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Serial-Order Short-Term Memory Predicts Vocabulary Development: Evidence From a Longitudinal Study

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Serial-order short-term memory (STM), as opposed to item STM, has been shown to be very consistently associated with lexical learning abilities in cross-sectional study designs. This study investigated longitudinal predictions between serial-order STM and vocabulary development. Tasks maximizing the temporary retention of either serial-order or item information were administered to kindergarten children aged 4 and 5. At age 4, age 5, and from age 4 to age 5, serial-order STM capacities, but not item STM capacities, were specifically associated with vocabulary development. Moreover, the increase of serial-order STM capacity from age 4 to age 5 predicted the increase of vocabulary knowledge over the same time period. These results support a theoretical position that assumes an important role for serial-order STM capacities in vocabulary acquisition.

Keywords: verbal short-term memory, serial-order processing, vocabulary development

Many studies have demonstrated an association between verbal short-term memory (STM) capacities, such as measured by nonword repetition and digit span, and receptive vocabulary development in children aged 2–13 (e.g., Bowey, 1996; Gathercole & Adams, 1993, 1994; Gathercole & Baddeley, 1989, 1990, 1993; Gathercole, Hitch, Service, & Martin, 1997; Gathercole, Tiffany, Briscoe, Thorn, & The ALSPAC Team, 2005; Gathercole, Willis, & Baddeley, 1991; Gathercole, Willis, Emslie, & Baddeley, 1992; Majerus, Poncelet, Greffe, & Van der Linden, 2006). However, the precise nature of this association remains a matter of debate. Theoretical proposals diverge with respect to the directional relationship between these two abilities.

Some authors have suggested that verbal STM capacity is a causal factor of vocabulary development (e.g., Adams & Gathercole, 1995; Avons, Wragg, Cupples, & Lovegrove, 1998; Baddeley, Gathercole, & Papagno, 1998). This hypothesis proposes that verbal STM is an obligatory doorway for any new phonological information to enter long-term memory (Baddeley, 2003; Baddeley et al., 1998). In such a view, any new phonological information has to be stored and rehearsed in STM before entering long-term memory. The better the temporary phonological representation of a new word in verbal STM, the quicker a new representation will be created in long-term memory for the same word. Longitudinal correlational data support this proposal showing that verbal STM performance, as measured by nonword repetition, predicts later vocabulary knowledge. For example, Gathercole and Baddeley (1989) observed that nonword repetition capacities at the age of 4 predict vocabulary knowledge at the age of 5. This position is also supported by studies showing that verbal STM capacities are associated with the ability to acquire new words or foreign vocabulary, in both children and adults (Cheung, 1996; Gathercole & Baddeley, 1990; Gathercole et al., 1997; Papagno, Valentine, & Baddeley, 1991; Papagno & Vallar, 1992; Service, 1992; Service & Kohonen, 1995).

A second position, however, suggests that vocabulary growth itself increases verbal STM capacity (Bowey, 2006; Fowler, 1991; Metsala, 1999). For example, Metsala (1999) proposed the lexical restructuring hypothesis, following which children's initially holistic lexical representations get more and more segmented until the phoneme becomes the basic unit of oral language processing. In this view, as lexical knowledge increases, underlying phonological representations become more precise under pressure to discriminate between similar sounding words. Consequently, these richer phonological representations will also enhance the ability to process sublexical phonological information of new, unfamiliar words in any linguistic task, including nonword repetition. A number of studies corroborate the dependency of STM tasks on the development of language knowledge, by showing that verbal STM performance is strongly influenced by language knowledge. Several psycholinguistic variables, such as lexical status, word frequency, and word imageability, have been shown to influence performance on STM tasks, suggesting that lexical and semantic knowledge supports the short-term maintenance of verbal information. For example, word span is well above nonword span in children and adults (e.g., Hulme, Roodenrys, Brown, & Mercer, 1995; Majerus & Van der Linden, 2003; Turner, Henry, & Smith, 2000). Moreover, even sublexical knowledge has been shown to influence verbal STM performance. Immediate serial recall is better for nonwords containing phoneme combinations that are frequent relative to the phonotactic structure of a given language, in comparison to nonwords containing less frequent phoneme combinations (e.g., Gathercole, Frankish, Pickering, & Peaker, 1999; Majerus & Van der Linden, 2003; Majerus, Van der Linden, Mulders, Meulemans, & Peters, 2004).

