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Short-and long-term memory determinants of novel word form learning

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ABSTRACT

It is widely assumed that a strong positive link exists between memory and vocabulary development. Nevertheless, the exact involvement of short-term memory (STM) and long-term memory (LTM) is poorly understood. STM for serial order information is argued to play a crucial role in temporarily maintaining and refreshing the order of phonemes representing novel word forms. LTM for serial order information, in contrast, is involved in the consolidation of phoneme sequences into unitary word form representations. Here, we tested 131 6-year-old children on tasks that targeted STM for serial order versus item information, on a Hebb repetition task targeting long-term serial order learning, and on a paired-associate novel word learning task. Bayesian analyses revealed a strong correlation between STM for serial order information, and both the initial and final stages of word form learning. LTM was associated with the final stages of word form learning. These findings are discussed in light of existing theories about the role of memory in language.

Keywords: Short-term memory; Long-term memory; Serial order; Vocabulary learning

1 Introduction

In the past decades, a large number of studies have investigated the link between verbal short-term memory (STM) and vocabulary development. A series of correlational studies have shown reliable associations between STM tasks such as nonword repetition, immediate verbal serial recall, digit span, and vocabulary measures like novel word learning tasks (Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1990; Gathercole, Willis, Emslie, & Baddeley, 1992; Gupta, 2003; Gupta et al., 2004; Gupta & MacWhinney, 1997). Baddeley, Papagno, and Vallar (1988) were among the first to provide evidence for the verbal memory hypothesis of word learning in a neuropsychological patient. In their case study, they observed very poor paired-associate word learning abilities in a patient exhibiting a selective impairment of verbal STM. A large set of studies in children have also shown that nonword repetition is a reliable predictor of second language vocabulary learning (Gathercole, Hitch, Service, & Martin, 1997; Service & Kohonen, 1995). Nevertheless, although there is considerable evidence for an association between verbal STM and vocabulary development, prior studies remain relatively vague about the nature of the precise cognitive processes that underlie this association. One important aspect to consider when studying vocabulary learning is that learning a new word entails two main subcomponents: First, the learning of the phonological representation of the new word, or the learning of the word form, and second, the mapping of this word form to its meaning (semantic representation; Swingley, 2010). In the present study we will focus on one specific aspect of vocabulary learning, namely the acquisition of *word forms* (i.e. the phonological representation of a word) in the absence of meaning in order to examine the role of serial order memory in phonological form learning as directly as possible.

It is nowadays well-accepted that language is sequential in nature (Hsu & Bishop, 2014; Saffran, Aslin, & Newport, 1996). Burgess and Hitch (1992), for instance, postulated in their connectionist model of STM that when a new word is encountered, the phonemes of this word will be activated in the sublexical system and the STM system will simultaneously encode and temporarily maintain the order of activation of these phonemes in the sublexical system. This will allow the reactivation of the new word form with each phoneme in its correct serial position. Acquiring the phonological form of a word is thus obviously driven by learning the serial order of its constituent phonemes. In order to shed new light on the cognitive processes underpinning novel word form learning, an increasing number of STM models focusing on serial order processing have emerged (Burgess & Hitch, 1999; Gupta, 2003, 2006; Page & Norris, 2009a, 2009b). Many of these models further suggest to make a distinction between the mechanisms driving the recall of item (i.e., the identity of the items) versus serial order (i.e., the serial order amongst these items) information (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999, 2006; Gupta, 2003, 2006; Gupta & MacWhinney, 1997; Henson, 1998; Majerus & Boukebza, 2013; Majerus & D'Argembeau, 2011; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Page & Norris, 2009a, 2009b). They suggest that the recall of item information depends on the temporary activation of the language system, while order information is stored in a specific STM system (Brown et al., 2000; Burgess & Hitch, 2006; Gupta, 2006; Majerus & D'Argembeau, 2011). In other words, the recall of item information is assumed to be affected by knowledge encoded in the language system such as (sub)lexical and semantic knowledge, while the recall of serial order information is much less influenced by this knowledge (Majerus & Boukebza, 2013; Majerus & D'Argembeau, 2011; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 2005). According to these findings, the existence of an association between item STM and vocabulary measures is likely to reflect the common reliance on current language knowledge. Because serial order recall is known to be less affected by language knowledge (Nairne & Kelley, 2004), it has been assumed that the observation of a link between serial order STM and vocabulary measures would provide evidence for a specific and language-independent association between STM and vocabulary development (Leclercq & Majerus, 2010). At the same time, some models, like for instance the (C-)SOB models, do not consider a distinction between item and order codes and assume that item and order information of to-be-recalled lists are processed simultaneously and may thus be supported by a single mechanism. According to these models, serial order is encoded via item-to-context association mechanisms, and the encoding strength of to-be-recalled items decreases across serial position since only what is novel at each item position is encoded. At recall, a context cue is used to find an individual context-item association, which may sometimes be distorted by the encoding of other context-item associations. After recall, an item is subsequently suppressed (Farrell, 2012; Farrell & Lewandowsky, 2002; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Thus, it seems that the maintenance of order is directly affected by list items (Camos, Lagner, & Loaiza, 2017). These models however, have difficulties in accounting for item and order processing dissociations that have been observed at behavioral and neural levels. In addition to the studies mentioned at the beginning of this paragraph, neuropsychological and neuroimaging studies further support the distinction between item and order information processing. Functional neuroimaging studies (Henson, 1998; Majerus, 2013; Majerus et al., 2010a; Majerus, Poncelet, Van der Linden, et al., 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008; Marshuetz, Smith, Jonides, DeGutis, & Chenevert, 2000) have shown activation of distinct brain networks for item (i.e., bilateral temporal regions) versus order processing (i.e., left and right intraparietal sulci). Neuropsychological studies have also observed dissociations between item and serial order STM abilities (Majerus, Norris, & Patterson, 2007).

