in a partially repeated list of a simple span task. Are they being excluded completely from the LTM representation of a list and from the comparison of new lists to LTM representations of previous lists? If that is the case, distractors should not have any influence on the Hebb repetition learning.

To test that prediction, we created three conditions in which both the main task and transfer cycles consisted of complex span tasks. In the *item-repetition* condition, only the to-be-remembered items of the Hebb lists were repeated, but distractor stimuli were randomly selected in the main task (i.e., the learning phase was exactly the same as Experiment 1), and the transfer cycles were just a continuation of the main task, that is, a complex span task. In the *item-distractor-repetition* condition, the Hebb list repeated the to-be-remembered list with the exact same distractors in between each item, and in the transfer cycles, the distractors were random (i.e., only the memory items were repeated). The *distractor-repetition* condition had a Hebb list in which only the distractors were repeated, and in the transfer cycles, both items and distractors were selected at random.

We hypothesized that if the distractors are also part of the LTM representation of the repeated lists, then when the distractors are repeated, we should see improved list recall, and better performance in the distractor task, compared to the *item-repetition* condition in which only list items could be learned. Moreover, we predicted a drop in performance in the transfer cycle in which only the memory items were repeated. Following the same assumption, in a condition where only the distractors are repeated, we might also find some benefit to the memory list accuracy, or at least to distractor performance.

Method

Participants

One hundred eighty volunteers recruited via Prolific AC took part in a single 40-min session in exchange for £8; the inclusion criteria were the same as in Experiment 1.

The total sample was 128 participants divided into three conditions: the *item-repetition* condition had 42 participants (15 female and 27 male) ages between 18 and 30 years old ($M = 24.45$); the *item-distractor-repetition* condition had 45 participants (17 female and 28 male) with ages between 18 and 30 years old ($M = 24.91$); and the *distractor-repetition* condition had 41 participants (27 female and 14 male) with ages between 18 and 30 years old ($M = 24.85$). Participants gave informed consent prior to the experiment.

Materials

The same materials as in Experiment 1 were used.

Procedure

The procedure was nearly the same as Experiment 1. However, there were three experimental conditions, each with a different type of repetition and two (rather than one) transfer cycles. That is (a) *item-repetition* condition: The same memory items sequence was repeated every third trial and the transfer cycles continued the same way; (b) *item-distractor-repetition* condition: Both the memory items and distractors were repeated every third trial, the transfer cycles repeated only the memory items; and (c) *distractor-repetition* condition: Only the distractors were repeated every third trial, the transfer cycles had no repetition.

Data Analysis

As in the previous experiments, we analyzed the data with Bayesian linear regression models using the *lmBF* function in the BayesFactor package (Morey & Rouder, 2018) for R (R Core Team, 2020) using the default settings for priors. The Bayes factors for the main effect of repetition and cycle and their interaction in each experimental condition are summarized in Table 3. Additionally, to assess the effects of each experimental condition, we created two orthogonal contrasts. Contrast 1 compared the distractor-repetition condition to the mean of the *item-repetition* and *item-distractor-repetition* conditions; Contrast 2 compared the *item-repetition* condition to the item-distractors repetition conditions. We then proceeded to estimate a full model, including all main effects (i.e., Contrast 1, Contrast 2, Cycle, and Repetition); all two-way interactions (i.e., Contrast 1 × Repetition, Contrast 2 × Repetition, Contrast 1 × Cycle, and Contrast 2 × Cycle); and all three-way interactions (i.e., Contrast 1 × Cycle × Repetition and Contrast 2 × Cycle × Repetition).

Table 3
Experiment 5: Bayes Factors for the Linear Models

Effects	Item-repetition	Item-distractor-repetition	Distractor-repetition
	Memory accuracy		
Cycle	1.88	933.70	0.10
Repetition	1.58×10^6	4.15×10^3	0.10
Cycle × Repetition	0.39	6.53	0.40
	Letter case judgment accuracy		
Cycle	0.59	1.49	19.61
Repetition	0.09	0.46	0.15
Cycle × Repetition	0.52	0.15	0.16
	Letter case judgment RT		
Cycle	3.45×10^{16}	1.18×10^{18}	4.64×10^7
Repetition	3.30×10^3	2.43×10^4	5.33
Cycle × Repetition	0.11	0.39	0.74

We compared that full model to a progression of reduced models created by eliminating the first one of the three-way interactions, then the other, and so on, always keeping the best model for comparison. The Bayes factors for the main effects of these contrasts, their interactions with cycle and repetition, and the three-way interactions are shown in Table 4.