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In the present article, we propose that a more precise understanding of the complex relationship between vocabulary development and verbal STM capacity can be achieved by distinguishing between two types of information that have to be maintained in STM: order information (i.e., the sequential order in which the items are presented) and item information (i.e., the phonological, lexical, and semantic characteristics of an item). These two types of information are typically confounded in verbal STM tasks. However, some studies suggest that distinct cognitive processes underlie STM for item information and STM for order information (e.g., Henson, Hartley, Burgess, Hitch, & Flude, 2003; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996). For example, Henson et al. (2003) showed that variables known to affect phonological loop functioning, such as irrelevant speech and articulatory suppression, affect the retention of item and order information in different ways: These had a greater detrimental effect on tasks that require maintenance of serial order in comparison with tasks requiring maintenance of item information. Moreover, some psycholinguistic variables such as semantic relatedness and lexical frequency have been shown to specifically reduce errors on item information (fewer missing or wrong items for recall of word vs. nonword lists, or for lists comprising semantically related vs. unrelated words), while having less impact on order errors (items recalled in the wrong serial position; Nairne & Kelley, 2004; Saint-Aubin & Poirier, 1999).

With respect to vocabulary acquisition, Majerus, Poncelet, Greffe, and Van der Linden (2006) showed that item STM capacities (as measured by a single nonword delayed repetition task) and serial-order STM capacities (as measured by a serial-order reconstruction task) were independently associated with vocabulary development in 4- to 6-year-olds. More precisely, serial-order STM ability was a specific predictor of vocabulary achievement at 4 and 6 years of age. Serial-order STM capacities have also been shown to correlate independently with new-word learning in monolingual and bilingual adults (Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008).

At a theoretical level, recent STM models propose that item and order information are stored and processed by separate, although highly interconnected systems: A specialized system encodes the sequential order of items, while item information is represented via temporary activation of corresponding representations in the language network (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999, 2006; Gupta, 2003, 2009; Gupta & MacWhinney, 1997). At recall, the serial-order STM reconstruction system operates as an external signal enabling the item representations to be reactivated in correct order within the language system. Concerning vocabulary development, Gupta (2003) has suggested that lexical acquisition and verbal STM capacity are driven by the same system ensuring short-term maintenance of serial order. When a new phonological form is encountered (either during a nonword repetition task or when learning new names), corresponding phonemes are activated at the level of the sublexical language representations and a new lexical node is created in the lexical system. At the same time, the STM system encodes the order in which the representations in the lexical and sublexical systems are activated. This enables the STM system to replay the activated language representations in correct order, reinforcing a newly created lexical representation and hence contributing to building up stable lexical representation. In contrast, storage of item information is assumed to rely on the temporary activation of lexical and sublexical knowledge. Hence, if there is an impact of STM abilities on vocabulary development, then a specific relationship should be observed between STM tasks maximizing retention of order rather than item information and vocabulary development. An association between performance on item STM tasks and vocabulary knowledge would merely reflect the common reliance on language knowledge (e.g., Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus et al., 2008; Martin & Saffran, 1992).

In the present study, we reexamine the complex mechanisms underlying the well-documented association between vocabulary development and verbal STM using a longitudinal design. A longitudinal study by Gathercole and colleagues has shown a strong correlation between initial verbal STM ability and vocabulary knowledge 1 year later (Gathercole & Baddeley, 1989; Gathercole et al., 1992). However, since verbal STM was assessed using a multisyllabic nonword repetition task confounding item and serial-order retention requirements, this study remains unclear on the precise mechanisms underlying this longitudinal association. On the other hand, recent studies distinguishing between the short-term maintenance for order and item information used only cross-sectional designs and are unable to demonstrate a specific longitudinal predictive power of serial-order STM capacities for vocabulary development; this longitudinal association is nevertheless assumed in the theoretical framework underlying these studies (Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus et al., 2008). Hence, statements on observed transversal associations between serial-order STM capacities and vocabulary development cannot go far beyond the conclusion that a factor is statistically associated to another (Loeber & Farrington, 1994). Longitudinal data are necessary for drawing conclusions about a directional relationship with high internal validity while eliminating plausible alternative explanations such as the effect of preexisting differences between groups. Only a longitudinal design permits the assessment of the hypothesis that a variable precedes another one and predicts its development.

Our study adopted this more powerful longitudinal approach to assess the relationship between vocabulary development and verbal STM, while distinguishing between serial-order and item STM capacities. If verbal STM influences vocabulary development (e.g., Baddeley et al., 1998; Gathercole & Baddeley, 1989) and if this capacity specifically resides in the short-term maintenance of serial order as recently suggested (Gupta, 2003, 2009; Gupta & MacWhinney, 1997; Majerus, Poncelet, Elsen, & Van der Linden, 1996; Majerus, Poncelet, Greffe, & Van der Linden, 1996; Majerus et al., 2008), we should expect a strong association between initial serial-order STM capacity and later vocabulary knowledge.