In the light of this item-order dissociation, Majerus and colleagues have tried to clarify the nature of the association between verbal STM and novel word form learning by using tasks allowing to make a distinction between item and serial order recall performance (Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006). These studies have demonstrated the existence of a specific association between STM for serial order, compared to item information, and word form learning. In their study, Majerus and Boukebza (2013) hypothesized that especially serial order STM would support the learning of unfamiliar phoneme sequences. Given that a considerable number of words in any language are rearrangements (or anagrams) of the same set of phonemes (e.g., leaf vs. flea, eat vs. tea), the exact order of phoneme sequences is essential to differentiate these word forms. According to Majerus and Boukebza (2013), serial order STM not only seems to support the temporary maintenance of the phoneme sequences defining a novel word, but also facilitates the capacity to distinguish two phonologically similar words (see also Smalle et al., 2016). In order to control for the impact of language knowledge, Majerus and Boukebza administered two STM tasks to a developmental sample of children – one maximizing serial order demands and another maximizing item information demands. Serial order STM was assessed via a serial order reconstruction task minimizing item STM requirements by providing all items at recall. Item STM was measured via a single nonword delayed repetition task whose consonant-vowel-consonant (CVC) structure allowed to minimize the opportunity to make serial order errors (Leclercq & Majerus, 2010). In order to operationalize novel word form learning, the children were asked to learn the names of aliens in a paired-associate novel word learning task. The findings obtained in this study showed that serial order STM predicts novel word form learning above and beyond item STM, relational learning abilities, and non-verbal intellectual efficiency. These results demonstrate that especially serial order STM is involved in the temporary maintenance and reactivation of to-be-learned phonological word forms.

Other recent studies have tried to better understand how exactly these sequential short-term representations are mapped into stable long-term representations (Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). To study the transition from STM to long-term memory (LTM), these studies used the Hebb repetition paradigm. In the Hebb repetition paradigm (Hebb, 1961), participants perform an immediate verbal serial recall task of repeating (Hebb) sequences and non-repeating (filler) sequences of nine digits, with the Hebb sequence being repeated on every third trial. Hebb observed that the recall for repeated sequences gradually increased compared to non-repeating sequences. This observation is known as the Hebb repetition effect (HRE). In their computational model, Page and Norris (2009b) assumed that the repeated exposure to one particular sequence in a Hebb repetition task is functionally equivalent to the learning of a novel word form. In other words, they suggest that the HRE might basically rely on the same mechanisms as those underlying novel word form learning. This model was one of the first computational attempts at clarifying the link between the long-term learning of sequential information and word form learning. Correlational work using the Hebb repetition paradigm corroborated this assumption (Archibald & Joanisse, 2013; Mosse & Jarrold, 2008). Mosse and Jarrold, for instance, showed that performance for both verbal and visuospatial variants of the Hebb learning tasks in young children correlates significantly with a paired-associate novel word learning task. These studies suggest that a core ability to represent serial order information, independently of stimulus modality, underlies the acquisition of novel word forms. At about the same time, an increasing number of studies using the Hebb repetition paradigm as a laboratory analogue of novel word form learning emerged (Smalle et al., 2016; Szmalec et al., 2009; Szmalec et al., 2012). Szmalec et al. (2012) presented a set of nine consonant-vowel (CV) syllables for immediate serial recall to their participants. These sequences were grouped by pauses between each set of three syllables. The repeating Hebb sequence contained groups of three syllables (e.g., la-va-bu, sa-fa-ro, re-si-di) that resembled existing Dutch words (lavabo, safari, residu). Hebb learning was followed by a pause-detection task containing the Dutch base-words (e.g., lavabo) and control words. Participants were asked to detect artificial pauses in connected speech that were embedded inside some of the Dutch base-words and the control words. Results showed that participants took more time to detect the pauses on the Dutch base-words that overlapped with the Hebb sequence, compared to the control words. These findings indicate that participants created novel long-term lexical representations during the Hebb task which became potential lexical competitors of the Dutch base-words and therefore slowed down pause detection.

Taken together, the serial order STM approach and the Hebb learning approach reach very similar theoretical conclusions regarding the role of serial order memory in novel word form learning. However, these two approaches are also known to tap into different memory processes, by implicating short-term versus long-term memory systems. This is also supported by recent neurophysiological and neuroimaging data showing an involvement of the intraparietal sulcus and the dorsolateral prefrontal cortex in STM tasks (Majerus et al., 2010b), and hippocampal and medial temporal lobe structures in Hebb learning tasks (Gagnon, Foster, Turcotte, & Jongenelis, 2004; Kalm, Davis, & Norris, 2013). In sum, although the link between novel word form learning and both serial order STM and the long-term learning of sequential information has been well established, these two lines of research have not yet addressed the questions of *how* and *when* exactly serial order STM and the long-term learning of sequential information are involved in the acquisition of novel word forms.

The purpose of the present study was thus to bring both lines of research together to obtain a more detailed view of how and when serial order short- and long-term memory contribute to novel word form learning. In other words, we were interested in contrasting STM for serial order information and long-term serial order learning abilities and examining their respective role in the acquisition of novel word forms. To improve readability, we will use the term "serial order LTM" when referring to serial order long-term learning as operationalized via the Hebb repetition learning task.

