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Determining the developmental requirements for Hebb repetition learning in young children: Grouping, short-term memory, and their interaction

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Abstract

The Hebb repetition paradigm has recently attracted attention as a measure of serial order learning, which underlies word-form learning abilities. Although children are good vocabulary learners, it is surprising that previous Hebb learning studies with young children show rather weak Hebb effects. In this study, we conducted two experiments to identify developmental factors that drive an increase of the size of the Hebb effect in young children. Motivated by evidence from adult work, we focused on an ability to group a sequence into consistent subsequences and on phonological short-term memory (STM) capacity. In Experiment 1 (*N* = 98), it was shown that 3- to 5-year-old children with high phonological STM capacity showed a Hebb effect, particularly in the later experimental trials. In Experiment 2 (*N* = 97), temporal grouping of the sequences in 2-2 subsequences further encouraged children with high phonological STM capacity to show the Hebb effect even in the earlier experimental trials and children with low STM capacity to show a trend towards a Hebb effect in the later trials. Moreover, across Experiments 1 and 2 we found robust evidence of transfer of the Hebb effect to recall of new sequences that partially overlapped in item-by-item pairings with the Hebb sequence, indicating that children use consistent grouping strategies when learning above-span Hebb sequences. These findings indicate that phonological STM, grouping consistency, and their interaction are developmental requirements for the Hebb effect to emerge.

Key words: Hebb repetition learning, temporal grouping, phonological short-term memory, preschoolers

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Introduction

Phonological short-term memory (STM) – an ability to temporarily retain a phonological sequence – plays a crucial role in learning a novel phonological word-form (Baddeley, Gathercole, & Papagno, 1998). As each word consists of a limited set of elements (e.g., phonemes), retention of the order of those constituent element is a key requirement for novel word-form learning, where repeated short-term retention of a novel word-form leads to consolidation into long-term memory (LTM). To date, many developmental studies have explored the precise nature of the association between phonological STM and language development (Gathercole, Hitch, Service, & Martin, 1997; Gathercole, 2006; Majerus & Boukebza, 2013; Jarrold, Baddeley, Hewes, Leeke, & Phillips, 2004; Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Mosse & Jarrold, 2008). For example, correlational studies have shown an association between STM capacity and vocabulary acquisition, with greater ability to repeat nonwords predicting higher performance on novel word learning tasks in young children (e.g., Gathercole, 2006; but see, Melby-Lervåg et al., 2012).

Hebb Repetition Learning and Its Link to Phonological Word-form Learning

Beyond these correlational studies, the Hebb repetition paradigm (Hebb, 1961) has recently attracted attention as a measure of serial order learning (Archibald & Joanisse, 2013; Hsu & Bishop, 2014; Mosse & Jarrold, 2008; Smalle, Bogaerts, Simonis, Duyck, Page, Edwards, & Szmalec, 2016), leading to the assumption that the Hebb repetition paradigm provides a laboratory analogue of real-life word learning (Mosse & Jarrold, 2008, 2010; Page & Norris, 2009; Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). In a typical Hebb repetition paradigm, participants are instructed to recall two types of sequence in the correct serial order. Unbeknownst to participants, some sequences (Hebb sequences) are repeatedly presented every few trials (e.g., every third trial) and the other sequences (filler sequences) are unique and are each presented once in between these repeated Hebb sequences. Recall performance on Hebb sequences improves substantially across the course of the experiment supporting the notion that repeated maintenance of a sequence leads to learning. In addition, Szmalec et al. (2009, 2012) provide direct evidence for the role of the Hebb effect in word-form learning. For example, Szmalec et al. (2009) required participants to engage in serial recall of nine-syllable sequences where specific three-syllable subsequences were repeated through the serial recall session. Subsequently participants engaged in a lexical decision task and rejected nonwords that took the form of the repeated subsequences from the recall phase more slowly than control nonwords, suggesting a degree of lexical learning of these repeated sequences. In line with this, the degree of Hebb repetition learning in 5- and 6-year-olds has been shown to be related to children's ability to learn novel 'nonword' names of associated objects but not known name associations (Mosse & Jarrold, 2008).

Vocabulary Development and Developmental Studies of Hebb Repetition Learning

Children's vocabulary is slowly accumulated at the beginning of life, but rapidly increases subsequently – at the age of 16 months the typical number of word produced is around 40 words, but by school age children learn about 3000 words each year (Bates et al., 1994; Nagy, Herman, McKeown, & Curtis, 1987). Thus, early childhood is a period when children learn a very large number of novel words. If the Hebb effect plays a critical role in children's vocabulary learning, especially word-form learning, then one would expect the Hebb effect to emerge along with the vocabulary spurt. As far as we know, few studies have examined the Hebb effect in children. Moreover, previous developmental studies of Hebb repetition learning have found weak Hebb effects in children (Archibald & Joanisse, 2013; Bogaerts, Szmalec, Maeyer, Page, & Duyck, 2016; Hsu & Bishop, 2014; Mosse & Jarrold, 2008). For example, Mosse and Jarrold (2008) found that 5- to 6-year-old children showed the Hebb effect only on later experimental trials that occurred in the second-half of their experiment. However, this relatively weak Hebb effect observed in young children seems inconsistent with the evidence of strong new word learning skills seen in early childhood in the vocabulary spurt. Given that the Hebb effect in adults emerges on early experimental trials (e.g., Szmalec et al., 2009), it is possible that there are developmental requirements for strong Hebb effects to emerge, with the development with age of these constraining abilities driving the increase in the size of the Hebb effect across childhood and into adulthood. Thus, we aimed to explore the developmental requirements of Hebb repetition learning by referring to findings from Hebb repetition learning experiments with both adults and children.

Phonological Short-term Memory (STM) and the Hebb Effect

First, we assumed that one requirement for Hebb repetition learning to occur is the development of phonological STM. According to Jones (2012), an individual's performance on a phonological STM task (e.g., a digit span test) reflects the size of chunk they are able to hold in immediate memory. Given that individuals would be expected to rehearse and recall only a subset of to-be-remembered items when required to recall supra-span sequences (Jarrold & Hall, 2013), children with low phonological STM capacity might only maintain a relatively small sized chunk of items at the beginning of the experimental trials and this might then require more repetition for those children to exhibit the same magnitude of the Hebb effect as children with higher phonological STM capacity who might rehearse a larger sized chunk of items[1]. To date, few empirical studies have investigated the relationship between the Hebb effect and individual differences in phonological STM capacity. However, Mosse and Jarrold (2008) found that the degree of Hebb repetition learning was related to children's memory performance for non-repeated filler sequences, which they assumed directly indexed phonological STM. We can therefore infer that an increase in phonological STM capacity might be one of developmental requirements for the growth of the Hebb effect.

Consistent Grouping of the Sequence and the Hebb Effect

The Hebb effect is sensitive to consistency of grouping of sequences (Burgess & Hitch, 1999, 2006; Hitch et al., 2009; Szmalec et al., 2009, 2012). If the Hebb sequence is presented with varying patterns of temporal grouping (i.e., encouraging inconsistent grouping), the learning of the sequence is reduced or even abolished (Hitch et al., 2009). In contrast, if the sequence is grouped into a coherent set of subsequences, such subsequences receive a Hebb repetition benefit even if presented in a varying order within a larger list (Szmalec et al., 2009). In Szmalec et al.'s (2009) study, adult participants were required to recall nine-syllable sequences with longer pauses inserted between the three sets of three-syllable subsequences (e.g., "lo-fo-du, so-wu-jo, le-ki-vi"). Repetition of these coherently grouped subsequences led to a Hebb effect despite the violation of whole-sequence level coherence. Thus, consistently grouped subsequences are subject to Hebb repetition learning, and consistent grouping into subsequences would be a critical factor for the Hebb effect to occur. Although it is unclear how adults segment a presented sequence in the absence of an explicit grouping cue such as temporal pauses, they tend to

[1] Though if children with high phonological STM capacity are able to retain the whole list in a single chunk, the Hebb effect will be hard to detect due to a ceiling effects. In other words, to allow room to find the Hebb effect it is important to use supra-span lists.

spontaneously parse a sequence into one or more different groups (Bower, 1970; Henson, 1996; Kahana & Jacobs, 2000; Farrell, 2012). Given that inconsistent grouping in repeated Hebb sequences disrupts Hebb repetition learning (Hitch et al., 2009), one can infer that adults are *consistently* grouping the repeated sequence despite the fact that sequence length exceeds the typical chunk size of adults. Thus, we can assume that an ability to group a sequence into consistent subsequences across repetitions is another developmental requirement for the growth of the Hebb effect.

The Current Study

Through two experiments, we aimed to test whether the two developmental requirements highlighted above, namely phonological STM capacity and consistent grouping of the sequence, have the potential to enhance the often observed weak Hebb repetition learning in early development. In Experiment 1, we examined the Hebb effect among preschoolers and its relationships with phonological STM. In Experiment 2, we directly investigated the effect of grouping consistency on the Hebb effect by manipulating the temporal structure of sequences. In both experiments, as an indirect measure of consistent grouping, we also tested the transfer of the Hebb effect to the recall of sequences that shared some similarity to the Hebb sequence (hereafter *partial Hebb sequences*). As shown in Figure 1, the three types of partial Hebb sequences were composed of both one common item-item pairing within the Hebb sequence and two items from the stimulus set for filler sequences in which item order varies on every trial (e.g., if the Hebb sequence was "ABCD" and the filler sequences sampled from the set of stimuli "EFGH", the partial Hebb sequences would be "**AB**EF", "H**BC**G", and "FH**CD**"). Szmalec et al.'s (2009, 2012) findings would suggest that when children spontaneously group or are forced to consistently group a sequence into subsequences (e.g., "AB/CD"), they would learn each subsequence when the whole sequence is repeated. Thus, we expected that if children segmented a whole sequence into two two-item groups, and show Hebb repetition learning, then their recall performance for the partial Hebb sequences including these subsequences (e.g., "**AB**EF" and "FH**CD**") would be improved. In contrast they would have difficulty in recalling the partial Hebb sequence that includes the consistently repeated pairing that spans the two subsequences (e.g., "H**BC**G"). Although two-by-two grouping is not the only pattern of spontaneous grouping that children might employ, we expected it to be the most natural and likely pattern of grouping for participants to adopt.

Insert Figure 1 about here

Experiment 1

Extending the work of Mosse and Jarrold (2008) into a substantially younger age range, Experiment 1 explored the Hebb effect among 3-to 5-year-olds and the impact of phonological STM capacity on the size of their Hebb effect. We predicted that children with higher phonological STM would show a stronger Hebb effect than those with lower phonological STM over and beyond any effects of age group. As mentioned above, grouping consistency was also tested by examining the transfer of Hebb repetition learning to partial Hebb sequences.

Methods

Participants. Ninety-seven children (52 boys and 45 girls) attending a kindergarten school in Japan participated in Experiment 1. Two 4-year-old children and five 3-year-old children were tested but excluded from data analysis due to either experimenter error (n = 1) or failure to cooperate (n = 6). The final sample consisted of thirty 3-year-old children (M = 42.10

months, *SD* = 3.37 months, *range* = 37-50 months), thirty 4-year-old children (*M* = 56.87 months, *SD* = 3.34 months, *range* = 50-61 months) and thirty 5-year-old children (*M* = 67.53 months, *SD* = 3.51 months, *range* = 62-74 months). All participants had no history of neurological disorders or neurodevelopmental delay and were native Japanese speakers. Their socioeconomic background was predominantly middle class. Informed consent was obtained from the parents or the kindergarten staff members for all children prior to participating in the study. This and subsequent studies were approved by the institutional ethics committee for experimental psychology research at Graduate School of Education, Kyoto University (approval number: CPE-127; title: 'The association between Hebb repetition learning and temporal grouping in young children').

Procedure. All participants undertook a digit span test and a verbal Hebb repetition learning task (Majerus et al., 2006). The order of the two tasks was counterbalanced across participants. To put the children at ease, both sessions were conducted in a quiet room at the kindergarten. The experimenter visited the kindergarten for several days prior to the experiment to establish rapport with the children. The testing required approximately twenty minutes.

Measures.

Verbal Hebb repetition learning task.

Materials. In this task, we used twelve Japanese names of familiar animals (inu, neko, uma, tora, kame, kaba, kirin, panda, nezumi, iruka, histuji, raion [dog, cat, horse, tiger, turtle, hippopotamus, giraffe, panda, mouse, dolphin, sheep and lion]), which were selected from the National Language Research Institute Research Report (1981). These twelve items were highly familiar to all the children because they readily named pictures of them when asked to do so by the experimenter. Hebb repetition learning reflects whether participants gradually consolidate short-term memory for order information into long-term memory; thus we adapted a serial order reconstruction paradigm which minimizes the need for retention of item information. In the paradigm items needed to be visually presented on the screen at recall; thus we did not use sublexical items that most children cannot read aloud. As suggested by Smalle et al. (2016), using existing lexical items as stimuli risks making a Hebb repetition learning task less comparable to naturalistic word-form learning than one using sublexical stimuli. However, sublexical items are not needed to examine the learning of memory for serial order because item and order information are assumed to be stored and processed separately in short-term memory (e.g., Nairne & Kelley, 2004).