Results

Memory Accuracy

Figure 8 shows the proportion of correct responses by cycle and repetition for Experiment 5 in each condition. Table 3 summarizes the BFs reflecting the strength of evidence for the main effects and the interaction. In the *item-repetition* condition, there was ambiguous evidence toward a main effect of the cycle and an interaction, and the model including repetition had very strong evidence. In the *item-distractor-repetition* condition, every main effect and interaction had very strong evidence. Finally, the *distractor-repetition* condition did not yield evidence for any main effect; rather, evidence was strong in favor of the null model. The mean of the posterior effect of repetition can be seen in Table 2. Conditions *item-repetition* and *item-distractor-repetition* had a comparable effect size; in the *distractor-repetition* condition, there was no effect on memory performance.

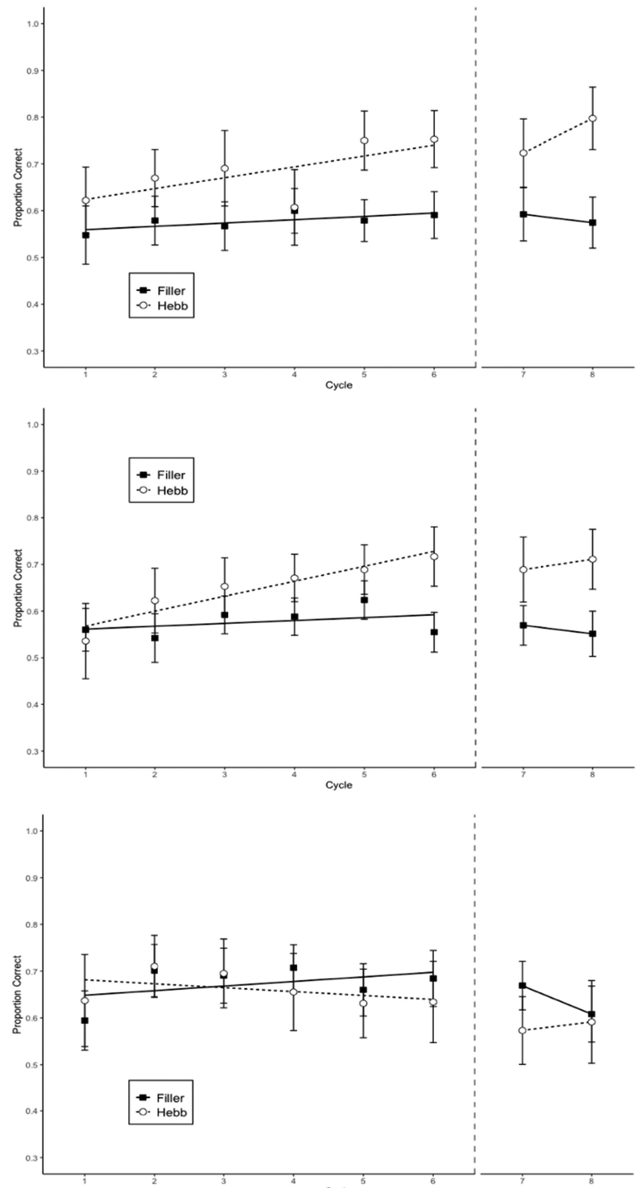
Letter Case Judgment Performance

The BFs are shown in Table 3, and the proportion of correct answers and RTs are presented in Figure 9. As for the distractor task accuracy, *item-repetition* and *item-distractor-repetition* conditions had similar results, showing no evidence for any of the main effects and interaction. In the *distractor-repetition* condition, there was strong evidence toward a main effect of the cycle, but against an effect of repetition and the interaction.