In the current study, we hypothesize that an interaction between STM and LTM mechanisms allows children to capture linguistic input from their environment and to consolidate it in long-term, stable linguistic representations. In other words, we suggest that serial order STM will first allow to temporarily maintain and refresh the phoneme sequence of the novel word, while Hebb-like learning processes in serial order LTM will allow to consolidate this sequence into a unitary representation, so that it can evolve towards a more stable long-term lexical representation. For assessing serial order STM, we used a serial order reconstruction task maximizing retention requirements for serial order information and further control for phonological item retention processes via a separate item STM task. The serial order reconstruction task had been used in a number of previous studies (e.g. Attout & Majerus, 2015; Attout, Noël, & Majerus, 2014; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus, Poncelet, Greffe, et al., 2006; Martinez Perez, Majerus, & Poncelet, 2012), and used a closed set of highly familiar animal names that allowed for item predictability of the memory sequences while only the serial order of the items within the sequence changed. Given that no task can be considered to be a completely pure serial order STM task, phonological item retention abilities were further controlled using a single nonword delayed repetition task also validated in previous studies (e.g. Attout & Majerus, 2015; Attout et al., 2014; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus, Poncelet, Greffe, et al., 2006; Martinez Perez et al., 2012). The item STM tasks used single nonwords in order to minimize the intervention of list-level serial ordering processes as much as possible. Note that both tasks are assumed to recruit general attentional demands to a similar extent as suggested by a recent study by Camos et al. (2017), who showed that item and serial order STM components involve attentional processes, such as attentional refreshing, to a similar extent. Serial order LTM was assessed by Hebb repetition learning of sequences of syllables. Word form learning was operationalized through a paired-associate novel word learning task inspired by Majerus and Boukebza (2013) and previously used in multiple studies (Gathercole, Willis, Baddeley, & Emslie, 1994; Gupta, 2003, 2006; Gupta et al., 2004).

Overall, we predicted that, if there is a specific and language-independent association between STM and novel word form learning, serial order STM, rather than item STM, should be related to recall performance in the *initial* stages of novel word form learning, i.e. when the phonemes that constitute a novel word form need to be temporarily maintained and rehearsed in correct serial order. On the other hand, we anticipated that serial order LTM (Hebb learning) would be associated with recall performance rather in the *final* stages of novel word form learning, i.e. when the phoneme sequences are consolidated into a unitary long-term lexical representation.

2 Method

2.1 Participants

A total of 131 typically developing French-speaking children (66 females) from first grade participated in this study. Their mean age was 80.64 months (SD = 4.92). The children were recruited in nine different primary schools in the region of Walloon Brabant, Belgium. We distributed a written description of the study as well as a parental and anamnestic questionnaire to the parents to ensure that the children's native language was French, that the children were monolingual and that they had no history of neurological disorder, neurodevelopmental delay, sensory, or learning impairments. The children were recruited from families with a middle-class socio-economic background. All children participated voluntarily in this study and parental consent was obtained. The experiment has been approved by the Ethics Commission of the Université catholique de Louvain.

2.2 Materials and Procedure

Note that the present study is part of a larger project on the role of serial order STM and LTM in the development of spoken and written language abilities, meaning that children were administered additional tasks that will be reported elsewhere. Each school that participated in our study made a quiet room available in which the children were tested individually.

2.2.1 Order short-term memory task (Animal Race task)

This task was designed and validated by Majerus, Poncelet, Greffe, et al. (2006) to assess serial order STM by minimizing item information processing requirements. After the auditory presentation of sequences of a maximum of seven animal names (chat, chien, coq, lion, loup, ours, singe [cat, dog, cock, lion, wolf, bear, monkey, respectively]) participants were asked to rearrange cards with the depicted animals in the order of presentation. They were required to remember sequences from two to seven items with three trials per sequence length. During the task, children heard a prerecorded female voice through headphones announcing the animal sequences at a rate of one item per second. In order to make the task more playful, we told the children that animals organized a race and that they had to put the pictures of the animals on the podium (staircase with seven steps on a sheet) in the order of their arrival. For each sequence, we only provided them with the animal cards that were announced through the headphones. Item memory requirements were minimized, given that all items were available to the participants at recall. The animal names were all monosyllabic, highly familiar and of low age of acquisition, therefore further reducing item information processing requirements (for a more detailed description of the task, see Majerus &

Boukebza, 2013; Majerus et al., 2006). Given the considerable amount of experimental tasks in this study, we reduced the number of trials per length from four to three relative to the original version of the task. Given the variable level of difficulty of the items, internal consistency as measures by Cronbach's alpha was relatively low (.65). At the same time, test-retest reliability for this task has been proven to be high ($r = .82$, $p < .05$; Majerus, Poncelet, Greffe, et al., 2006). The number of items that were placed in the correct order of presentation was the dependent variable.