The items were used to form stimulus sequences with the constraint that no item could appear twice in the same sequence. The sequences were recorded at a pace of one animal per second with Japanese text-to-speech software (VoiceText editor SAYAKA; HOYA). The mean duration of the auditorily presented items was 549ms (range: 371–696). In the practice trials, four of twelve animal items (mouse, dolphin, sheep, and lion) were used to form four sequences of two items in length, and two sequences of four items in length. In the learning and transfer phase (see Figure 1), a further four animals (tiger, panda, dog, and turtle) were used to form one fixed sequence of four items in length that appeared repeatedly as the Hebb sequence. The remaining four animals (horse, cat, hippopotamus, and giraffe) were also used to form eleven differently ordered sequences of these four items that each appeared once as a non-repeated, or filler, sequence. Eight of the filler sequences appeared in the learning phase and the other three filler sequences appeared in the transfer phase. The number of syllables of words used in the Hebb and filler sequence was matched with each sequence consisting of three two-syllable words and one three-syllable word. In the current study, the filler sequences did not include the items used in the Hebb sequence. As shown in adults (Page, Cumming, Norris, McNeil, & Hitch, 2013) and 12-year-olds (Smalle et al., 2016), if items used in Hebb sequences overlap with those in filler sequences, recall of these Hebb sequences suffers interference from the 'anagram' representations generated by filler sequences. Although the use of overlapping Hebb and filler sequences is common in adult versions of the Hebb repetition paradigm, and although recent work has indicated that item-overlap does not obliterate the Hebb effect with relatively long repetition intervals (St. Louis, Hughes, Saint-Aubin, & Tremblay, 2018), to maximize the Hebb effects observed in preschoolers we used Hebb and filler sequences that did not involve any item overlap, and thereby minimized the potential interference between the two different kinds of sequences. As the Hebb sequence was repeated every second trial (see below the "Procedure" section and Figure 1), item set repetition frequency was equated between the Hebb and filler sequences. To control for any differences in the learning effectiveness of any one particular Hebb sequence, we prepared two sets of filler sequences and Hebb sequences by manipulating the order of the animals in the Hebb (and filler) sequences across sets (e.g., a Hebb sequence from one sequence set was *tiger, panda, dog, turtle* and the other Hebb sequence was *panda, turtle, tiger, dog*). Half of the children in each age group received each set of filler and Hebb sequences.

In the transfer phase, we also used partial Hebb sequences of three types; Start same condition sequences, Middle same condition sequences, and End same condition sequences (see Figure 1). The same item-position and item-item pairings as in Hebb sequences (e.g., "ABCD") were used for both the first and second position in Start same condition sequences (e.g., "**AB**EF"), both the second and third position were maintained in Middle same condition sequences (e.g., "E**BC**F"), and both the items in the third and fourth position were the same as in the Hebb sequence in the End same condition sequences (e.g., "EF**CD**"). The items used in filler sequences were randomly used for the remaining positions of these partial Hebb sequences.

Procedure. We conducted the serial recall task using the same basic procedure as Majerus et al. (2006). The children were instructed that the animals (pointing to the sheet depicting all animals) had taken part in a race and then through headphones they heard someone announce the animals' order of arrival at the finish line from the first to the last animal. They were also asked to remember the order and to touch the animal pictures in the same order as presented. In each trial, an image of a 'winner's podium' appeared on the screen of a laptop computer (Surface pro 4; Microsoft) to encourage them to attend to the screen, then the sequences of animal names were auditorily presented via headphones. During the auditory presentation, four question marks that corresponded to each animal name were presented. Next, children were encouraged to touch the pictures depicting the animals, which randomly appeared at the cardinal corners of the display, and to do so in their order of presentation. They were instructed to touch all animals on the screen as auditorily presented. At the end of each trial, famous cartoon characters were presented to motivate children to pay attention to the task regardless of whether they answered correctly. In the practice phase, children were first given sequences of two items in length. If they correctly recalled the two sequences in succession, they practiced another two sequences of four items in length. All children correctly recalled two sequences of two items in length within three trials. In the learning phase (see Figure 1), over sixteen trials, children alternatively recalled both types of sequences; eight filler sequences occurred on every even trial and Hebb sequences occurred on every odd trial. After the learning phase, children immediately entered into the nine-trial transfer phase where they alternatively encountered, filler sequences, partial Hebb sequences, and Hebb sequences in this order, with each type of sequence presented three times. The ordering of three different types of partial Hebb sequence (Start same condition, Middle same condition, End same condition) was counterbalanced. Children were not informed about the repetition of some sequences. The main dependent measure was the number of the items recalled in the correct serial position.

Digit span test. This test was administrated to measure phonological STM capacity. The stimuli were the digits 1–9 that were prerecorded and presented auditorily via computer at a rate of 1 per second. At the end of each trial, children were required to recall the sequence in the correct order. No digit could appear twice in the same trial. If a child perfectly recalled more than one trial at each length sequence, they proceeded to the next length sequence. When they could not correctly recall any trials at a given sequence length the testing ended. Each sequence length included four trials, ranging from sequence lengths 1 to 7. Following Conway, Kane, Bunting, Hambrick, Wilhelm, and Engle (2005), we calculated the sum of the proportion of elements recalled in correct serial position within each trial, across all trials.

Results and Discussion

Data analysis. In the verbal Hebb repetition learning task, each item was scored as correct if the item was recalled in the correct position. For analyzing these binary data, we used logistic mixed-effects regressions in the statistical software package R (R Core Team, 2013). Logistic regression tests whether independent variables predict proportional change in accuracy just as ANOVA and linear regression tests whether independent variables predict linear change in the dependent variable. Scaling effects in testing linear change in accuracy complicate any comparison between different age groups with different baseline accuracy (Jarrold & Citroën, 2013). We used logistic regression to avoid such statistical artifact which might underestimate the Hebb effect among children. We conducted two main sets of analyses to predict the accuracy of recalling each item. Our first main analysis aimed to model the degree of Hebb repetition learning in young children and consisted of three steps. The first of these was a test of the degree of Hebb repetition learning in young children (*Model of the Hebb effect*). The second step examined developmental changes in the degree of Hebb repetition learning (*Model of the Hebb effect + age group*). In a third and final step we tested the extent to which phonological STM moderated any developmental changes in Hebb repetition learning (*Model of the Hebb effect + age group + digit span*). Through these three steps we aimed to elucidate Hebb repetition learning in preschoolers and in its relation with phonological STM capacity. In a second main analysis we then tested the transfer of any Hebb repetition learning to the three partial Hebb sequences.

Modelling the degree of Hebb repetition learning in young children. First, we aimed to examine whether 3-to 5-year-olds showed a meaningful Hebb effect. Mosse and Jarrold (2008) observed the Hebb effect in 5-and 6-year-olds, but only in the second half of trials within their experiment. Thus, especially for preschoolers, one might expect the differences between recall performance for Hebb and filler sequences to be found only in later trials. Given this, in the *Model of the Hebb effect* the factors of sequence type (filler sequence, Hebb sequence) and trial number (1–8), as well as their interaction, were included as fixed effect variables. As already noted, we employed different sequence set of which consisted same item set. A preliminary analysis indicated no significant effect of sequence set (b = 0.03, z = 0.44, p = .657, χ^2 = 0.20, df = 1, p = .658); thus, the sequence set factor was excluded from the above model.

The fixed effect variables were coded to be centered: sequence type (filler = -1, Hebb = 1), and trial number (trial 1 = - 4 ~ trial 8 = 4). The interaction between sequence type and trial number is an important measure of the Hebb repetition effect[2]. In addition to these fixed effects, random effects included in the model were a random intercept for participant and a random by-participant slope for the interaction between sequence type and trial number.

Using a likelihood ratio test, fixed effects were tested by comparing the fit of the full model with the fit of the model missing each fixed effect (Barr, Levy, Scheepers, & Tily, 2013). Results indicated a significant main effect of sequence type ($b = 0.14$, $z = 4.90$, $p < .001$, $\chi^2 = 29.21$, $df = 1$, $p < .001$), reflecting higher performance on Hebb sequences than filler sequences. Moreover, as shown in Figure 2, a significant interaction between factors was found ($b = 0.09$, $z = 2.80$, $p = .005$, $\chi^2 = 89.83$, $df = 1$, $p < .001$). A simple slope test[3] revealed that the main effect of sequence type was not significant in the earlier trials ($b = 0.02$, $z = 0.69$, $p = .491$); whereas the main effect of sequence type was significant in the later trials ($b = 0.26$, $z = 6.26$, $p < .001$). These results indicate that the emergence of the Hebb effect through sequence repetition can be extended, for the first time, even down to 3-to 5-year-olds. Consistent with Mosse and Jarrold (2008), the Hebb effect observed in 3-to 5-year-olds appears relatively weak. However, there were individual differences in the Hebb effect as indicated by a significant random slope for the interaction between sequence type and trial number ($\chi^2 = 50.37$, $df = 2$, $p < .001$)[4].

Insert Figure 2 about here

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[2] Although a main effect of sequence type can also indicate a Hebb effect if participants learn the repeated sequence very quickly (see, Oberauer, Jones, & Lewandowsky, 2015).
[3] Simple slopes between sequence type and trial number were calculated at 1 standard deviation above the mean of the trial number (earlier trials) and at 1 standard deviation below the mean of the trial number (later trials).
[4] In our analysis, the interaction between sequence type and trial number provides the most direct measure of the magnitude of the Hebb effect. The random slope of the interaction represents the degree of variation in the extent to which each child shows this Hebb effect.

Next, to clarify the developmental changes in the size of the Hebb effect among 3-to 5-year-olds, we added the factor of age group (3-year-olds, 4-year-olds, 5-year-olds) as a fixed effect variable to the above *Model of the Hebb effect*. 3-year-olds were set as the baseline group, and for the comparison with 4-year-olds (*hereafter 4-year-olds factor*), we coded 3-year-olds as 0, 4-year-olds as 1 and 5-year-olds as 0. For the comparison with 5-year-olds (*hereafter 5-year-olds factor*), we also coded 3-year-olds as 0, 4-year-olds as 0 and 5-year-olds as 1. In the *Model of the Hebb effect + age group*, the three-way interaction among age group, sequence type, and trial number allowed us to explore the developmental changes in the degree of Hebb repetition learning with age among young children.

The results of this mixed logit model are also shown in Table 1. As we predicted, we found a significant three-way interaction among the three fixed effect variables. Table 1 shows that the interaction between sequence type and trial number, namely the degree of the Hebb effect, was marginally significantly higher in 4-year-olds and significant higher in 5-year-olds, compared with 3-year-olds. These results clearly show that developmental changes in the extent to which Hebb effects are seen occurred between 4 and 5 years of age.

Insert Table 1 about here

Finally, we aimed to test whether a factor of phonological STM capacity, as measured by the digit span test, moderated the developmental change in the Hebb effect. The average score for the digit span test in each age group was as follows: 3-year-olds (M = 9.60, SD = 1.57), 4-year-olds (M = 12.28, SD = 2.61), and 5-year-olds (M = 13.53, SD = 2.60). To visually understand the relationships between the Hebb effect, age group, and digit span score, we generated Figure 3, which plots the difference between 3-to 5-year-olds' recall of items from Hebb and filler sequences in the second-half trials as a function of their digit span score.

Insert Figure 3 about here

Given the above-mentioned aim, we added the factor of the standardized digit span score as a fixed effect variable to the above *Model of the Hebb effect + age group*. However, the *Model of the Hebb effect + age group + digit span* failed to converge. Thus, we compared the *Model of the Hebb effect + digit span* with the *Model of the Hebb effect + age group* using a likelihood test. This showed that the former model including digit span fitted significantly better than the latter model including age ($\chi^2 = 75.75$, $df = 0$, $p < .001$). The final model is shown in Table 2, and the correct recall percentages of the Hebb and filler sequence trials in children with high and low phonological STM capacity are shown in Figure 4. As expected, we observed a significant three-way interaction among sequence type, trial number, and digit span. According to simple slope tests[5], the interaction between sequence type and trial number was significant in children with high phonological STM ($b = 0.25$, $z = 5.59$, $p < .001$), but was not observed or was even in an opposite direction in those with low phonological STM ($b = -\ 0.05$, $z = -1.31$, $p = .189$). This clearly shows that phonological STM is a key predictor of developmental changes in the magnitude of the Hebb effect. However, a random slope for the interaction between

[5] Simple slopes between the digit span test, sequence type, and trial number were calculated at 1 standard deviation above the mean of the digit span test (high phonological STM) and at 1 standard deviation below the mean of the digit span test (low phonological STM).

sequence type and trial number was still significant ($\chi^2 = 26.71$, $df = 2$, $p < .001$), indicating that phonological STM did not explain all the individual differences in the Hebb effect in this sample.

Insert Table 2, Figure 4 about here

Transfer effects of Hebb repetition learning. As an indirect measure of consistent grouping, we explored whether the Hebb effect transferred to partial Hebb sequences which shared the same item-position and item-item pairings of Hebb sequences. To measure these transfer effects we compared the accuracy of recalling each partial Hebb sequence with its immediately preceding filler sequence. As shown in Figure 1, in each condition we compared the same item-position and item-item pairings of partial Hebb sequences and preceding filler sequences. For example, in the case of the Start same condition, we compared recall performance for only the first position and the second position. Similarly, for the other two types of sequence our analysis focused only on the second and third positions (Middle same condition), or the third and fourth positions (End same condition).