Table 4
Experiment 5: Bayes Factors for Contrasts

Effects	Memory accuracy
Contrast 1	0.59
Contrast 2	0.42
Contrast 1 × Repetition	4.86×10^3
Contrast 2 × Repetition	0.23
Contrast 1 × Cycle	4.70
Contrast 2 × Cycle	0.17
Contrast 1 × Cycle × Repetition	15.40
Contrast 2 × Cycle × Repetition	0.21

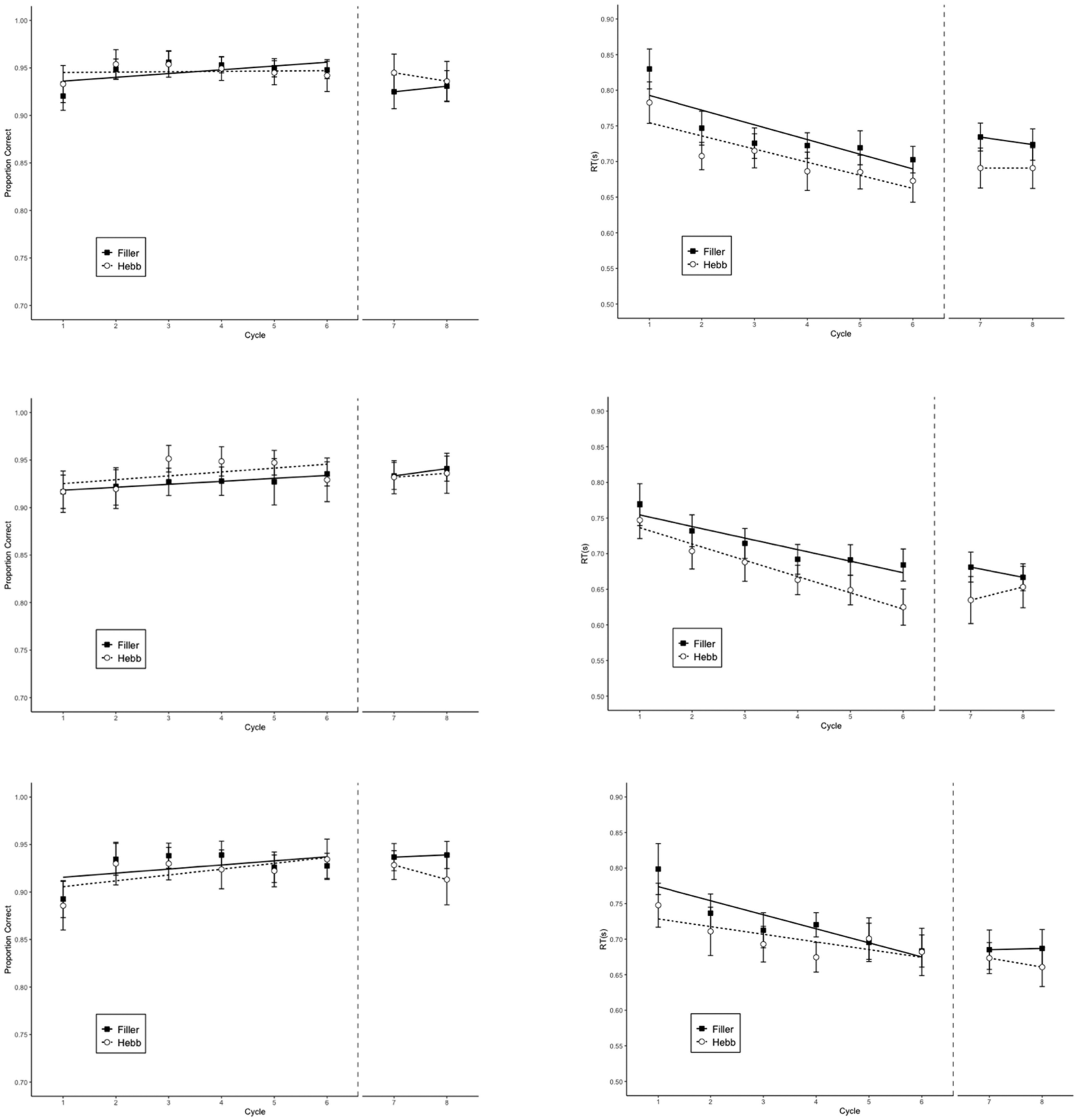
Figure 8
Memory Accuracy in Experiment 5: Item-Repetition (Top), Item-Distractor-Repetition (Middle), and Distractor-Repetition (Bottom)



Note. Error bars are 95% CIs for within-subject comparisons (Bakeman & Mcarthur, 1996). The CIs can be interpreted in terms of classical null-hypothesis tests for pair-wise comparisons between data points. Two means differ significantly ($p < .05$) when their CIs overlap by less than 50% of the interval between each mean and the corresponding CI boundary (G. Cumming & Finch, 2005). The straight lines are regression lines estimated from fitting a linear model (Cycles 1–6); Cycles 7 and 8 correspond to the transfer cycles. CIs = confidence intervals.