2.2.2 Item short-term memory task (Princess task)

We used this single nonword delayed repetition task, also validated by Majerus et al. (2006), to assess the retention of item information in STM. During the task, children were told that they are an adventurer (for a boy) or a princess (for a girl) and that someone locked them up in the tower of a castle. In order to escape, they have to open 20 doors by remembering magic passwords (i.e., the nonwords). Participants needed to repeat the nonword immediately after its presentation to ensure that they had correctly perceived the item. Subsequently, participants were asked to repeatedly produce the syllable "bla" for a total of 3 seconds to block their articulatory rehearsal process and thus, to prevent sequential rehearsal of the phonemes constituting the item. Finally, they were asked to recall the nonword that they heard 3 seconds before. The items were CVC nonwords with low diphone frequencies (CV mean = 138, range = 7-361; VC mean = 126, range = 7-708) relative to the phonological structure of French (Tubach & Boe, 1990). This allowed us to maximize phonological item STM requirements. Given that only a single item had to be recalled at a time, serial order information demands were reduced to a minimum. The CVC structure of each item allowed reducing the occurrence of order errors, given that the only error that could be done was to invert both consonants (e.g., *dub* becomes *bud*). Also, note that this kind of error has been proven to be very rare in young children (Leclercq & Majerus, 2010). Items were recorded by a female voice and were presented using headphones (for a detailed description of the task, see Majerus & Boukebza, 2013; Majerus et al., 2006). In order to reduce the overall testing time, the task consisted of 20 monosyllabic nonwords instead of 34 as in the original task. Cronbach's alpha indicated a reliability of .70 for this task. The proportion of correctly repeated phonemes for the delayed recall was used as the dependent variable.

2.2.3 Hebb repetition learning task

Sequences of nonsense CV syllables were presented auditorily to the children for immediate serial recall. Some sequences of syllables were repeated (Hebb sequences) while the other sequences contained random syllable successions (filler sequences). The length of the sequences was 6 syllables, which corresponds to the mean digit span of 6-year-old children (i.e., 4; Case, Kurland, & Goldberg, 1982; Dempster, 1981) plus two more items to provide a range for progression through repetition learning. The filler sequences contained different syllables than the Hebb sequence (Mosse & Jarrold, 2010). To this end, two sets of 6 syllables were matched for diphone frequency by using the French database "Diphones-fr" (see Table 1; New & Spinelli, 2013). The WordGen software was used in order to match all sequences according to their summed diphone frequency (Duyck, Desmet, Verbeke, & Brysbaert, 2004). We ensured that two (or more) consecutive syllables never resulted in an existing French word. Four different Hebb sequence orders were created from the Hebb items set. The four resulting Hebb sequences were counterbalanced across participants to avoid sequence-specific effects. The Hebb learning task consisted of 18 sequences in total: 9 repetitions of the Hebb sequence interspersed with 9 filler sequences, for which the order of the six syllables was pseudo-random in the sense that we controlled that none of the syllable sequences contained existing French words. All syllables were recorded by a female voice and presented one at a time through headphones. The inter-stimulus interval was 100 ms.

Before the learning phase, the child first had to repeat each syllable, to ensure that he or she correctly perceived the items. This familiarization phase was repeated three times. The task started with the recall of two filler sequences, which were introduced as a practice. During the learning phase, filler and Hebb sequences were presented alternately: f, H, f, H, f, H, f, H, f … Each participant was instructed to verbally recall each sequence immediately after its auditory presentation. If the participant forgot an item among the six syllables, he or she was allowed to say “blanc” (“blank” in English) and to continue the recall. Task reliability was .70 for filler and .94 for Hebb sequences according to Cronbach’s alpha. Hebb scores were computed based on a method introduced by McKelvie (McKelvie, 1987; Smalle et al., 2016; Staels & Van den Broeck, 2015). This method takes into account the *absolute position* of the recalled items, but also their *relative serial position*. It is composed of four steps. In the two first steps, the number of items recalled in correct position (1) from left to right and (2) from right to left up to the first error is determined. In the two subsequent steps, items recalled in any correct order (in groups of two or more items) are counted (3) from left to right (4) and from right to left. For instance, for the target sequence “da, lu, fi, pa, ve, ti”, the recalled sequence “da, lu, blank, fi, pa, ti”, would be scored as 2 items correct in step (1) (i.e., da, lu), 1 item correct in step (2) (i.e., ti), 2 items correct in step (3) (i.e., “fi, pa” occur together), and finally, 0 items correct in step (4), yielding a total score of 5 (2+1+2+0) out of 6.

Table 1

Stimulus material for the Hebb task. French diphone frequency for each syllable is reported.

Filler		**Hebb**	
CV	**Diphone**	**CV**	**Diphone**
TI [ti]	3440	RI [ʁi]	3880
PA [pa]	1755	MI [mi]	1670
FI [fi]	1142	NA [na]	1262
VE [və]	50	BE [bə]	29
DA [da]	497	GU [gy]	173
LU [ly]	615	SO [sɔ]	492

2.2.4 Paired-associate novel word learning task

This task has been designed and validated by Majerus and Boukebza (2013). It requires children to learn the names of three aliens: Nour, Bam, and Rize. The three aliens appear one by one on a computer screen and present themselves to the child by saying "Hello, my name is …". Immediately after the presentation of the three aliens, they reappear in a different order and the child is asked to recall their names. After the recall procedure, each alien reappears one by one and presents himself again. This procedure was repeated for a total of six learning and recall trials. The children were told that the three aliens wanted to make their acquaintance and that they therefore had to remember their names. Like Majerus and Boukebza (2013), we calculated the learning speed index as the dependent variable. This index represents the earliest trial number after which the participant could recall all three items correctly on all subsequent trials. For instance, a score of 2 was given if the participant recalled all items on trial 2 and all subsequent trials. A score of 7 was allocated to 26% of the participants who could not correctly recall all three items after the six learning trials. A similar procedure has been used by Gathercole and Baddeley (1990).

2.2.5 Receptive vocabulary knowledge

Receptive vocabulary knowledge was assessed using the standardized EVIP scales (Dunn, Theriault-Whalen, & Dunn, 1993), a French adaptation of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981). Raw scores were used as the dependent measure.

2.2.6 Nonverbal intelligence

General nonverbal intelligence was assessed using the standardized Raven's colored progressive matrices (RCPM, Raven, Court, & Raven, 1998). Raw scores were used as the dependent measure.