The transfer effect was also analyzed with logistic mixed effects regressions using R. Here we immediately included the factor of digit span to the model given the above evidence that the degree of the Hebb repetition learning depended on digit span score more than on age. In this analysis, our interest was whether recall of partial Hebb sequences in the Middle same condition was poorer than that seen in the Start same and End same conditions, which would suggest that children grouped into a 2 - 2 pattern; thus planned comparisons were conducted in which the Middle same condition was compared with the average of the Start same and End same conditions. The fixed effect variables were sequence type (preceding filler sequence = -1, partial

Hebb sequence = 1), digit span, position and all possible interactions among them. In terms of a position factor (Start same, Middle same, End same), we adapted Helmert coding. For the comparison of the Middle same condition with the average of the other two conditions (*hereafter Middle same factor*), we coded, the Middle same condition as - 0.67, and the other two conditions as 0.33. The Start same condition and the End same condition were compared by constructing a *primacy factor*. We coded the Start same condition as 0.5, the Middle same condition as 0, and the End same condition as - 0.5. For the random effects, a random intercept for participant and a random by-participant slope for sequence type were included.

According to the analysis (see overall results shown in Appendix A), we identified a significant interaction between sequence type and digit span ($b = 0.10$, $z = 3.33$, $p < .001$, $\chi^2 = 10.84$, $df = 1$, $p < .001$), indicating that children with high phonological STM recalled the items in partial Hebb sequences better than in preceding filler sequences ($b = 0.48$, $z = 4.05$, $p < .001$), in contrast to no benefit to partial Hebb sequences in those with low phonological STM ($b = -0.08$, $z = -0.74$, $p = .457$). These findings indicate that children with higher levels of phonological STM capacity were able to transfer their learning of the Hebb sequence to partial Hebb sequences (see descriptive data shown in Table 3). However, contrary to our prediction, we did not find a reliable three-way interaction between sequence type, digit span, and the Middle same factor which would have been indicative of a 2-2 grouping strategy ($b = 0.06$, $z = 1.21$, $p = .228$, $\chi^2 = 1.45$, $df = 1$, $p = .229$). This suggests that children who showed transfer effects might not necessarily segment a sequence in a 2-2 grouping strategy.

We also explored the potential relation between the degree of the Hebb effect across the learning phase of the experiment and the size of any transfer effect. For filler sequences, Hebb sequences, and the three types of partial Hebb sequences, we summed memory performance for the same item-position and item-item pairings in each condition. The performance of partial Hebb sequences was significantly related to that of Hebb sequences, controlling for the performance of filler sequences ($r = .57$, $p < .001$). The performance of transfer sequences was not significantly different from that of Hebb sequences ($b = -0.03$, $z = -0.40$, $p = .687$) and the interaction between sequence type and digit span was not significant ($b = -0.05$, $z = -1.43$, $p = .154$). This result suggests that the transfer effect derives directly from the Hebb effect. Consistent with Szmalec et al. (2009, 2012), subsequences in each condition benefitted from the Hebb effect, suggesting that children who showed the Hebb effect might have *consistently* segmented the repeated Hebb sequence into subsequences.

Summary of Experiment 1

Experiment 1 successfully demonstrated that phonological STM is one of a potential set of developmental requirements for Hebb repetition learning among preschoolers. It was also shown that children's Hebb repetition learning can transfer to the recall of subsequences that are included in the Hebb sequence, suggesting that children who spontaneously showed the Hebb effect did so by virtue of grouping the supra-span Hebb sequence into a subset of consistent subsequences.

Insert Table 3 about here

Experiment 2

The purpose of Experiment 2 was to explore the impact of encouraging consistent grouping on the size of the Hebb effect seen among young children, and on the subsequent transfer of any Hebb repetition learning.

Consistent Grouping, Phonological STM, and the Hebb Effect

Externally encouraged consistent grouping. Experiment 1 did not manipulate grouping consistency directly. As a result we could not definitively conclude that segmenting a sequence into consistent subsequences is a developmental requirement for the Hebb effect. In Experiment 2, we therefore directly encouraged the consistency of grouping by inserting a consistent pause in the middle of sequences. It is well known that temporal grouping is beneficial for serial order recall (e.g., Henson, Burgess, & Frith, 2000; Hitch, Burgess, Towse, & Culpin, 1996; Ryan, 1969). In the context of Hebb repetition learning, inconsistent grouping reduces the learning (Hitch et al., 2009), and consistent grouping promotes learning (Smalle et al., 2016). For example, Smalle et al. (2016) demonstrated that encouraging adults to group Hebb sequences into small two-syllable chunks (e.g., jave rika beti somu) resulted in a rapid memorization of Hebb sequences if no items overlapped between filler and Hebb sequences. Thus, if a given child shows no Hebb effect due to their inability to spontaneously group a sequence into consistent subsequences, providing supportive temporal grouping may generate a Hebb effect in that individual.

The interaction between externally encouraged consistent grouping and phonological STM. One might ask whether encouraging consistent grouping will necessarily always be effective in increasing the size of the Hebb effect. Smith and Jarrold (2014) provided direct evidence for the influence of phonological STM capacity on the extent to which grouping benefits recall. They asked individuals with Down syndrome (DS) to serially recall sequences with or without temporal grouping, in both a verbal only condition where each item was presented in an auditory format and in a verbal plus visual condition where each item was auditorily presented along with the corresponding picture. The individuals with DS did not show grouping benefits in the verbal condition, but did so in the verbal and visual combined condition, probably because their phonological STM capacity was lower than their capacity for visual STM (Jarrold, Baddeley, & Hewes, 2000). This suggests that if children with low phonological STM capacity are able to rehearse only a smaller portion (e.g., one item) of a grouped part (i.e., a two-item group), then an external cue to consistent grouping will not necessarily effectively induce grouping or its inter-sequence consistency. We predicted that the effect of encouraging consistent grouping on Hebb repetition learning would therefore be constrained by children's phonological STM capacity.

Encouraging Consistent Grouping and Transfer Effects of Hebb Repetition Learning

In Experiment 1 we did not find the expected interaction between position of overlap of partial Hebb sequences and any transfer effects, suggesting that the item-item parings in all three conditions benefitted from Hebb repetition learning. We expected that most children would consistently segment a sequence in a single grouping pattern (a 2 - 2 pattern), and that transfer effects to the Middle same condition would not be observed because the subsequence in the middle position was internally split. However, as Spurgeon, Ward, Matthews, and Farrell (2015) have suggested, each individual might consistently segment a whole sequence but with inter-individually different grouping patterns. For example, one child might employ a 1 - 3 grouping strategy, another the expected 2 - 2 pattern, and a third a 3 - 1 grouping approach. If a child adopted a 1 - 3 grouping strategy, then transfer effects in the Start same condition would not be observed. Thus, inconsistent grouping patterns among individuals would reduce the possibility of transfer effects in the Start same and End same conditions, and preclude a significant interaction between position and the size of any transfer effect. One reason why children might employ grouping strategies that vary across individuals is that the size of the first group that they seek to maintain might depend directly on their STM capacity (Jarrold & Hall, 2013). Given this, another advantage of encouraging temporally consistent grouping in Experiment 2 is that this may well reduce the degree of individual differences in grouping patterns employed by children. In the condition where sequences are consistently temporally grouped in a 2 - 2 pattern we might therefore expect to find reduced transfer of learning to partial Hebb sequences in the Middle same condition. In contrast, if transfer effects in the Middle same condition are observed even with consistent temporal grouping, then one would need to consider another explanation of the transfer of the Hebb repetition learning to the temporally split subsequences in the Middle same transfer condition.

Methods

Participants. A total of ninety-eight children (50 boys and 48 girls) attending kindergarten schools in Japan participated in Experiment 2, but two children were excluded due to fatigue. Thus, forty-eight 4-year-old children (M = 50.52 months, SD = 4.58 months, *range* = 44–55 months) and forty-eight 5-year-old children (M = 61.25 months, SD = 4.23 months, *range* = 57–68 months) were included in the final analyses (none of whom took part in Experiment 1). To confirm the effects of consistent grouping in the Hebb learning paradigm, children in each age group were divided into either a control group or a temporal grouping group.

The children in both groups were matched for phonological STM capacity using the digit span test (4-year-olds: control M = 15.71, SD = 3.33, temporal grouping M = 15.72, SD = 2.99; 5-year-olds: control M = 18.59, SD = 3.57, temporal grouping M = 18.77, SD = 3.54). No children were reported to have developmental atypicalities. The predominant socioeconomic background was middle class. Informed consent was obtained from the parents prior to participating in the study.

Procedure. The same tasks employed in the first experiment were given to participants across two days. On the first day, all children received the digit span test to allow for matching of phonological STM capacity across the control and temporal grouping groups within each age. On the second day, we conducted the verbal Hebb repetition learning task. On both days testing was conducted in the same quiet room at the kindergarten and lasted for fifteen minutes.

Measures.

Verbal Hebb repetition learning task. In Experiment 2 the materials and procedures were nearly the same as in Experiment 1, with one exception. To allow a consistent grouping manipulation we changed the duration of the auditorily presented items (see Figure 1). Participants in the control group received sequences that were recorded at a pace of one item per second in the same way as in Experiment 1; whereas participants in the temporal grouping group received items that were each spaced by intervals of 800 ms, with an additional 800 ms interval after the first two items. Thus, the overall duration of each trial given to the control group and the temporal grouping group was equivalent.

Digit span test. We measured phonological STM capacity using the same digit span task as in Experiment 1.

Results and Discussion

Externally encouraged consistent grouping, phonological STM, and Hebb repetition learning. We initially examined the effect of grouping consistency on the Hebb effect. In line with Experiment 1, we analyzed the degree of the Hebb repetition learning with logistic mixed effects regressions using R. As an individual differences factor we selected phonological STM capacity measured by the digit span test. The reason for selecting this model was that the age distribution in Experiment 2 was relatively small, and phonological STM capacity was more closely associated with the degree of Hebb repetition learning than age group in the previous experiment. Thus, sequence type (filler = -1, Hebb = 1), trial number (trial 1 = - 4 ~ trial 8 = 4), grouping (control and temporal grouping were coded -1 and 1, respectively), digit span performance, and their interactions were included in the model as fixed effect variables. A preliminary analysis indicated no significant effect of sequence set (b = - 0.003, z = - 0.03, p = .977, χ^2 = 0.00, df = 1, p = .977); thus, the sequence set factor was excluded from the above analyses. For random effects, a random intercept for participant, and a random by-participant slope for the interaction between sequence type and trial number were included. Our interest was the higher-order interactions (sequence type x trial number x grouping and sequence type x trial number x grouping x digit span), indicating the effect of grouping consistency on the Hebb effect and its interaction with phonological STM. As in Experiment 1, a likelihood ratio test was used for significance testing.

Effect of encouraged consistent grouping. The results of the mixed logit model are also shown in Table 4. In line with Experiment 1, both significant main effects of sequence and digit span and significant interactions (sequence type x trial number, sequence type x digit span, and sequence type x trial number x digit span) were found. As described earlier, the sequence type x trial number interaction is a key indicator of the degree of the Hebb effect, and we replicated the result of Experiment 1 in a different sample in finding this interaction to be significant (see Figure 2). We also observed a significant main effect of grouping, indicating that temporal grouping contributes to memory performance. However, we did not find a significant interaction between sequence type, trial number, and grouping, suggesting that simply encouraging children to group a sequence into subsequences was not enough to increase every child’s Hebb effect.

Insert Table 4 about here

Interaction between encouraged consistent grouping and phonological STM. As expected, we observed a significant interaction between sequence type, trial number, grouping, and digit span (see Table 4). To develop a deeper understanding of the effect of grouping on the Hebb effect, simple slopes of the significant higher-order interaction (sequence type x trial number x grouping x digit span) were analyzed. The correct recall percentages of the Hebb and filler sequence trials in children with high and low phonological STM capacity are shown in Figure 5A and 5B.

Consistent with Experiment 1, children in the control group with high phonological STM showed the Hebb effect (superior Hebb than filler sequence recall) only in the later trials (b = 0.97, z = 7.91, p < .001), whereas children in the temporal grouping group with high phonological STM exhibited strong Hebb repetition learning even in the earlier trials (b = 0.36, z = 2.92, p = .003), even though their recall performance was already high. In the case of children with low phonological STM, control participants did not show significant Hebb repetition learning even in the later learning phase (b = - 0.16, z = - 1.75, p = .080). However, those children with low phonological STM in the temporal grouping group showed a marginally significant difference between Hebb sequences and filler sequences recall in the later trials (b = 0.15, z = 2.45, p = .091).

Insert Figure 5A and 5B about here

Encouraged consistent grouping and transfer effects of Hebb repetition learning. Our next aim was to examine whether encouraging consistent grouping resulted in the facilitation of learning of the subsequences included in the Hebb sequences. To this end we conducted the same logistic mixed effects regression analysis of transfer effects to partial Hebb sequences as used in Experiment 1, with the recall performance of the same item-position and item-item pairings as a dependent variable (see Figure 1). For the fixed effect variables, sequence type (partial Hebb sequence, preceding filler sequence), grouping (control, temporal grouping), a Middle same factor, a primacy factor, digit span, and their interactions were included, and we used the same coding system as in Experiment 1. For random effects, only a random intercept for participant was included because the model including a random by-participant slope for sequence type failed to converge.