Study

Vocabulary knowledge, item STM, serial-order STM, and nonverbal reasoning capacities of 60 children were assessed when they were 4 years old and then again 1 year later. Receptive vocabulary knowledge was assessed using the French adaptation of the Peabody Picture Vocabulary Test (Dunn, Thériault-Whalen, & Dunn, 1993).

Two experimental tasks were used to independently assess serial-order STM and item STM abilities, according to recent STM models (e.g., Gupta, 2003). These tasks had initially been developed by Majerus, Poncelet, Greffe, and Van der Linden (2006). The serial-order STM reconstruction task maximized serial-order storage requirements, while minimizing phonological, lexical, and semantic information-processing demands. This task involved the auditory presentation of sequences of animal names, by increasing list length. The names were repeatedly sampled from a pool of seven animals and were known in advance. These names were highly familiar to the participants: They were of a high lexical frequency and had a low age of acquisition. Moreover, their monosyllabic phonological structure reduced phonological processing demands. Finally, item information was fully available at recall since children used cards depicting the animals to reconstruct their order of presentation.

In contrast to the serial-order STM task, the single nonword delayed repetition task maximized phonological processing demands by requiring the children to process, store, and repeat unfamiliar phonological information, similar to the nonword repetition task used in most developmental studies on verbal STM and vocabulary development. These nonwords respected French phonotactic rules, but they were new at every trial and diphone combinations were of relatively low familiarity with respect to the phonological structure of French, minimizing the influence of lexical knowledge on this item STM task—since high-frequency diphone combinations are also associated with an increased number of phonological lexical neighbors, (i.e., familiar words differing from the nonword by a single phoneme; Majerus et al., 2004; Vitevitch & Luce, 1998). Serial-order processing requirements were reduced given that only one item had to be maintained for each trial and given that, at the sublexical level, all items had the same short monosyllabic structure. This last characteristic distinguishes the present task from most nonword repetition tasks, which generally use nonwords increasing in length and thus require processing of the serial order of syllables. Finally, serial rehearsal was prevented using a filled delay between the presentation of the target and its recall.

Method

Participants

Sixty typically developing children (25 girls and 35 boys; mean age: 55 months; range: 50–62) were tested at the age of 4 and 5. Children were selected from five kindergarten schools of the city of Liege, Belgium. All children were qualified as having middle-class socioeconomic status, as measured by their parents' profession. The ethnic composition of the study sample reflected the composition of the Belgian French-speaking population: 70% of White Caucasian origin, 8% of African origin, 6% of Asian origin, and 15% of North-African (Maghreb) origin. Every parent was sent a written description of the study, an informed consent form, and an anamnestic questionnaire; this questionnaire allowed us to ensure that children spoke French as a first language and that they had no history of neurological disorder, neurodevelopmental delay, sensory impairment, speech or language impairment, or more general learning impairments. Children who did not meet these criteria or whose parents did not give their consent were excluded. During the 1st year, 72 children participated in the study, but 12 children changed school after the 1st year, so only 60 children participated in the study during the two assessment periods. Children were seen in their respective schools, and no compensation was given.

Materials and Procedure

Serial-order reconstruction: The animal race task. This serial-order reconstruction task used here was adapted from Majerus, Poncelet, Greffe, and Van der Linden (2006). This task was designed to maximize the short-term retention demands for order information while minimizing processing demands for item information. This task, presented to the child as an animal race game, consisted of the auditory presentation of sequences of animal names (*chat*, *chien*, *coq*, *lion*, *loup*, *ours*, and *singe* [cat, dog, cock, lion, wolf, bear, monkey]) by increasing list length, from Length 2 to 7. After each sequence, the child had to reconstruct the order of presentation of the names using cards depicting the animals. The seven stimuli had been selected for their high lexical frequency (mean lexical frequency: 50,631; range: 16,432–90,926; Lambert & Chesnet, 2001) and their low age of acquisition (mean age of acquisition: 20 months; range: 13–24 months; Alario & Ferrand, 1999; Ferrand & Alario, 1998) ensuring that they were highly familiar to the children. Moreover, their monosyllabic structure minimized phonological processing demands. Item information was fully available at recall given that, after each sequence presentation, cards depicting the presented animals were given to the children who simply had to arrange them in their order of presentation. These characteristics ensured the high sensitivity of this task to serial-order information and minimized the processing demands for item information.

The experimenter presented the task as follows:

> Every year, animals from all over the world gather to have a huge race. This year, seven animals are participating: a cat, a dog, a cock, a lion, a wolf, a bear, and a monkey [the experimenter shows the cards of the corresponding animals]. Several races take place. Sometimes only two animals are participating. Sometimes there are three, four, or five animals. At other times, there are big races with six or seven animals. Through the headphones, you will hear someone announce the animal's order of arrival at the finish line, from the first to the last animal. Immediately after, you have to put the pictures of the animals on the podium in their order of arrival. The animal arriving first has to be put on the highest step and the last one on the lowest step. Okay?