Estimates of vocabulary knowledge and nonverbal intelligence were collected to ensure that our participant sample was homogeneous with respect to receptive vocabulary and nonverbal intelligence abilities, and that no participant showed developmental delay or cognitive impairment. All children were tested in three different sessions. Each session lasted approximately 35 minutes. To avoid fatigue effects, the first session always began with the Hebb task followed by the order STM task and the novel word learning task, with the order of presentation of the latter two tasks counterbalanced across participants. The item STM task and the receptive vocabulary task were administered one day later during the second session, and the order of presentation was again counterbalanced across participants. Finally, each participant performed Raven’s colored progressive matrices, organized in small groups of more or less six children.

3 Results

Three participants (1 female) were excluded from the analyses because they suddenly made mistakes at the last trial of the novel word learning task, probably due to fatigue, after at least three successive trials with correct responses. This allowed us to ensure that the results were not biased by lapses of attention. Consequently, the sample was reduced to 128 participants. Skewness and Kurtosis estimates showed that item STM and Hebb scores were not normally distributed. Hence, we transformed them by using an arcsine square root transformation approach allowing to normalize percentage scores (Archibald & Joanisse, 2013; Smalle et al., 2016). After transformation, all variables were normally distributed as revealed by the Kolmogorov-Smirnov test. Untransformed descriptive statistics are shown in Table 2.

Table 2

Descriptive statistics for all tasks.

	M	SD	Skew[a]	Kurt[b]
EVIP (raw score)	89.23	13.49	-.46	.45
RCPM (raw score)	26.88	4.37	-.46	-.55
Short-term memory				
Serial order	.55	.09	.22	-.46
Item	.73	.13	-.92	1.34
Long-term memory				
Filler (mean score)	.24	.15	.96	3.56
Hebb (mean score)	.38	.26	.70	-.46
Filler (1st half)	.26	.17	-	-
Filler (2nd half)	.22	.15	-	-
Hebb (1st half)	.33	.26	-	-
Hebb (2nd half)	.42	.29	-	-
Novel word learning				
LSI	4.70	1.88	-.26	-1.16
Initial trials	.54	.23	-	-
Final trials	.85	.22	-	-

Note. All scores reflect proportion of correct responses except for EVIP, RCPM and LSI. EVIP = vocabulary knowledge measure; RCPM = Raven’s colored progressive matrices; LSI = learning speed index.

[a] Standard error Skewness cutoff = ± 0.21.

[b] Standard error Kurtosis cutoff = ± 0.42.

The Hebb learning data were analyzed according to the procedure put forward by Mosse and Jarrold (2008), Archibald and Joanisse (2013), and Smalle et al. (2016). This procedure consists of collapsing the trials of each sequence type into first- and second-half scores (in the present study, the data on trials 1 to 4 were collapsed into a first-half score, the data on trials 6 to 9 into a second-half score). Half-scores allow to define learning in terms of improvement from the first- to the second-half of the task. The Hebb data are plotted in Figure 1. Split-half reliability correlations were reasonable to good (r = .55 to .80).

In the present study, we ran a 2 (Sequence type: filler vs. Hebb) x 2 (Half: first vs. second) Bayesian repeated measures ANOVA in order to evaluate the long-term learning of serial order information in the Hebb task. Bayesian analyses were computed using JASP (2016). We report the BF_{10} as support for the alternative hypothesis (H1) over the null-hypothesis (H0). Small values ($BF_{10} < 1$) indicate that there is more evidence for the null hypothesis, and large values ($BF_{10} > 1$) indicate more evidence for the alternative hypothesis. Note that we relied on the guidelines proposed by Jeffreys (1961) for interpreting Bayes factors. Results of the Bayesian repeated measures ANOVA are summarized in Table 3. Results indicated decisive evidence for an effect of Sequence type and anecdotal evidence against an effect of Half. Importantly, there was decisive evidence for the alternative hypothesis regarding the model including both main effects and the interaction, under which the data were most likely. The interaction between Sequence type and Half, reflecting higher scores on the second-half ($.73 \pm .03_{SE}$[1]) than on the first-half ($.61 \pm .02_{SE}$) of Hebb sequence repetitions, provides evidence for the occurrence of Hebb learning (Archibald & Joanisse, 2013). These results were confirmed by an analysis of specific effects (see Table 4) showing high $BF_{Inclusion}$ scores for both main effects and their interaction.

[1] Mean and standard error after arcsine square root transformation.

Table 3

Bayesian repeated measures ANOVA: Model comparison.

Models	P(M)	P(M|data)	BF_M	BF_{10}	% error
Null model (incl. subject)	0.200	$6.701e^{-18}$	$2.680e^{-17}$	1.000	
Type	0.200	$4.262e^{-6}$	$1.707e^{-5}$	$6.368e^{+11}$	1.022
Half	0.200	$3.873e^{-18}$	$1.549e^{-17}$	0.578	1.837
Type + Half	0.200	$3.369e^{-6}$	$1.348e^{-5}$	$5.028e^{+11}$	2.973
Type + Half + Type*Half	0.200	1.000	523819.26	$1.492e^{+17}$	2.165

Note. P(M) = prior model probabilities; P(M|data) = posterior model probabilities; BF_M = change from prior to posterior model odds; BF_{10} = Bayes factor against the null model.