Overall results are shown in Appendix B. In line with Experiment 1, we replicated the significant interaction between sequence type and digit span ($b = 0.07$, $z = 3.35$, $p < .001$, $\chi^2 = 11.32$, $df = 1$, $p < .001$). Post-hoc analysis showed that the performance for partial Hebb sequences was superior to that for preceding filler sequences in children with high phonological STM ($b = 0.60$, $z = 5.14$, $p < .001$), but that a sequence type difference was not observed in children with low phonological STM ($b = - 0.18$, $z = -1.33$, $p = .186$). Furthermore, there was a significant three-way interaction between sequence type, the Middle same factor, and digit span ($b = - 0.14$, $z = - 3.14$, $p = .002$, $\chi^2 = 9.92$, $df = 1$, $p = .002$). Simple slope tests of the two-way interaction between sequence type and the Middle same factor for each STM group indicated that children with high phonological STM exhibited a transfer of Hebb repetition learning to the middle two sequence positions in particular ($b = - 1.01$, $z = - 4.26$, $p < .001$), but that this was not observed among children with low phonological STM ($b = - 0.002$, $z = - 0.01$, $p = .990$). Given the main effect of sequence type, one can infer that the decreased memory performance in the middle positions of filler sequences made the transfer effect in the Middle same partial Hebb sequences appear more salient than in the other two conditions. More important, contrary to our prediction, a significant higher order interaction between sequence type, the Middle same factor, grouping, and digit span was not significant (b = - 0.01, z = - 0.14, p = .892, χ^2 = 0.02, df = 1, p = .890), suggesting that temporally consistent grouping did not reduce the transfer of learning to partial Hebb sequences in the Middle same condition.

To examine the association of the magnitude of the Hebb effect with its subsequent transfer, we also conducted the same correlational analysis as employed in Experiment 1. Children's performance on partial Hebb sequences was significantly correlated with the size of the Hebb effect in the learning phase (r = .63, p < .001). The magnitudes of the Hebb and the transfer effects were similar especially for children with high phonological STM, who showed a significant transfer effect (Table 3). In the transfer phase, the transfer sequences were not significantly different from the Hebb sequences (b = - 0.05, z = - 0.53, p = .596) and the interaction between sequence type and digit span was not significant (b = 0.04, z = 1.24, p = .214).

Summary of Experiment 2

For children with high phonological STM, encouraging consistent grouping led to a strong Hebb effect, whereas for children with low phonological STM, providing external grouping cues was not so effective in prompting a discernable Hebb effect, but might still weakly contribute to Hebb repetition learning. Consistent with Experiment 1, this result suggests that not only externally segmented subsequences (e.g., "**AB**/EF" and "FH/**CD**") but also subsequences that span a temporal pause (e.g., "G**B/C**F") are subject to Hebb repetition learning.

General discussion

Previous studies have demonstrated that the Hebb effect can be observed in 5- and 6-year-olds, but that this effect is weaker than that seen in adults (e.g., Mosse & Jarrold, 2008). However it was unclear whether the Hebb effect can be seen in children younger than 5, and what the developmental requirements for Hebb repetition are. Motivated by evidence from previous studies of adults and children, we speculated that both inconsistent grouping of the sequence and low phonological STM capacity might cause young children to show weak or even no Hebb repetition learning. To confirm whether children group a sequence into subsequences, we also investigated the transfer of Hebb repetition learning to the recall of similar sequences which shared selective item-item pairings from the Hebb sequence. In Experiment 1, we tested whether 3- to 5-years-olds exhibited the Hebb effect and the impact of phonological STM capacity on this effect. Experiment 1 also tested the transfer of Hebb repetition learning. In Experiment 2, by manipulating item presentation timing using temporal pauses, we directly examined the effect of grouping consistency on the Hebb effect and its transfer in 4- and 5-year-olds.

Hebb Repetition Learning in Young Children

The two experiments reported here demonstrated developmental changes in the size of the Hebb effect during the preschool ages. Early childhood is a crucial developmental period that contains the vocabulary spurt; thus our findings suggest that young children have the ability to acquire novel word-forms from early ages through Hebb-like repetition learning. However, the Hebb effect was weak compared to what is typically seen in adults assessed on supra-span sequences. Note that, in this study, to minimize the interference between Hebb and filler sequences, we developed Hebb sequences that shared no items with the filler sequences. Compared with Mosse and Jarrold (2008) who did use overlapping Hebb and filler sequences, children in the current study would be expected to show stronger Hebb repetition learning. Despite this, we did not observe particularly strong Hebb effects. It is not clear whether the weak Hebb effects observed here in the absence of direct interference between the items in the Hebb and filler sequences is based on genuine developmental constraints. Any comparisons of the size of the Hebb effect between adults and children must be conducted carefully. In the next sections, we discuss developmental requirements for the Hebb repetition learning.

Phonological STM Capacity and the Hebb Effect

In our two experiments, phonological STM capacity was a clear predictor of the degree of Hebb repetition learning of verbal materials, and more so than simple age group differences. Among preschoolers, children with low phonological STM capacity did not show the Hebb effect on the 4-item sequences used here; in contrast children with high phonological STM capacity showed a Hebb effect especially in the later trials of the experiment. Our findings are therefore consistent with the suggestion (see Jarrold & Hall, 2013) that children with low phonological STM capacity might only maintain a very small subsequence in the earlier trials, whereas children with higher phonological STM capacity might rehearse a larger chunk of items. Future research might test this claim further by directly assessing phonological coding (e.g., via phonological similarity) in children's Hebb repetition learning. Another possible mechanism whereby phonological STM contributes to the Hebb effect is via error learning. Erroneous outputs as well as correct ones are learned in the Hebb repetition task constraining the increase in correct performance (Couture, Lafond & Tremblay, 2008; Lafond, Tremblay & Parmentier, 2010). Phonological STM determines the extent of initial error (with less error being associated with higher STM capacity for a given sequence length) and learning of any error responses would limit the actual performance increase that is observed as a “Hebb effect”, even if the efficiency of learning mechanism per se was identical across individuals. Future studies might also usefully address this topic.

Phonological STM, Consistent Grouping, and Hebb Repetition Learning

Externally encouraged consistent grouping. A key feature of our studies is that we tested the effect of consistent grouping on the performance of filler sequences and the Hebb effect. The results of Experiment 2 demonstrated that consistent grouping alone was not sufficient to produce a reliable Hebb effect in all children. However, our study is the first to demonstrate that temporal grouping improved recall performance in preschoolers consistent with findings from adults and elementary school children (Harris & Burke, 1972; Towse et al., 1999; Smith & Jarrold, 2014). Although Towse et al. (1999) suggested that grouping was a relatively late-developing, strategic process, our data indicate that even preschoolers are sensitive to the temporal structure of sequences. One possibility for this inconsistency across studies follows from differences in variability in a grouping pattern. Specifically, in our study all the sequences in the temporal grouping condition of Experiment 2 consisted of four items with a pause after the first two items, and the pattern was therefore consistent and predictable. In contrast, sequence length in Towse et al.’s (1999) study varied between two and eight items, with three item sequences grouped in a 2 – 1 pattern and with other sequences segregated after every three items. Thus, the pattern in Towse et al. (1999) varied with sequence length and was inconsistent and unpredictable. Although Hartley, Hurlstone, and Hitch (2016) have recently reported that grouping effects for adults were independent of the predictability of the temporal pattern, and were largely attributable to a bottom-up grouping mechanism, it is still possible that children are susceptible to consistency (or inconsistency) of grouping in serial order memory. Thus, an inconsistent grouping pattern might have led to a limited grouping effect among children in Towse et al. (1999). As a result, we confirmed that the temporal pauses imposed in Experiment 2 effectively introduced a degree of consistent grouping.

The interaction between encouraged consistent grouping and phonological STM. A key strength of our approach is that it allowed us to also investigate the interaction between phonological STM capacity and external encouragement of consistent grouping on Hebb repetition learning. We found that the extent to which the Hebb effect is facilitated by providing consistent grouping depends on phonological STM capacity. Children with high phonological STM showed a boosted Hebb effect when consistent grouping was encouraged. However, children with low phonological STM exposed to the temporal grouping manipulation in Experiment 2 showed at best a limited Hebb effect in the later experimental trials. Consistent with our findings, Kalm, Davis, and Norris (2012) showed that those brain areas involved in encoding group structure were more active when adults recalled supra-span sequences than when they recalled sub-span sequences, suggesting that encoding group structure is more demanding when the input exceeds phonological STM capacity. Thus, externally segmenting a sequence into the *right-sized* consistent subsequences, depending on phonological STM capacity, is therefore suggested to be important for Hebb repetition learning. However, it should be noted that although our study was successful in demonstrating Hebb effects that interacted with phonological STM capacity, it would necessarily have had less power to accurately estimate the size of the three-way interaction between the Hebb effect, phonological STM, and grouping consistency. Thus a replication study based on a power analysis of the current results would be of value.

An Ability to Retain Consistent Grouping

Our findings are consistent with evidence from adults that the Hebb effect is also sensitive to grouping consistency (e.g., Hitch et al., 2009). Thus, an ability to retain a degree of consistency of grouping is beneficial in the absence of any external grouping cue. This ability to retain consistency of grouping might be underpinned by the two potential mechanisms.

One is memory for rhythm. Lew-Williams and Saffran (2012) showed that infants are able to form an expectation of word length after an exposure to words of a certain length. As this expectation interfered with the phonotactic-based grouping of unlearned phonological "word-forms", memory for rhythms (in this case, an expectation of a typical word length) might be separable from memory for, or learning of, phonological contents. Furthermore, an ability to retain consistency of grouping is constrained by phonological STM capacity, as previous research has shown a correlation between the ability to retain rhythm and phonological STM capacity in adults (Saito, 2001) and in children (Hall & Gathercole, 2011). Consistent with this correlational evidence, Gilbert, Hitch, and Hartley (2016) directly examined the role of phonological STM on the maintenance of rhythm. They developed a novel task measuring adults' ability to retain rhythm, showing that an additional memory load decreased the precision with which a rhythm was maintained, and that this precision was positively correlated with participants' digit span. Given the existence of temporal grouping effects on phonological STM (e.g., Hitch et al., 1996), they suggested that a common pool of resources limits memory for rhythms and phonological STM. Thus, it is possible that the relationship between memory for rhythms and phonological STM is reciprocal with both developing interdependently. Future studies might therefore usefully investigate the development of STM for rhythm, perhaps using techniques similar to Gilbert et al. (2016), and its relationships with phonological STM and the size of the Hebb effect in children.

Another possibility is that chunking underlies the ability to retain consistency of grouping. Chunking depends on the amount of exposure to the stimuli in the environment, and experience with subsequences of patterns is assumed to contribute to robust recognition of a chunk (Page & Norris, 2009, see also French, Addyman, Mareschal, 2011; Perruchet & Vinter, 1998; Saffran, Aslin, & Newport, 1996). The robustness of chunk recognition leads to both short-term retention of a sequence and to consistent grouping of that sequence. In our case, as a result of knowledge accumulated before and during the experimental session, children with high phonological STM might have been able to consistently segment a supra-span sequence into the same sized chunks. Following the chunking hypotheses, Smalle et al. (2016) showed that imposing consistent chunking caused adults to show larger Hebb effects in a task involving novel verb sequences that would not normally have been expected to encourage robust chunk recognition. However, they imposed a smaller chunk size (i.e., two-syllable) than adults typically use, and also confounded the size of chunk and the consistency of chunking; thus further study is also needed to test the relation between chunk size, the consistency of chunking, and Hebb repetition learning.

Either way, a common feature of the two possible mechanisms described above is that phonological STM capacity constrains the ability to retain grouping consistency. Although our present data are not sufficient to fully specify the precise relationships between these two constructs, one can reasonably infer that phonological STM capacity and the ability to retain grouping consistency are separable but interrelated.

Consistent Grouping and Transfer Effects of Hebb Repetition Learning

In both experiments we explored whether children learned beneficial information about subsequences through the repetition of whole sequences. We found robust evidence of the transfer of Hebb repetition learning in children with high phonological STM capacity, and of its association with the magnitude of initial Hebb repetition learning. In Experiment 2, contrary to our prediction, children showed transfer effects in the middle two positions of the sequence, although sequences were auditorily split by pauses after two items in the temporal grouping condition. One possibility is that the two segmented subsequences experienced by children in the temporal grouping condition led them to learn a whole sequence as one single chunk. Learning the repeated sequences as a unified sequence representation might help children to recall item-item pairings in the middle two sequence positions. Taken together with the result of Experiment 1, our findings suggest that the repeated retention of a whole sequence might lead to acquisition of long-term knowledge of subsequence representations and, as a result of this acquisition, of a whole sequence representation itself. Another possibility is that learning a whole sequence as two segmented subsequences in Experiment 2 is independent from learning it as one single chunk. Thus, learning the subsequence representations did not directly help children to recall item-item pairings in the middle two sequence positions. Given the results of Experiment 1, the repeated retention of a whole sequence may lead to acquisition of long-term knowledge of both the subsequence representations and of a whole sequence representation. Our findings, however, did not provide strong evidence to support either possibility; thus future studies would no doubt shed light on the relationships between subsequence and whole sequence learning.