Figure 9

Performance in the Letter Case Judgement Task in Experiment 5: Item-Repetition (Top), Item-Distractor-Repetition (Middle), and Distractor-Repetition (Bottom)



Note. Error bars are 95% CIs for within-subject comparisons. The straight lines are regression lines estimated from fitting a linear model. CIs = confidence intervals.

For the RTs, again, *item-repetition* and *item-distractor-repetition* had similar results, with no evidence for an interaction but very strong evidence for the main effect of cycle and repetition. The *distractor-repetition* condition also showed no evidence for an interaction, substantial evidence for the main effect of repetition, and very strong evidence for the main effect of cycle.

Table 5
Experiment 5: Means and Bayes Factors for the Paired t *Tests on Transfer Trials*

Condition	Means (Filler, Hebb)	Bayes factors
Item-repetition	.58, .76	325.17
Item-distractor-repetition	.59, .70	29.47
Distractor-repetition	.63, .58	2.10

Transfer Trials Performance

Memory accuracy in the transfer trials was scored as the proportion of letters recalled in their correct within-list position. Cycles 7 and 8 of Figure 8 represent the two transfer cycles. The transfer cycle performance was analyzed independently for each condition, as they served to test different predictions. We tested whether there is a difference between Hebb and Filler lists for each condition. Bayesian paired-samples *t* test was used for each comparison. The means and BFs can be found in Table 5. The results showed very strong evidence of a difference between Filler and Hebb lists in *item-repetition* and *item-distractor-repetition*. As for the *distractor-repetition* condition, we did not expect any difference because there was no Hebb effect, and the results support that.

Discussion

Repeating both the memory items and distractors, as in the *item-distractor-repetition* condition, did not make the Hebb effect larger than in a condition repeating only the memory items. Additionally, when only the distractors were repeated, there was no repetition effect for memory and very little for distractor performance. The transfer cycles analysis shows no difference between *item-repetition* and *item-distractor-repetition*. If distractors were included in the LTM representation of Hebb lists, we expected that in a condition where both memory items and distractors are repeated and in the transfer cycle only the memory items were repeated, with random distractors, we would not find a transfer effect because the learned representation would not match the new one. However, we could still find strong evidence of both Hebb and transfer effects.

The results of Experiment 5 imply that distractors are excluded from the LTM trace of memory lists. One way in which this can be accomplished is by removing distractors from working memory (Oberauer et al., 2012) before the formation of a LTM representation.

General Discussion

The present experiments provide the first evidence that the mechanism underlying the Hebb effect in complex span tasks is the same as in simple span tasks. These findings speak against a positional account of the Hebb effect in complex span tasks and against our previous proposal that participants employ differential learning mechanisms for simple and complex span tasks (Araya et al., 2022).

We set out to test three predictions from our hypothesis that Hebb repetition learning in complex span relies on strengthening individual position–item associations. All three predictions were refuted by our findings: (a) The learning acquired during a complex span task could not be transferred to a simple span task list where only every second item was repeated (Experiment 2); (b) only partially repeating a list in a complex span task did not lead to Hebb repetition learning (Experiment 3); and (c) learning during repetition in a simple span task could be transferred to a complex span task (Experiments 4a and 4b).

Our results suggest that the representations created in both simple and complex span tasks are virtually equivalent. The long-term representations created through Hebb repetition learning in complex span tasks appear to be unified representations of the memory items, excluding the distractors. The exclusion of distractors was demonstrated directly by our finding that repeating the distractors in addition to the items did not affect the Hebb effect (Experiment 5).

The two most prominent computational models on sequence learning are the Burgess and Hitch (2006) revised model and the primacy model by Page and Norris (2009). Both models explain the Hebb effect in terms of a cumulative matching process. The former does so via position–item associations that create LTM representations of each list with its own context set; the latter via a primacy gradient of association strengths of items to novel chunks. Even though the Burgess and Hitch (2006) model is not strictly a chunking model, we believe that what the authors refer to as context sets strongly resemble what Page and Norris (2009) refer to as chunks. In both cases, it is a unified representation of an entire list that is learned and retrieved as a whole.