Table 4

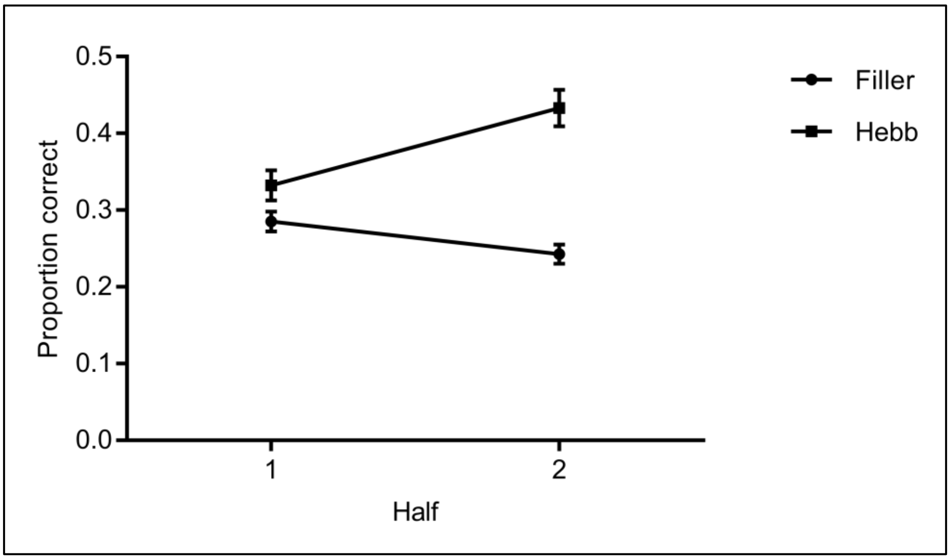
Bayesian repeated measures ANOVA: Specific effects.

Effects	P(incl)	P(incl|data)	$BF_{Inclusion}$
Type	0.600	1.000	> $1e^{+305}$
Half	0.600	1.000	156239
Type*Half	0.200	1.000	523819

Note. P(incl) = prior inclusion probability; P(incl|data) = posterior inclusion probabilities; $BF_{Inclusion}$ = change from prior to posterior inclusion odds.

Figure 1

Mean proportion of items correctly recalled (with standard errors) for Hebb and filler sequences by sequence halves.



Bayesian partial correlations were conducted using the JZS method (Jarosz & Wiley, 2014; Zwaan & Pecher, 2012) from the BayesMed package (Nuijten, Wetzels, Matzke, Dolan, & Wagenmakers, 2015) in R. Partial correlation coefficients were calculated using the ppcor package (Kim, 2015) in R. These analyses allowed us to investigate (1) the specific link between serial order STM (animal race task) and novel word form learning by controlling for item STM (princess task) and (2) the specific link between serial order LTM (recall of Hebb sequences) and novel word form learning by controlling for serial order STM (recall of filler sequences). In analysis (2), serial order STM is operationalized as recall performance for filler sequences, which is the common way to control for STM baseline differences in the Hebb paradigm (Bogaerts, Szmalec, De Maeyer, Page, & Duyck, 2016; Bogaerts, Szmalec, Hachmann, Page, & Duyck, 2015; Mosse & Jarrold, 2008; Staels & Van den Broeck, 2015). We should also note that Hebb repetition tasks reflect the transition from a temporary sequence to a more durable representation of this sequence in LTM, and hence reflect both STM and LTM components (Szmalec et al., 2009). Therefore, in order to isolate the LTM component as directly as possible, we decided to calculate two distinct scores. A first score represented performance averaged over the first-half of the Hebb task, which can be considered to rely more on STM than on LTM processes. A second score represented performance averaged over the second-half of the Hebb task, which can be considered to more strongly reflect LTM capacity for serial order information. In our analyses, variables of interest were correlated with performance on the second-half of repeated Hebb sequences after controlling for performance on the second-half of filler sequences. Note that we chose to control for second-half filler sequences (Archibald & Joanisse, 2013; Smalle, Page, Duyck, Edwards, & Szmalec, 2017) rather than for first-half repeated trials performance (Mosse & Jarrold, 2008), in order to make sure that attentional factors and fatigue affected both scores in a similar way.

The data confirmed previous findings showing that there is very strong evidence for a link between serial order STM and the learning speed index of the novel word learning task when controlling for item STM. Additionally, there was anecdotal evidence for the absence of a link between item STM and the learning speed index ($BF_{01} = 1/BF_{10}$, thus $BF_{01} = 1/0.78 = 1.28$), when controlling for serial order STM. Bayesian analyses showed only anecdotal evidence in favor of a link between serial order LTM (Hebb learning) and the learning speed index (cf. Table 5).

Table 5

Partial correlations between memory tasks and the learning speed index.

Memory measures	Word learning measure	*r*	BF_{10}
Order STM	LSI[a]	-.31***	54.24
Item STM	LSI[b]	-.18*	0.78
2nd half Hebb	LSI[c]	-.19*	1.22

Note. STM = short-term memory; LSI = learning speed index of the novel word learning task.

[a] Item short-term-memory task partialled out.

[b] Order short-term-memory task partialled out.

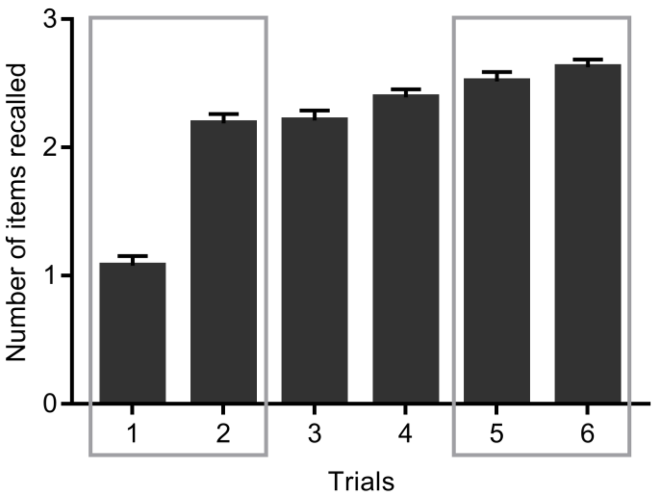
[c] Second-half of filler sequences partialled out.