It is worth noting that children with high phonological STM capacity showed transfer effects even when temporal pauses were not inserted into the sequence – both in Experiment 1 and in the control condition of Experiment 2. It is possible that these children initially spontaneously grouped the sequence into subsequences and learned these through repetition. In contrast, some studies of the Hebb effect in adults (e.g., Fastame et al., 2005) have reported limited transfer effects of Hebb repetition learning. Our results imply that additional factors may have prevented adults from segmenting a whole sequence into consistent subsequences in these studies. For example, the repeated sequences used by Fastame et al. (2005) shared common subsequences but had different lengths (e.g., R**JXVDHZPK**, RS**JXVDHZPK**, QSR**JXVDHZPK**). If participants segment sequences into consistently sized subsequences, perhaps based on their STM capacity, then these segmented subsequences will not be consistent over repetitions when overall sequence length changes, resulting in poor transfer. Hence, our findings are not necessarily incompatible with previous studies with adults. In addition, even if children and adults learn repeated sequences using the same materials, children are likely to learn the subsequence representations more rapidly than adults do. Recently, Smalle, Muylle, Szmalec, and Duyck (2017) asked adults and 9-year-olds to rapidly recite sequences of novel mono-syllabic word-forms including experiment-wide phonotactic constraints within a syllable (e.g., /t/ can only be an onset if the vowel is /i/) over a period of 4 days. Smalle et al. (2017) focused on participants' speech errors that reflected these phonotactic constraints and found that adults demonstrated a learning effect for the phonotactic constraints on the second day consistent with adults' slowly emerging transfer effect in a variant of the Hebb paradigm (Nakayama & Saito, 2017). However, 9-year-olds had already started learning the constraints by the middle of the first day. Thus it is possible that children in the current experiments rapidly learned position-specific representations for an item or item-item pairings.

Vocabulary Development and Hebb Repetition Learning

Given that the Hebb repetition paradigm is a laboratory analogue of real-life word learning (e.g., Page & Norris, 2009), one might ask what we learn from our developmental findings on the Hebb effect for the broader issue of vocabulary development. We believe that our findings have two implications in this regard, which follow from the fact that the interaction between phonological STM capacity and grouping consistency determined the size of the Hebb effect. First, when children are presented with a sequence that is segmented into the 'right-sized' subsequences given their phonological STM capacity, they are good learners of that sequence. However, if the segmented subsequence is beyond their phonological STM span, children show poorer learning. This means that children can be good vocabulary learners if lengths of presented words are below-span. Consistent with this, young children firstly begin to imitate and learn relatively short length, or 1, 2, and 3-syllable, words through social interactions (Fenson et al., 1993; Hoff, Core, & Bridges, 2008). The real language environment around them might be broadly in line with their STM span and so help them to increase their vocabulary rapidly. We also suggest that children learn a large number of long words by segmenting them into sub-span sequences. This leads us to the second implication. If temporal grouping keeps sub-span sequences consistent, children learn more rapidly. Educators would therefore benefit from recognizing that encouraging children to group consistently is an effective means of supporting their word-from learning, but one that crucially needs adjustment for each child depending on his or her phonological STM capacity. However, it is well known that environmental factors, such as social economic status and the presence of siblings (Hoff, 2006), or other cognitive factors such as object categorization (Gopnik & Meltzoff, 1992), also strongly affect vocabulary development. Therefore, future studies should take a broad perspective and consider the relationships between such environmental and cognitive factors, phonological STM, groping consistency, Hebb repetition learning, and vocabulary development.

Limitations and Conclusions

Our study has generated a set of notable findings, but was subject to two potential limitations. First, in our version of the verbal Hebb repetition learning task children were required to listen to the presented names of animals and then touch these animals' pictures; thus, children needed to map auditory representations onto a response made to visual stimuli. Developmental differences in this conversion processes might potentially have an influence on serial recall performance, and this cannot be verified in our study. Further studies could clarify the effect of modality on children's recall and learning by repetition, however Jarrold and Citröen (2013) showed no meaningful change in phonological recording abilities between the ages of 5 and 9.

Second, we used familiar animal names as materials in the verbal Hebb repetition learning task, partly because of our desire to work with relatively young children coupled with the practical constraints on task design that followed from this. Although our task required children to recall the order of these animal names, the resultant sequence of familiar lexical items did not correspond to a novel word-form. Smalle et al. (2016) found weaker Hebb effects in children for familiar lexical items than for sublexical items. Thus, a task employing sequences of nonwords would allow for further exploration of the Hebb effect as an analogue of children's real-world word-form acquisition. Alternatively, it is possible to use a single spoken nonword as the sequence of syllables in the context of the Hebb repetition paradigm (Norris, Page, & Hall, 2018). Consequently, replicating our findings using nonword lists or natural spoken single nonwords would be a useful next step.

Despite these potential limitations, the current findings provide the first evidence for two, key, separable but related developmental requirements of the Hebb effect. We have demonstrated that phonological STM capacity, grouping consistency, and their interaction determine the size of the Hebb effect in young children[6]. We believe that our findings therefore offer important insights into the relationship between phonological STM and vocabulary acquisition in young children.

[6] At a conceptual level, the separation between phonological STM capacity and grouping consistency might not be so straightforward. On the one hand, some cognitive/neural models of phonological STM are, for example, based on the idea that STM function emerges from an interaction between speech perception and speech production (e.g., Acheson & MacDonald, 2009; Jacquemot & Scott, 2006; Saito & Baddeley, 2004). A more extreme version of this view might also be possible, that is, phenomena associated with phonological STM can be explained solely by a combination of perceptual/acoustic and motor/articulatory processes (e.g., Jones, Hughes, & Macken, 2006; Jones, Macken, & Nichollas, 2004; Maidment & Macken, 2012). On the other hand, the temporal grouping of auditory items can be seen to reflect the organization of speech sounds at a perceptual level (e.g., Frankish, 1989, 1996). This idea resonates with a recently proposed model of temporal grouping effects (Hartley et al., 2016), which suggests that grouping effects emerge from stimulus-driven constraints on immediate serial memory. These and other previous studies together suggest that both phonological STM capacity and grouping consistency might be underpinned, to some degree at least, by perceptual-acoustic processing of spoken sequences. This is one example of the potential inter-dependence of phonological STM and grouping. Although our present data are not sufficient to argue that these two constructs are conceptually separable, the assumption that phonological STM and grouping might operate relatively independently still provides a useful framework within which our data on the development of the Hebb repetition learning can be interpreted.

References

Acheson, D. J., & MacDonald, M. C. (2009). Verbal working memory and language production: Common approaches to the serial ordering of verbal information. *Psychological Bulletin*, *135*, 50–68. http://doi.org/10.1037/a0014411

Archibald, L. M., & Joanisse, M. F. (2013). Domain-specific and domain-general constraints on word and sequence learning. *Memory and Cognition*, *41*, 268–280. https://doi.org/10.3758/s13421-012-0259-4

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*, 158–173. https://doi.org/10.1037/0033-295X.105.1.158

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*, 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, E., Marchman, V., Thal, D., Fenson, L., Dale, P., Reznick, J. S., . . . Hartung, J. (1994). Developmental and stylistic variation in the composition of early vocabulary. *Journal of Child Language*, *21*, 85–123. doi:10.1017/S030500090000868

Bower, G. H. (1970). Organizational factors in memory. *Cognitive Psychology*, *1*, 18–46. https://doi.org/10.1016/0010-0285(70)90003-4

Bogaerts, L., Szmalec, A., De Maeyer, M., Page, M. P., & Duyck, W. (2016). The involvement of long-term serial-order memory in reading development: a longitudinal study. *Journal of Experimental Child Psychology*, *145*, 139–156. https://doi.org/10.1016/j.jecp.2015.12.008

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, *106*, 551–581. https://doi.org/10.1037/0033-295X.106.3.551

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*, 627–652. https://doi.org/10.1016/j.jml.2006.08.005

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, *12*, 769–786. https://doi.org/10.3758/BF03196772

Couture, M., Lafond, D., & Tremblay, S. (2008). Learning correct responses and errors in the Hebb repetition effect: two faces of the same coin. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 524–532. https://doi.org/10.1037/0278-7393.34.3.524.

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

Farrell, S. (2012). Temporal clustering and sequencing in short-term memory and episodic memory. *Psychological Review*, *119*, 223–271. https://doi.org/10.1037/a0027371

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

Fenson, L., Dale, P. S., Reznick, J. S., Thal, D., Bates, E., Hartung, J. P., Pethick, S., & Reilly, J. S. (1993). *MacArthur Communicative Development Inventories: User's guide and technical manual.* San Diego: Singular Publishing Group. Inc.

Frankish, C. (1989). Perceptual organization and precategorical acoustic storage. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 469–479. http://dx.doi.org/10.1037/0278-7393.15.3.469

Frankish, C. R. (1996). Auditory short-term memory and the perception of speech. In S. E. Gathercole (Ed.), *Models of short-term memory* (pp. 179-207). Hove: Psychology Press.

French, R. M., Addyman, C., & Mareschal, D. (2011). TRACX: a recognition-based connectionist framework for sequence segmentation and chunk extraction. *Psychological Review*, *118*, 614–36. https://doi.org/10.1037/a0025255

Gathercole, S. E., Willis, C. S., Baddeley, A. D., & Emslie, H. (1994). The children's test of nonword repetition: A test of phonological working memory. *Memory*, *2*, 103–127. https://doi.org/10.1080/09658219408258940

Gathercole, S. E., Hitch, G. J., Service, E., & Martin, A. J. (1997). Phonological short-term memory and new word learning in children. *Developmental Psychology*, *33*, 966–979. http://dx.doi.org/10.1037/0012-1649.33.6.966

Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics*, *27*, 513–543. https://doi.org/10.1017/S0142716406060383

Gilbert, R. A., Hitch, G. J., & Hartley, T. (2016). Temporal precision and the capacity of auditory–verbal short-term memory. *Quarterly Journal of Experimental Psychology*, 1–16. http://dx.doi.org/10.1080/17470218.2016.1239749

Hall, D., & Gathercole, S.E. (2012). Does working memory underpin memory for rhythm and phonological awareness in childhood? Poster presented at the Experimental Psychology Society Festschrift for Graham Hitch, University of Bristol, Bristol, UK.

Harris, G. J., & Burke, D. (1972). The effects of grouping on short-term serial recall of digitsby children: Developmental trends. *Child Development*, *43*, 710–716. https://doi.org/10.2307/1127572

Hartley, T., Hurlstone, M. J., & Hitch, G. J. (2016). Effects of rhythm on memory for spoken sequences: A model and tests of its stimulus-driven mechanism. *Cognitive Psychology*, *87*, 135–178. https://doi.org/10.1016/j.cogpsych.2016.05.001

Hebb, D. O. (1961). Brain mechanisms and learning. In J. F. Delafresnaye (Ed.), Distinctive features of learning in the higher animal. New York: Oxford University Press.

Henson, R. N. A. (1996). Short-term memory for serial order (Unpublished Doctoral Thesis). Cambridge, UK: Cambridge University.