To the best of our knowledge, no computational model that can explain Hebb repetition learning has done so with distractor stimuli (i.e., complex span tasks). Therefore, at this point, it is not possible to apply a computational model to explain the Hebb effect in complex span tasks, we can only hypothesize.

The results of the present study can be easily explained by the cumulative matching process assumed in both of these models. That is, partial repetition does not produce Hebb repetition learning because the cumulative matching process is interrupted; learning transfer from a fully repeated to a partially repeated sequence again does not occur because the cumulative matching process in the transfer trial is interrupted by the random memory items. What cannot be explained without extensions of the existing models is the part played by distractors processing.

The simplest way of applying current models of the Hebb effect to complex span is to assume that the distractors are not being encoded into working memory. This is unlikely, however, in light of evidence that distractor items are not only encoded but compete with memory items at recall (Oberauer & Lewandowsky, 2016, 2019). Another option could be that memory items and distractors are represented as two separate sequences or streams (Farley et al., 2007; D. Jones et al., 1999; D. M. Jones & Macken, 1995), and each sequence is encoded into LTM as a separate chunk. However, that would only explain the results of experiments in which only the memory items were repeated, that is, the cumulative matching process would work for the to-be-remembered items but not for the distractors. In a condition where the distractors are repeated (Experiment 5), we would expect to have seen some improvement in the distractor task accuracy, which was not the case.

A third explanation, which we find most promising, builds on the assumption that distractors are rapidly removed from working memory after they have been processed. In this way, they could be excluded from the formation of a chunk representing the memory list, and they could also be excluded from the representation of each new list that builds up in working memory and is being compared to chunks in LTM in the cumulative matching process. Recent work suggests that the removal of no-longer relevant representations from working memory is fairly rapid (Dames & Oberauer, 2022; Oberauer, 2019; Oberauer & Lewandowsky, 2019). Therefore, it is conceivable that distractors are largely removed from working memory before an LTM trace is formed on the basis of the remaining representation of the memory list in working memory.

Our results might appear to contrast with those of Hitch et al. (2005), demonstrating no Hebb repetition learning when the repeated memory items were interleaved with nonrepeated items, and those of N. Cumming et al. (2003) where a learned Hebb list showed no transfer to a list in which only every second item matched the learned list. However, there is a key difference between those studies and ours, that is whether the interleaved not-repeated events are memory items (in the earlier studies) or distractors (in our experiments). Given that memory items and distractors were the same kind of stimuli—letters—in our experiments, that difference boils down to participants knowing that the distractors will not have to be remembered. Future studies could investigate at which point in time participants need to know which stimuli in a sequence they need to remember and which they can forget in order to exclude the to-be-forgotten stimuli from the LTM representation that builds up in Hebb repetition learning.

Conclusion

The creation of LTM traces by Hebb repetition learning occurs through the same mechanism in both simple and complex span tasks. This mechanism is likely to be the acquisition of a chunk that represents the memory items in their correct order but excludes the distractors.

References

Araya, C., Oberauer, K., & Saito, S. (2022). The Hebb repetition effect in complex span tasks: Evidence for a shared learning mechanism with simple span tasks. *Memory & Cognition*, *50*(5), 925–940. https://doi.org/10.3758/s13421-021-01261-3

Bakeman, R., & Mcarthur, D. (1996). Picturing repeated measures: Comments on Loftus, Morrison, and others. *Behavior Research Methods, Instruments & Computers*, *28*(4), 584–589. https://doi.org/10.3758/BF03200546

Burgess, N., & Hitch, G. J. (2006). A revised model of short-term memory and long-term learning of verbal sequences. *Journal of Memory and Language*, *55*(4), 627–652. https://doi.org/10.1016/j.jml.2006.08.005

Couture, M., & Tremblay, S. (2006). Exploring the characteristics of the visuospatial Hebb repetition effect. *Memory & Cognition*, *34*(8), 1720–1729. https://doi.org/10.3758/BF03195933