*p < .05. ***p < .001.

With regard to our hypothesis that serial order STM would be involved in the *initial* stages of novel word form learning and that serial order LTM (Hebb learning) would rather be associated to *later* stages of word form learning (when consolidation takes place), we decided to calculate an initial (1st and 2nd trial) and a final (5th and 6th trial) score for the novel word learning task (cf. Figure 2). These scores are assumed to mimic the initial and final stages of naturalistic novel word form learning, respectively.

Figure 2

The two first and the two last trials of the novel word learning task representing the initial versus final stages of naturalistic word form learning, respectively.



As expected, Bayesian partial correlations (cf. Table 6) showed very strong evidence in favor of a link between serial order STM and initial stages of novel word form learning. However, in contrast to our hypothesis, results also showed very strong evidence for a link between serial order STM and final stages of novel word form learning. Additionally, there was strong evidence for a link between serial order LTM (Hebb learning) and the final stages of the novel word form learning. Finally, substantial evidence (BF_{01} = 1/0.20 = 5) for the absence of a link between serial order LTM (Hebb learning) and the initial stages of novel word form learning has been shown.

Table 6

Partial correlations between memory tasks and the novel word learning task.

Memory measures	Word learning measures	*r*	BF_{10}
Order STM	Initial trials[a]	.30***	53.47
	Final trials[a]	.30***	51.80
2nd half Hebb	Initial trials[b]	.10	0.20
	Final trials[b]	.26**	10.90

Note. STM = short-term memory.

[a] Item short-term-memory task partialled out.

[b] Second-half of filler sequences partialled out.

**p < .01. ***p < .001.

In a second step, we conducted the same correlational analyses by controlling for receptive vocabulary knowledge (EVIP) and nonverbal intelligence (RAVEN) in addition to memory measures. These analyses showed the same overall pattern of results as our previous analyses, indicating that our findings are robust (cf. Table 7). In line with our previous analyses, there was very strong evidence for a link between serial order STM and the learning speed index of the novel word learning task. Regarding item STM, there was anecdotal evidence (BF_{01} = 1/0.54 = 1.85) for the absence of a link with the learning speed of novel words. Finally, analyses showed anecdotal evidence for the absence of a link (BF_{01} = 1/0.79 = 1.26) between serial order LTM and the learning speed index.

When looking at initial and final trials of our novel word learning task (cf. Table 8), we observed decisive evidence for a link between serial order STM and both, initial and final stages. As shown in our previous analyses, there was substantial evidence (BF_{01} = 1/0.21 = 4.76) for the absence of a link between serial order LTM (Hebb learning) and the initial stages of novel word form learning. Finally, findings showed anecdotal evidence for a link between serial order LTM and the final stages of novel word form learning.

Table 7

Partial correlations between memory tasks and the learning speed index after controlling for receptive vocabulary knowledge and nonverbal intelligence.

Memory measures	Word learning measure	*r*	BF_{10}
Order STM	LSI[a]	-.26**	54.24
Item STM	LSI[b]	-.14	0.54
2nd half Hebb	LSI[c]	-.16	0.79

Note. STM = short-term memory; LSI = learning speed index of the novel word learning task.

[a] Item short-term-memory task, EVIP, and RAVEN partialled out.

[b] Order short-term-memory task, EVIP, and RAVEN partialled out.

[c] Second-half of filler sequences, EVIP, and RAVEN partialled out.

**p < .01.

Table 8

Partial correlations between memory tasks and the novel word learning task after controlling for receptive vocabulary knowledge and nonverbal intelligence.

Memory measures	Word learning measures	*r*	BF_{10}
Order STM	Initial trials[a]	.29**	555.70
	Final trials[a]	.28**	193.54
2nd half Hebb	Initial trials[b]	.08	0.21
	Final trials[b]	.18*	2.52

Note. STM = short-term memory.

[a] Item short-term-memory, EVIP, and RAVEN task partialled out.

[b] Second-half of filler sequences, EVIP, and RAVEN partialled out.

*p < .05. **p < .01.

4 Discussion

A complex interaction between short-term and long-term serial order memory mechanisms allows children to capture linguistic input from their environment and to consolidate it in long-term, stable linguistic representations. Although the association between serial order memory and vocabulary development is widely acknowledged, past research did not clarify how and when STM and LTM for serial order are involved in the acquisition of novel words.

In the present study, we examined the temporal dynamics characterizing the impact of serial order STM and LTM in learning new phonological word representations. We first aimed to replicate and extend previous findings that had shown the existence of an association between STM for serial order and novel word form learning (Majerus & Boukebza, 2013) and an association between serial order LTM (Hebb learning) and novel word form learning (Mosse & Jarrold, 2008), on the other hand. We examined at what time during the learning process serial order STM and LTM support novel word form learning. We hypothesized that serial order STM would be involved in the *first* stages of novel word form learning, allowing the learner to temporarily retain and refresh the sequences of phonemes in STM and that serial order LTM would be involved in *later* stages of novel word form learning, when these sequences are gradually consolidated and transformed into stable lexical representations.