Henson, R. N. A., Burgess, N., & Frith, C. D. (2000). Recoding, storage, rehearsal and grouping in verbal short-term memory: an fMRI study. *Neuropsychologia*, *38*, 426–440. https://doi.org/10.1016/S0028-3932(99)00098-6

Hitch, G. J., Burgess, N., Towse, J. N., & Culpin, V. (1996). Temporal grouping effects in immediate recall: A working memory analysis. *Quarterly Journal of Experimental Psychology*, *49*, 116–139. http://dx.doi.org/10.1080/713755609

Hitch, G. J., Flude, B., & Burgess, N. (2009). Slave to the rhythm: Experimental tests of a model for verbal short-term memory and long-term sequence learning. *Journal of Memory and Language*, *61*, 97–111. https://doi.org/10.1016/j.jml.2009.02.004

Hoff, E. (2006). How social contexts support and shape language development. *Developmental Review*, *26*, 55–88. https://doi.org/10.1016/j.dr.2005.11.002

Hoff, E., Core, C., & Bridges, K. (2008). Non-word repetition assesses phonological memory and is related to vocabulary development in 20-to 24-month-olds. *Journal of Child Language*, *35*, 903–916. https://doi.org/10.1017/S0305000908008751

Hsu, H. J., & Bishop, D. V. M. (2014). Sequence-specific procedural learning deficits in children with specific language impairment. *Developmental Science*, *17*, 352–365. https://doi.org/10.1111/desc.12125

Jacquemot, C., & Scott, S. K. (2006). What is the relationship between phonological short-term memory and speech processing? *Trends in Cognitive Sciences*, *10*, 480–486. http://doi.org/10.1016/j.tics.2006.09.002

Jarrold, C., Baddeley, A. D., & Hewes, A. K. (2000). Verbal short - term memory deficits in Down syndrome: A consequence of problems in rehearsal? *Journal of Child psychology and Psychiatry*, *41*, 233–244. https://doi.org/10.1111/1469-7610.00604

Jarrold, C., Baddeley, A., Hewes, A., Leeke, T., & Phillips, C. (2004). What links verbal short-term memory performance and vocabulary level ? Evidence of changing relationships among individuals with learning disability. *Journal of Memory and Language*, *50*, 134–148. https://doi.org/10.1016/j.jml.2003.10.004

Jarrold, C., & Citroën, R. (2013). Reevaluating key evidence for the development of rehearsal: Phonological similarity effects in children are subject to proportional scaling artifacts. *Developmental Psychology*, *49*, 837–847. http://dx.doi.org/10.1037/a002877

Jarrold, C., & Hall, D. (2013). The development of rehearsal in verbal short-term memory. *Child Development Perspectives, 7*, 182–186. https://doi.org/10.1111/cdep.12034

Jones, D. M., Hughes, R. W., & Macken, W. J. (2006). Perceptual organization masquerading as phonological storage: Further support for a perceptual-gestural view of short-term memory. *Journal of Memory and Language*, *54*, 265–281. https://doi.org/10.1016/j.jml.2005.10.006

Jones, D. M., Macken, W. J., & Nicholls, A. P. (2004). The phonological store of working memory: Is it phonological and is it a store? *Journal of Experimental Psychology: Learning Memory and Cognition*, *30*, 656–674. http://doi.org/10.1037/0278-7393.30.3.656

Jones, G. (2012). Why chunking should be considered as an explanation for developmental change before short-term memory capacity and processing speed. *Frontiers in Psychology*, *3*, 167. doi:10.3389/fpsyg.2012.00167

Kahana, M. J., & Jacobs, J. (2000). Interresponse times in serial recall: Effects of intraserial repetition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 1188–1197. http://dx.doi.org/10.1037/0278-7393.26.5.1188

Kalm, K., Davis, M. F., & Norris, D. (2012) Neural mechanisms underlying the grouping effect in short-term memory. *Human Brain Mapping*, *33*, 1634–1674. https://doi.org/10.1002/hbm.21308

Lafond, D., Tremblay, S., & Parmentier, F. (2010). The ubiquitous nature of the Hebb repetition effect: error learning mistaken for the absence of sequence learning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *36*, 515–522. http://dx.doi.org/10.1037/a0018469

Lew-Williams, C., & Saffran, J. R. (2012). All words are not created equal: expectations about word length guide infant statistical learning. *Cognition*, *122*, 241–246. https://doi.org/10.1016/j.cognition.2011.10.007

Maidment, D. W., & Macken, W. J. (2012). The ineluctable modality of the audible: Perceptual determinants of auditory verbal short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 989–997. http://doi.org/10.1037/a0027884

Majerus, S., & Boukebza, C. (2013). Short-term memory for serial order supports vocabulary development: New evidence from a novel word learning paradigm. *Journal of Experimental Child Psychology*, *116*, 811–828. https://doi.org/10.1016/j.jecp.2013.07.014

Majerus, S., Heiligenstein, L., Gautherot, N., Poncelet, M., & Van der Linden, M. (2009). The impact of auditory selective attention on verbal short-term memory and vocabulary development. *Journal of Experimental Child Psychology*, *103*, 66–86. https://doi.org/10.1016/j.jecp.2008.07.004

Majerus, S., Poncelet, M., Greffe, C., & Van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*, 95–119. https://doi.org/10.1016/j.jecp.2005.07.005

Melby-Lervåg, M., Lervåg, A., Lyster, S.-A. H., Klem, M., Hagtvet, B., & Hulme, C. (2012). Nonword-repetition ability does not appear to be a causal influence on children's vocabulary development. *Psychological Science*, *23*, 1092–1098. https://doi.org/10.1177/0956797612443833

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*, 505–514. https://doi.org/10.1080/17470210701680779

Mosse, E. K., & Jarrold, C. (2010). Searching for the Hebb effect in Down syndrome: Evidence for a dissociation between verbal short-term memory and domain-general learning of serial order. *Journal of Intellectual Disability Research*, *54*, 295–307. https://doi.org/10.1111/j.1365-2788.2010.01257.x

Nagy, W., & Herman, P. A. (1987). Breadth and depth of vocabulary knowledge: Implications for acquisition and instruction. In M. McKeown & M. Curtis (Eds.), The nature of vocabulary acquisition (pp. 19–59). Hillsdale, NJ: Lawrence Erlbaum.

Nairne, J. S., & Kelley, M. R. (2004). Separating item and order information through process dissociation. *Journal of Memory and Language*, *50*, 113-133. https://doi.org/10.1016/j.jml.2003.09.005

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

National Institute for Japanese Language and Linguistics. (1981). Tables of vocabulary obtained from Japanese children by association method. Tokyo: Tokyo Shoseki.

Norris, D., Page, M. P., & Hall, J. (2018). Learning nonwords: the Hebb repetition effect as a model of word learning. *Memory*, 1-6. https://doi.org/10.1080/09658211.2017.1416639

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

Page, M. P., 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*, 506–526. https://doi.org/10.1016/j.jml.2013.07.001

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

Perruchet, P., & Vinter, A. (1998). PARSER: A Model for Word Segmentation. *Journal of Memory and Language*, *39*, 246–263. https://doi.org/10.1006/jmla.1998.2576

R Core Team (2013). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Ryan, J. (1969). Grouping and short-term memory: Different means and patterns of grouping. *Quarterly Journal of Experimental Psychology*, *21*, 137–147. http://dx.doi.org/10.1080/14640746908400206

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926–1928.

Saito, S. (2001). The phonological loop and memory for rhythms: An individual differences approach. *Memory*, *9*, 313–322. https://doi.org/10.1080/09658210143000164

Saito, S., & Baddeley, A. D. (2004). Irrelevant sound disrupts speech production: exploring the relationship between short-term memory and experimentally induced slips of the tongue.

Quarterly Journal of Experimental Psychology: Human Experimental Psychology, *A57*, 1309–1340. http://doi.org/10.1080/02724980343000783

Smalle, E. H. M., Bogaerts, L., Simonis, M., Duyck, W., Page, M. P. A., Edwards, M. G., & Szmalec, A. (2016). Can chunk size differences explain developmental changes in lexical learning? *Frontiers in Psychology*, *6*, 1–14. https://doi.org/10.3389/fpsyg.2015.01925

Smalle, E. H. M., Muylle, M., Szmalec, A., & Duyck, W. (2017). The different time course of phonotactic constraint learning in children and adults: Evidence from speech errors. Journal of Experimental Psychology: Learning, Memory, and Cognition. https://doi.org/10.1037/xlm0000405

Smith, E., & Jarrold, C. (2014). Grouping, semantic relation and imagery effects in individuals with Down syndrome. *Research in Developmental Disabilities*, *35*, 3162–3174. https://doi.org/10.1016/j.ridd.2014.07.061

Spurgeon, J., Ward, G., Matthews, W. J., & Farrell, S. (2015). Can the effects of temporal grouping explain the similarities and differences between free recall and serial recall? *Memory & Cognition*, *43*, 469–488. https://doi.org/10.3758/s13421-014-0471-5

St-Louis, M. E., Hughes, R. W., Saint Aubin, J., & Tremblay, S. (2018). The resilience of verbal sequence learning: Evidence from the Hebb repetition effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

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*, 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*, 342–354. https://doi.org/10.1016/j.jml.2012.07.001

Towse, J. N., Hitch, G. J., & Skeates, S. (1999). Developmental sensitivity to temporal grouping effects in short-term memory. *International Journal of Behavioral Development*, *23*, 391–411. https://doi.org/10.1080/016502599383883

Table 1

Results of logistic mixed effects regression in the Model for the Hebb effect + age group in Experiment 1

Group	Variance	SD		Correlation		
Random effect						
Participant						
(Intercept)	0.83	0.91				
Sequence × Trial number	0.04	0.21		0.73		
Fixed effect	Estimate	SE	z value	Pr (>|z|)	χ^2	Pr (>χ^2)
(Intercept)	-0.92	0.17	-5.29	<.001		
Sequence	-0.07	0.05	-1.14	.152	2.03	.154
Trial number	-0.05	0.04	-1.36	.175	1.82	.177
4-year-olds	0.80	0.24	3.28	.001	10.14	<.001
5-year-olds	1.17	0.25	4.76	<.001	20.44	<.001
Sequence × Trial number	-0.04	0.05	-0.76	.447	0.58	.447
Sequence × 4-year-olds	0.28	0.07	3.89	<.001	15.05	<.001
Trial number × 4-year-olds	0.06	0.05	1.20	.232	1.42	.233
Sequence × 5-year-olds	0.37	0.07	4.97	<.001	24.67	<.001
Trial number× 5-year-olds	0.06	0.05	1.11	.267	1.22	.269
Sequence × Trial number × 4-year-olds	0.13	0.08	1.73	.083	2.97	.085
Sequence × Trial number × 5-year-olds	0.27	0.08	3.45	<.001	11.63	<.001

Table 2

Results of logistic mixed effects regression in the Model for the Hebb effect + digit span in Experiment 1

Group	Variance	SD		Correlation		
Random effect						
Participant						
(Intercept)	0.53	0.73				
Sequence × Trial number	0.03	0.19		0.64		
Fixed effect	Estimate	SE	z value	Pr (>|z|)	χ^2	Pr (>χ^2)
(Intercept)	-0.24	0.08	-2.94	.003		
Sequence	0.15	0.03	5.29	<.001	28.01	<.001
Trial number	0.00	0.02	-0.03	.977	0.00	.977
Digit span	0.27	1.03	8.97	<.001	59.56	<.001
Sequence × Trial number	0.10	0.03	3.27	.001	10.24	.001
Sequence × Digit span	0.09	0.01	7.81	<.001	62.46	<.001
Trial number × Digit span	0.02	0.00	1.98	.047	3.89	.048
Sequence × Trial number × Digit span	0.05	0.01	4.81	<.001	22.27	<.001

Table 3

Mean percentage of items correctly recalled for filler, partial Hebb, and Hebb sequences in Experiment 1 and 2. Figures in parentheses are standard errors for the recalled score. Children who obtained a high score (+1 SD) on the digit span test were allocated to the STM High group, and children who obtained a low score (- 1 SD) on the digit span test were allocated to the STM low group.

Digit span	Sequence type	Start Same	Middle same	End same
STM High (Exp 1)	Filler	.69 (.08)	.38 (.03)	.28 (.08)
	Partial Hebb	.91 (.05)	.69 (.08)	.75 (.08)
	Hebb	.88 (.06)	.75 (.08)	.84 (.07)
STM Low (Exp 1)	Filler	.38 (.08)	.30 (.08)	.39 (.08)
	Partial Hebb	.22 (.07)	.33 (.08)	.42 (.08)
	Hebb	.32 (.08)	.20 (.07)	.35 (.08)
STM High (Exp 2)	Filler	.90 (.05)	.14 (.07)	.70 (.08)
	Partial Hebb	.91 (.05)	.84 (.07)	.89 (.06)
	Hebb	.95 (.03)	.84 (.08)	.93 (.04)
STM Low (Exp 2)	Filler	.34 (.05)	.23 (.06)	.23 (.08)
	Partial Hebb	.43 (.08)	.43 (.08)	.27 (.08)
	Hebb	.26 (.08)	.17 (.06)	.30 (.08)

Table 4

Results of logistic mixed effects regression in Experiment 2

Group	Variance	SD		Correlation		
Random effect						
Participant						
(Intercept)	0.83	0.91				
Sequence × Trial number	0.02	0.15		-0.40		
Fixed effect	Estimate	SE	z value	Pr (>|z|)	χ^2	Pr (>χ^2)
(Intercept)	0.53	0.10	5.26	<.001		
Sequence	0.24	0.03	7.41	<.001	55.78	.020
Trial number	-0.01	0.03	-0.43	.666	0.18	.669
Digit span	0.34	0.03	11.99	<.001	92.73	<.001
Grouping	0.20	0.10	2.00	.045	3.92	.047
Sequence × Trial number	0.15	0.03	4.88	<.001	22.44	<.001
Sequence × Digit span	0.08	0.01	8.32	<.001	71.10	<.001
Trial number × Digit span	-0.01	0.01	-1.39	.166	1.89	.169
Sequence × Grouping	0.08	0.05	1.66	.097	2.86	.098
Trial number ×Grouping	0.03	0.02	1.21	.228	1.43	.231
Digit span ×Grouping	0.01	0.03	0.34	.736	0.11	.736
Sequence × Trial number × Digit span	0.03	0.01	3.40	<.001	11.43	<.001
Sequence × Trial number × Grouping	-0.03	0.03	-0.89	.375	0.77	.397
Sequence × Digit span × Grouping	-0.01	0.01	-0.81	.416	0.65	.420
Trial number × Digit span × Grouping	0.00	0.01	0.42	.673	0.18	.676
Sequence × Trial number × Grouping × Digit span	-0.02	0.01	-2.07	.038	4.12	.042

Figure Captions

Figure 1.

An example of a set of sequences used in Experiment 1 and 2. The first 8 Hebb trials (H) and 8 filler trials (F) make up the learning phase (A). The transfer phase is composed of the following three conditions (B, C, D). In the Start same condition (B), we examined whether children can correctly recall only the items in the first and second positions. Similarly, we only focused on the recall performance of second and third positions in the Middle same condition (C), and on the third and fourth positions in the End same condition (D). Each condition is composed of one Hebb trial (H), one filler trial (F), and one partial Hebb trial (pH).