Cumming, G., & Finch, S. (2005). Inference by eye confidence intervals and how to read pictures of data. *American Psychologist*, *60*(2), 170–180. https://doi.org/10.1037/0003-066X.60.2.170

Cumming, N., Page, M., & Norris, D. (2003). Testing a positional model of the Hebb effect. *Memory*, *11*(1), 43–63. https://doi.org/10.1080/741938175

Dames, H., & Oberauer, K. (2022). Directed forgetting in working memory. *Journal of Experimental Psychology: General*, *151*(12), 2990–3008. https://doi.org/10.1037/xge0001256

de Leeuw, J. R. (2015). Jspsych: A JavaScript library for creating behavioral experiments in a web browser. *Behavior Research Methods*, *47*(1), 1–12. https://doi.org/10.3758/s13428-014-0458-y

Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. *Frontiers in Psychology*, *5*, Article 781. https://doi.org/10.3389/fpsyg.2014.00781

Farley, L. A., Neath, I., Allbritton, D. W., & Surprenant, A. M. (2007). Irrelevant speech effects and sequence learning. *Memory & Cognition*, *35*(1), 156–165. https://doi.org/10.3758/BF03195951

Hebb, D. O. (1961). Distinctive features of learning in the higher animal. In J. F. Delafresnaye (Ed.), *Brain mechanisms and learning* (pp. 37–46). Blackwell.

Hitch, G. J., Fastame, M. C., & Flude, B. (2005). How is the serial order of a verbal sequence coded? Some comparisons between models. *Memory*, *13*(3-4), 247–258. https://doi.org/10.1080/09658210344000314

Horton, N., Hay, D. C., & Smyth, M. M. (2008). Hebb repetition effects in visual memory: The roles of verbal rehearsal and distinctiveness. *Quarterly Journal of Experimental Psychology*, *61*(12), 1769–1777. https://doi.org/10.1080/17470210802168674

Jarrold, C., Tam, H., Baddeley, A. D., & Harvey, C. E. (2010). The nature and position of processing determines why forgetting occurs in working memory tasks. *Psychonomic Bulletin & Review*, *17*(6), 772–777. https://doi.org/10.3758/PBR.17.6.772

Johnson, A. J., Dygacz, A., & Miles, C. (2017). Hebb repetition effects for non-verbal visual sequences: Determinants of sequence acquisition. *Memory*, *25*(9), 1279–1293. https://doi.org/10.1080/09658211.2017.1293692

Johnson, A. J., & Miles, C. (2019). Visual Hebb repetition effects: The role of psychological distinctiveness revisited. *Frontiers in Psychology*, *10*, Article 17. https://doi.org/10.3389/fpsyg.2019.00017

Jones, D., Alford, D., Bridges, A., Tremblay, S., & Macken, B. (1999). Organisational factors in selective attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(2), 464–473. https://doi.org/10.1037/0278-7393.25.2.464

Jones, D. M., & Macken, W. J. (1995). Phonological similarity in the irrelevant speech effect: Within- or between-stream similarity? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(1), 103–115. https://doi.org/10.1037/0278-7393.21.1.103

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association*, *90*(430), 773–795. https://doi.org/10.1080/01621459.1995.10476572

Majerus, S., & Oberauer, K. (2020). Working memory and serial order: Evidence against numerical order codes but for item–position associations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(12), 2244–2260. https://doi.org/10.1037/xlm0000792

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97. https://doi.org/10.1037/h0043158

Morey, R. D., & Rouder, J. N. (2018). *BayesFactor* (Version 0.9.12-4.2). https://CRAN.R-project.org/package=BayesFactor

Mosse, E. K., & Jarrold, C. (2008). Hebb learning, verbal short-term memory, and the acquisition of phonological forms in children. *Quarterly Journal of Experimental Psychology*, *61*(4), 505–514. https://doi.org/10.1080/17470210701680779

Musfeld, P., Souza, A. S., & Oberauer, K. (2023). Repetition learning is neither a continuous nor an implicit process. *Proceedings of the National Academy of Sciences*, *120*(16), Article e2218042120. https://doi.org/10.1073/pnas.2218042120

Nakayama, M., & Saito, S. (2017). Position-element frequency learning is dissociable from Hebb repetition learning. *Journal of Memory and Language*, *94*, 235–253. https://doi.org/10.1016/j.jml.2016.11.007