In the current study, we observed a link between STM for order information, but not STM for item information, and the learning speed index of the novel word learning task. These findings are consistent with previous studies showing that STM for serial order plays a crucial role in novel word form learning even after controlling for item STM (Majerus & Boukebza, 2013). These results support the assumption that it is especially the capacity to retain serial order information, rather than item information that supports learning of novel sequences of phonemes and, by extension, word forms (Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus, Poncelet, Elsen, et al., 2006; Majerus et al., 2008). Furthermore, these observations corroborate previous findings assuming a specific link between serial ordering abilities and novel word form learning, after accounting for existing vocabulary knowledge (Majerus & Boukebza, 2013; Majerus et al., 2009; Majerus, Poncelet, Elsen, et al., 2006; Majerus, Poncelet, Greffe, et al., 2006; Majerus et al., 2008). We examined the specific contribution of serial order STM on novel word form learning by using separate tasks for assessing serial order and item STM abilities. It could be argued that the item and serial order STM tasks used in this study differed beyond the item/order distinction. Indeed, the two tasks involved the processing of different amounts of information (single nonwords in the item STM task versus multiple items for the serial order STM task). This situation is the direct consequence of the need to maximize a given type of information and to minimize the other type of information in the same task: List-level serial order processing can only be prevented by presenting single items to be maintained and the measurement of serial order retention abilities can only be achieved by presenting multiple items. The necessity to individuate multiple items in the serial order reconstruction task is indeed closely related to serial order representation mechanisms: In the task we used, it is serial position information that differentiates individual items from each other given that items for a given length were fully predictable and only their serial position changed between trials. Furthermore, although item and serial order STM tasks have been shown to recruit similar general attentional processes such as attentional refreshing (Camos et al., 2017), it could be argued that the serial order reconstruction task involved additional spatial attentional processes given the need to reconstruct serial order by ordering the items on a horizontal line. However, these spatial attention processes have precisely been proposed as being a defining feature of the representation of serial order information (e.g. van Dijck, Abrahamse, Majerus, & Fias, 2013; van Dijck & Fias, 2011). Also, in a study estimating item and serial order STM abilities based on item and serial order errors from an immediate serial recall task, very similar results in terms of the item versus serial order distinction were observed, by showing a robust and specific association between serial order STM abilities and lexical abilities (Majerus et al., 2009). Hence, it is unlikely that the differences in task setup for the item and serial order

STM tasks in the present study led to a major bias in the results. At the same time, the exact serial order codes explaining the association between performance on the serial order STM task and lexical learning still need to be explored. Recent studies suggest that serial order information may be coded using phonological and non-phonological codes at the same time (Fischer-Baum & McCloskey, 2015; Kalm & Norris, 2014; Papagno et al., 2017; van Dijck et al., 2013). It could be that serial order reconstruction tasks put stronger requirements on spatial serial order codes while immediate serial recall tasks tap more directly phonological serial order codes. The question of which type of code is responsible for the association between serial order STM and lexical learning is of major theoretical interest and needs to be explored in future studies.

Moreover, although the present findings revealed no evidence for a correlation between item STM and novel word form learning measures, we should note that previous studies (e.g., Service, Maury, & Luotoniemi, 2007) have demonstrated that novel word learning is critically determined by the quality of long-term phonological representations. Our findings further show that serial order STM is involved not only in first, but contrary to what we hypothesized, also in later stages of novel word form learning. This could be explained by the fact that the sequence of phonemes is not yet entirely consolidated as a single chunked phonological representation after only six learning trials. Given that the entry is not unitary after only six repetitions, short-term serial order requirements are seemingly still needed to some extent until the end of the task. With regard to these observations, we hypothesize that a longer offline consolidation period that may or may not involve sleep is needed to acquire a unitary long-term lexical entry with minimal or no STM involvement (for more details, see Szmalec et al., 2012).

Furthermore, the current study showed a link between the serial order LTM (Hebb learning) and final, but not initial stages of novel word form learning. These findings are consistent with our assumption that Hebb learning principles drive the long-term consolidation of new phonological material (Smalle et al., 2016; Szmalec et al., 2009; Szmalec et al., 2012). This study is the first to directly show that Hebb learning principles are specifically involved in *later* stages, compared to initial stages, of novel word form learning, when children are about to create a stable, unitary representation in LTM of the phonological word forms that are being acquired.

Finally, the same pattern of results between serial order memory and novel word form learning remained even after controlling for participants' receptive vocabulary knowledge and nonverbal intelligence. These findings indicate that the observed link between serial order memory and word form learning is not mediated by receptive vocabulary knowledge or nonverbal intelligence. Thus, the evidence suggests that serial order memory is essential for acquiring novel word forms.

5 Conclusion

The current study allowed us to gain deeper insight into the involvement of memory in novel word form learning in young children. In this study, we replicated and extended recent findings suggesting that serial order short- and long-term memory determinants are a crucial aspect of the long-term learning of serial phonological information. To our knowledge, this study is the first to directly investigate the relationship between serial order STM, serial order LTM and novel word form learning in a large sample of young children. Doing this, we were able to dissociate to some extent the contributions of short- and long-term memory, especially the processes responsible for the representation of serial order in the gradual development of a word form. We showed that STM is especially important for the temporary maintenance of the phoneme sequences that represent the novel phonological form, whereas Hebb-like processes are primarily involved in the consolidation of these novel forms as unitary representations in LTM, presumably through chunking mechanisms (Page &

Norris, 2009b). Nevertheless, further experimental investigation is needed to obtain a clearer and integrated understanding of how exactly the human memory system supports novel word form learning and language more in general.

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