Figure 2.

Mean percentage of items correctly recalled for Hebb and filler sequences across trial number in Experiment 1 (n = 90) and in Experiment 2 (n = 96).

Figure 3.

The plots of the difference between the average proportions of correctly recalled items for Hebb and filler sequence in the second-half trials as a function of the digit span score among 3-to 5-yer-olds in Experiment 1

Figure 4.

Mean percentage of items correctly recalled for Hebb and filler sequences across trial number in children with high and low phonological STM capacity who took part in Experiment 1.

Figure 5A and 5B.

Mean percentage of items correctly recalled for Hebb and filler sequences across trial number in children with high and low phonological STM capacity who took part in control group (Figure 5A) and in temporal grouping group (Figure 5B) in Experiment 2.

Figure 1.

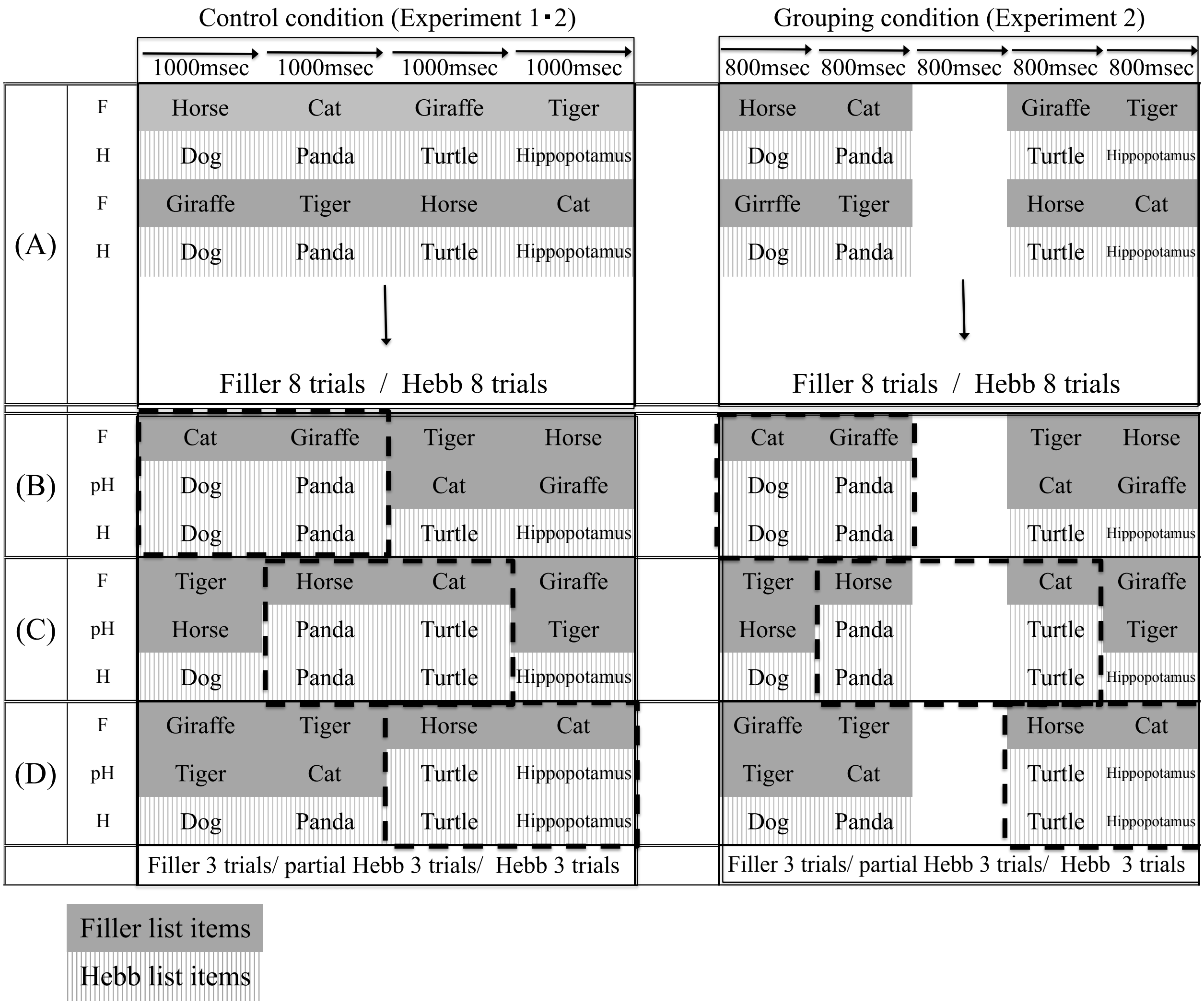

Control condition (Experiment 1・2)
Grouping condition (Experiment 2)
1000msec 1000msec 1000msec 1000msec
800msec 800msec 800msec 800msec 800msec
(A)
F Horse Cat Giraffe Tiger
H Dog Panda Turtle Hippopotamus
F Giraffe Tiger Horse Cat
H Dog Panda Turtle Hippopotamus
F Horse Cat Giraffe Tiger
H Dog Panda Turtle Hippopotamus
F Girrffe Tiger Horse Cat
H Dog Panda Turtle Hippopotamus
Filler 8 trials / Hebb 8 trials
Filler 8 trials / Hebb 8 trials
(B)
F Cat Giraffe Tiger Horse
pH Dog Panda Cat Giraffe
H Dog Panda Turtle Hippopotamus
(C)
F Tiger Horse Cat Giraffe
pH Horse Panda Turtle Tiger
H Dog Panda Turtle Hippopotamus
(D)
F Giraffe Tiger Horse Cat
pH Tiger Cat Turtle Hippopotamus
H Dog Panda Turtle Hippopotamus
Filler 3 trials/ partial Hebb 3 trials/ Hebb 3 trials
Filler 3 trials/ partial Hebb 3 trials/ Hebb 3 trials
Filler list items
Hebb list items

Figure 2.

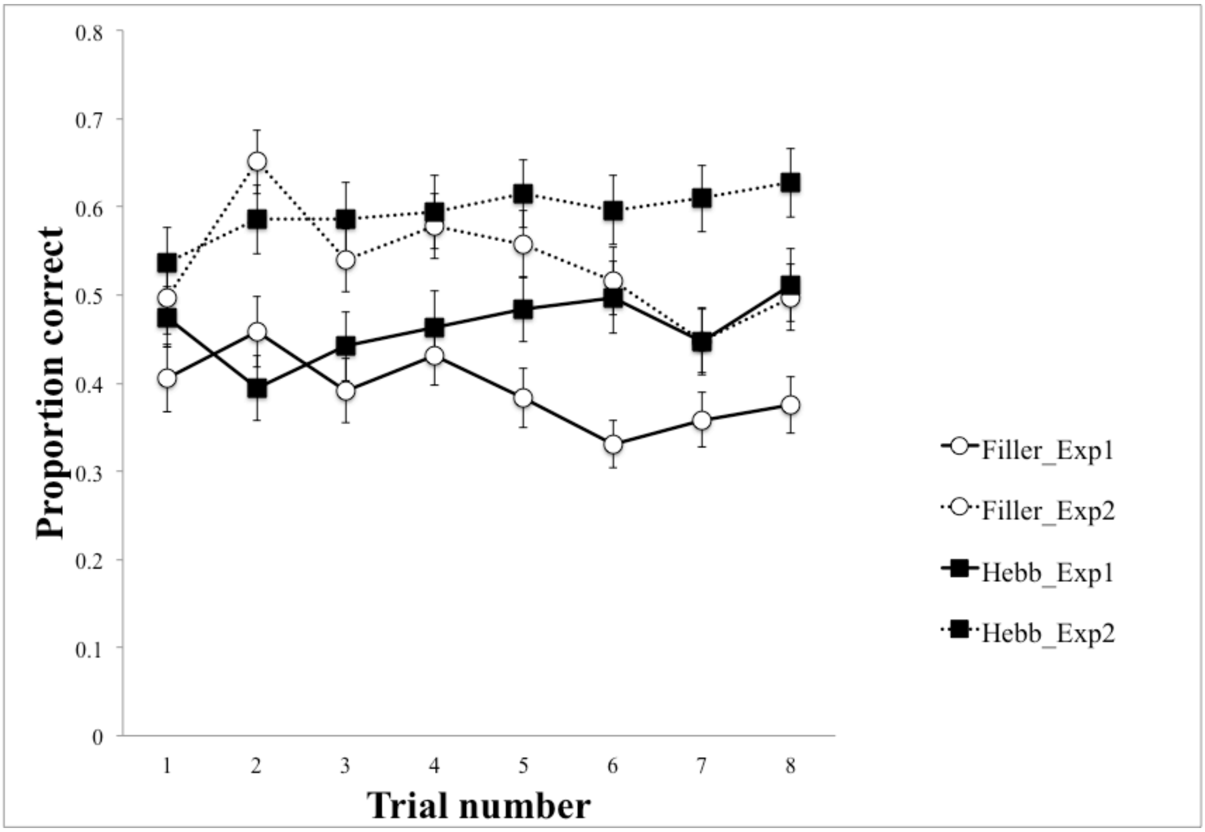
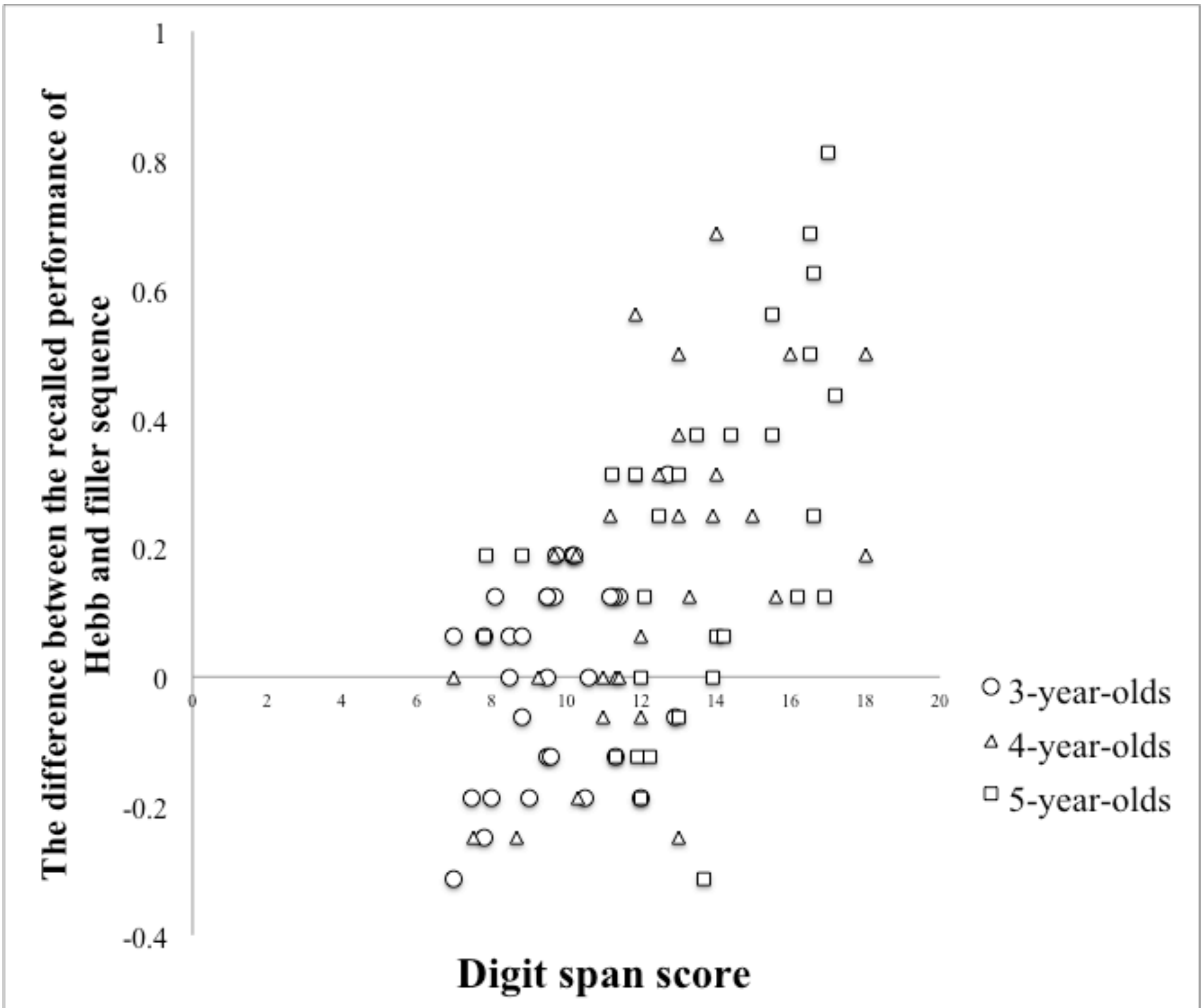

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion correct
1
2
3
4
5
6
7
8
Trial number
Filler_Exp1
Filler_Exp2
Hebb_Exp1
Hebb_Exp2

Figure 3.