Nakayama, M., Tanida, Y., & Saito, S. (2015). Long-term phonological knowledge supports serial ordering in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(5), 1570–1578. https://doi.org/10.1037/a0038825

Oberauer, K. (2019). Working memory and attention—A conceptual analysis and review. *Journal of Cognition*, *2*(1), Article 36. https://doi.org/10.5334/joc.58

Oberauer, K., Farrell, S., Jarrold, C., Pasiecznik, K., & Greaves, M. (2012). Interference between maintenance and processing in working memory: The effect of item-distractor similarity in complex span. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(3), 665–685. https://doi.org/10.1037/a0026337

Oberauer, K., Jones, T., & Lewandowsky, S. (2015). The Hebb repetition effect in simple and complex memory span. *Memory & Cognition*, *43*(6), 852–865. https://doi.org/10.3758/s13421-015-0512-8

Oberauer, K., & Lewandowsky, S. (2016). Control of information in working memory: Encoding and removal of distractors in the complex-span paradigm. *Cognition*, *156*, 106–128. https://doi.org/10.1016/j.cognition.2016.08.007

Oberauer, K., & Lewandowsky, S. (2019). Simple measurement models for complex working-memory tasks. *Psychological Review*, *126*(6), 880–932. https://doi.org/10.1037/rev0000159

Page, M. P. A., Cumming, N., Norris, D., McNeil, A. M., & Hitch, G. J. (2013). Repetition-spacing and item-overlap effects in the Hebb repetition task. *Journal of Memory and Language*, *69*(4), 506–526. https://doi.org/10.1016/j.jml.2013.07.001

Page, M. P. A., & Norris, D. (2008). Is there a common mechanism underlying word-form learning and the Hebb repetition effect? Experimental data and a modelling framework. In A. Thorn & M. Page (Eds.), *Interactions between short-term and long-term memory in the verbal domain* (pp. 136–156). Psychology Press.

Page, M. P. A., & Norris, D. (2009). A model linking immediate serial recall, the Hebb repetition effect and the learning of phonological word forms. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1536), 3737–3753. https://doi.org/10.1098/rstb.2009.0173

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rouder, J. N., Engelhardt, C. R., McCabe, S., & Morey, R. D. (2016). Model comparison in ANOVA. *Psychonomic Bulletin & Review*, *23*(6), 1779–1786. https://doi.org/10.3758/s13423-016-1026-5

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology*, *56*(5), 356–374. https://doi.org/10.1016/j.jmp.2012.08.001

Saito, S., Nakayama, M., & Tanida, Y. (2020). Verbal working memory, long-term knowledge, and statistical learning. *Current Directions in Psychological Science*, *29*(4), 340–345. https://doi.org/10.1177/0963721420920383

Schwartz, M., & Bryden, M. P. (1971). Coding factors in the learning of repeated digit sequences. *Journal of Experimental Psychology*, *87*(3), 331–334. https://doi.org/10.1037/h0030552

Souza, A. S., & Oberauer, K. (2022). Promoting visual long-term memories: When do we learn from repetitions of visuospatial arrays? *Journal of Experimental Psychology: General*, *151*(12), 3114–3133. https://doi.org/10.1037/xge0001236

St-Louis, M. È., Hughes, R. W., Saint-Aubin, J., & Tremblay, S. (2019). The resilience of verbal sequence learning: Evidence from the hebb repetition effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(1), 17–25. https://doi.org/10.1037/xlm0000566

Sukegawa, M., Ueda, Y., & Saito, S. (2019). The effects of Hebb repetition learning and temporal grouping in immediate serial recall of spatial location. *Memory & Cognition*, *47*(4), 643–657. https://doi.org/10.3758/s13421-019-00921-9

Szmalec, A., Duyck, W., Vandierendonck, A., Mata, A. B., & Page, M. P. A. (2009). The Hebb repetition effect as a laboratory analogue of novel word learning. *Quarterly Journal of Experimental Psychology*, *62*(3), 435–443. https://doi.org/10.1080/17470210802386375

Szmalec, A., Page, M. P. A., & Duyck, W. (2012). The development of long-term lexical representations through Hebb repetition learning. *Journal of Memory and Language*, *67*(3), 342–354. https://doi.org/10.1016/j.jml.2012.07.001

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