The difference between the recalled performance of Hebb and filler sequence
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
10
12
14
16
18
20
3-year-olds
4-year-olds
5-year-olds
Digit span score

Figure 4.

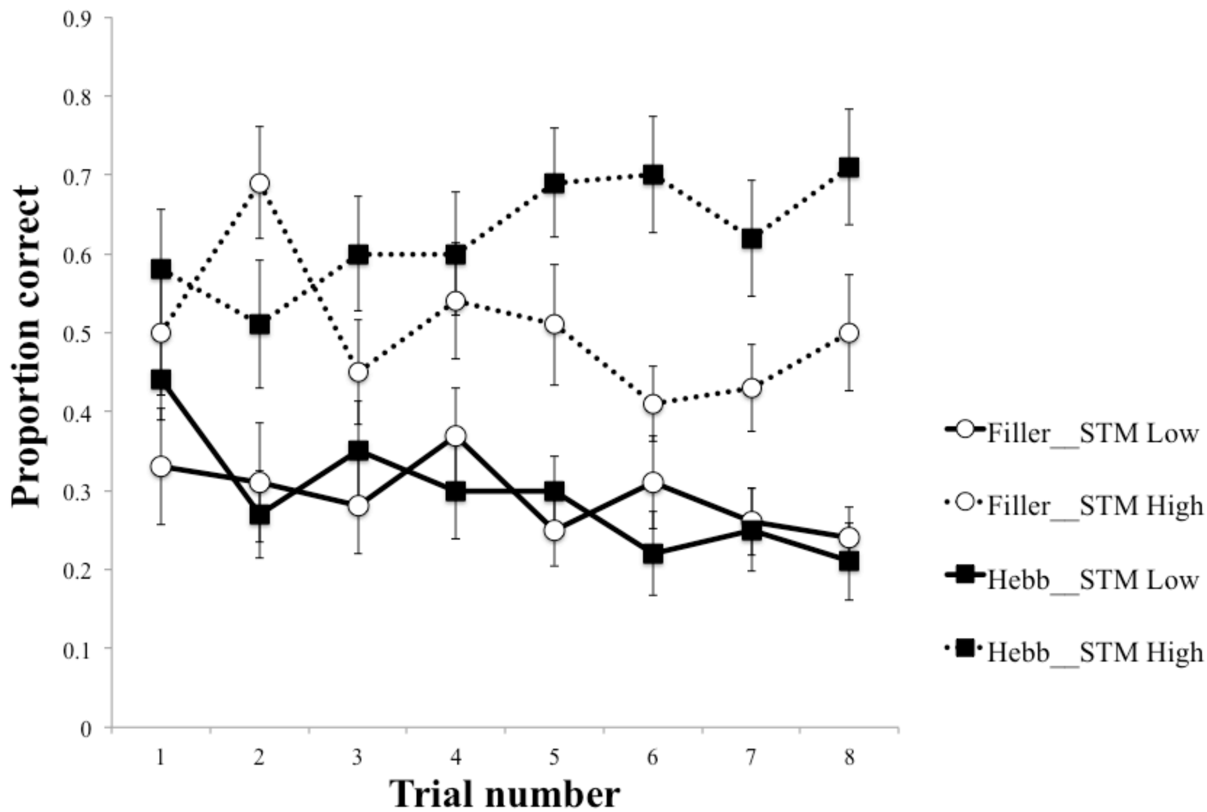

0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion correct
1
2
3
4
5
6
7
8
Trial number
Filler__STM Low
Filler__STM High
Hebb__STM Low
Hebb__STM High

Figure 5A.

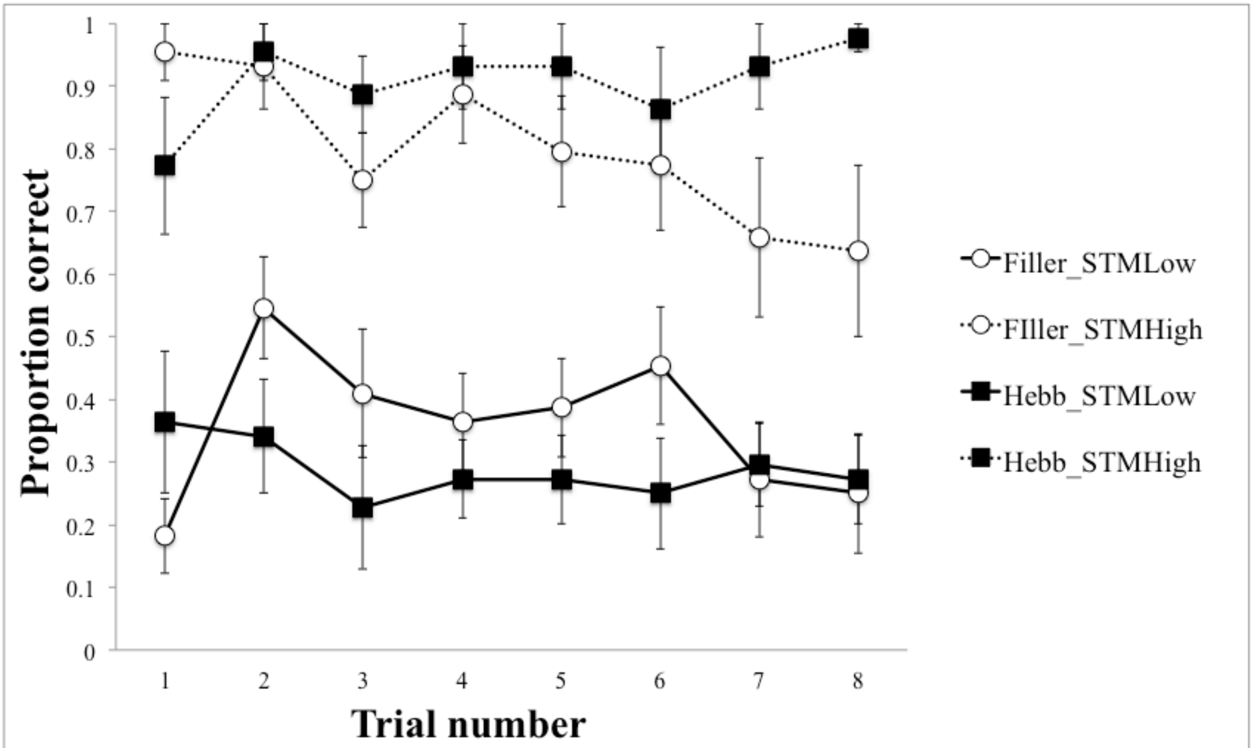
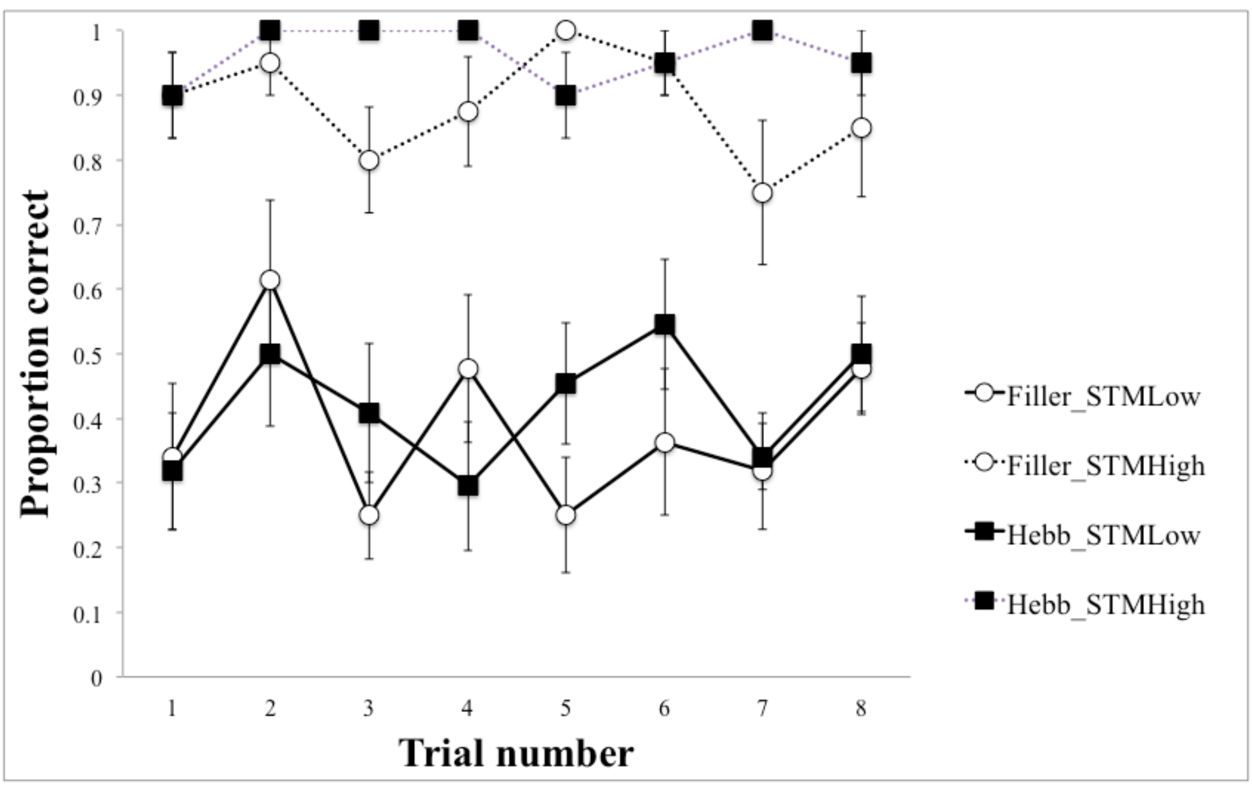


Figure 5B.



Appendix A

Results of logistic mixed effects regression for the transfer of Hebb repetition learning in Experiment 1

Group	Variance	SD		Correlation		
Random effect						
Participant						
(Intercept)	0.27	0.52				
Sequence	0.17	0.41		-0.07		
Fixed effect	Estimate	SE	z value	Pr (>|z|)	χ^2	Pr (>χ^2)
(Intercept)	-0.43	0.09	-4.94	<.001		
Sequence	0.19	0.08	2.38	.017	5.53	.019
Middle same	0.31	0.14	2.12	.034	4.52	.033
Primacy	0.58	0.17	3.41	<.001	11.79	<.001
Digit span	0.18	0.03	5.50	<.001	27.92	<.001
Sequence × Middle same	0.20	0.14	1.40	.162	1.95	.163
Sequence × Primacy	-0.31	0.17	-1.82	.069	3.30	.069
Sequence × Digit span	0.10	0.03	3.33	<.001	10.84	<.001
Middle same × Digit span	0.06	0.05	1.25	.212	1.54	.214
Primacy × Digit span	0.18	0.06	2.87	.004	8.28	.004
Sequence × Middle same × Digit span	0.06	0.05	1.21	.228	1.45	.229
Sequence × Primacy × Digit span	-0.05	0.06	-0.83	.407	0.68	.409

Appendix B

Results of logistic mixed effects regression for the transfer of Hebb repetition learning in Experiment 2

Group	Variance	SD				
Random effect						
Participant						
(Intercept)	0.45	0.67				
Fixed effect	Estimate	SE	z value	Pr (>|z|)	χ^2	Pr (>χ^2)
(Intercept)	0.13	0.09	1.03	.301		
Sequence	0.34	0.07	4.66	<.001	22.09	<.001
Middle	0.70	0.15	4.60	<.001	21.58	<.001
Primacy	0.95	0.19	5.12	<.001	27.30	<.001
Digit span	0.26	0.03	8.83	<.001	63.02	<.001
Grouping	0.15	0.10	1.45	.147	2.07	.149
Sequence × Middle same	-0.50	0.15	-3.32	<.001	11.11	<.001
Sequence × Primacy	-0.13	0.18	-0.72	.472	0.51	.473
Sequence × Digit span	0.07	0.02	3.35	<.001	11.32	<.001
Middle × Digit span	0.24	0.04	5.58	<.001	31.09	<.001
Primacy × Digit span	0.02	0.06	0.42	.678	0.18	.678
Sequence × Grouping	0.03	0.07	0.47	.640	0.22	.641
Middle × Grouping	0.22	0.15	1.44	.150	2.07	.150
Primacy × Grouping	0.04	0.18	0.21	.834	0.04	.835
Digit span × Grouping	0.02	0.03	0.52	.602	0.27	.602
Sequence × Digit span × Grouping	0.04	0.02	1.94	.053	2.76	.052
Sequence × Middle × Digit span	-0.14	0.04	-3.14	.002	9.92	.002
Sequence × Primacy × Digit span	-0.08	0.06	-1.53	.125	2.34	.126
Sequence × Middle × Grouping	0.15	0.15	0.99	.324	0.97	.325
Sequence × Primacy × Grouping	0.23	0.18	1.22	.221	1.49	.222
Middle × Digit span × Grouping	0.03	0.04	0.76	.449	0.57	.451
Primacy × Digit span × Grouping	-0.07	0.06	-1.27	.206	1.59	.207
Sequence × Middle × Grouping × Digit span	-0.01	0.04	-0.14	.892	0.02	.893
Sequence × Primacy × Grouping × Digit span	0.01	0.06	0.14	.889	0.02	.890