All items had been recorded by a female voice on a computer disk and were presented to the child through headphones. Their mean duration was 549 ms (range: 371–696), with an interstimulus interval of 650 ms. The experimenter activated the presentation of each list (animal race) and when the auditory presentation was completed gave the child corresponding cards (in alphabetical order) depicting the specific animals that had been presented in the list (race). The child had to rearrange them on a staircase with seven steps drawn on a sheet: He or she had to put the first item on the highest step, the second item on the second step, and so on. The experimenter wrote down the child's response and then removed the cards from the podium. Four different sequences were proposed for each list length, and all 24 trials were presented to each child. Each list contained items randomly selected from the pool of seven items with the only restriction that no item could occur twice in the same list. We determined the number of sequences accurately reconstructed as well as the number of correctly placed items by pooling over the different sequence lengths.

Delayed item repetition: The castle task. Item STM was assessed using a single nonword delayed repetition task, adapted from Majerus, Poncelet, Greffe, and Van der Linden (2006). This specific item memory task was designed to maximize the recruitment of sublexical phonological representations and segmentation processes assumed to be a major determinant of phonological item STM according to the theoretical models the current study relies on (Brown et al., 2000; Burgess & Hitch, 1992; Gupta, 2003), while minimizing the contribution of serial-order STM processes. The task consisted of a total of 30 nonwords presented separately. These nonwords were new at every trial and respected French phonotactic rules, but diphone combinations were of relatively low familiarity relative to the phonological structure of French (mean diphone frequency of the consonant–vowel segments: 149; range: 3–524; mean diphones frequency of the vowel–consonant segments: 129; range: 7–728; Tubach & Boë, 1990), maximizing the processing demands of phonological item information. By contrast, the need to retain order information in the item STM was minimized for several reasons: (a) All nonwords had exactly the same consonant–vowel–consonant monosyllabic structure, unlike traditional nonword repetition tasks using multisyllabic nonwords of unpredictable syllabic structure; hence the only order errors that could occur were inversions between the first and last consonant; (b) at the item level, only a single item had to be retained, contrary to the serial-order reconstruction task where several items and their arbitrary serial positions had to be retained; (c) sequential rehearsal of the to-be-stored information, assumed to be a major component of serial-order STM, was made impossible via the continuous and concurrent repetition of the syllable *bla* during the retention delay.

Nonwords were presented to the child as being passwords to be remembered and able to open a castle's doors. After each nonword, the child was instructed to continuously repeat the syllable *bla* during 3 s. Then the experimenter asked the child to recall the stimulus. Additionally, the child also had to repeat the nonword once immediately after its presentation in order to ensure that the stimulus had been correctly perceived and could be accurately reproduced. However, no corrective feedback was given to the child. A unit was scored as correct if the stimulus produced at recall was identical to the stimulus repeated immediately after presentation. This scoring method ensured that we assessed phonological short-term maintenance abilities without being biased by initial misperceptions.

The task was presented to the child as a game:

> You are an adventurer [for a boy]/a princess [for a girl] locked up in the tower of a castle [a drawing of the castle is shown to the child on the computer screen]. The castle has many doors. You have to find your way out of the castle. In order to do so, you have to open the doors by remembering passwords. More precisely, when you see a closed door [the experimenter shows the next computer slide depicting a closed door], you will hear through the headphones a word from a magic language which opens the door and which you have to remember. The door opens if you repeat "blablabla . . ." during a short time and if afterward, on my order, you repeat the password you just heard. Okay?

In order to avoid excessive frustration, the experimenter could open the doors with a golden key if the child forgot the nonword. However, the child was told that only a limited number of keys were available and that he or she had to do his or her best to remember the passwords. All responses were digitally recorded for later transcription and scoring. We determined the number of correct recalls over the 30 trials, relative to the initially repeated item form, in order to measure phonological short-term retention capacities rather than perceptual or articulatory abilities.

Receptive vocabulary knowledge. Vocabulary knowledge was measured using a French adaptation (Dunn et al., 1993) of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981). As a dependent variable, we used raw vocabulary scores.

Nonverbal reasoning. Raven's Colored Progressive Matrices (Raven, Court, & Raven, 1998) estimated general nonverbal reasoning abilities. Raw scores were used.

General Procedure and Task Order

Children were administered the different tasks in two different sessions lasting approximately 30 min. The nonword repetition task and the serial-order reproduction task were each split into two equal parts, one part being presented in the first session and the other in the second session in order to optimize the reliability of the estimate of a given child's performance level. Our reasoning was that performance measures at two time points for the same task give a more reliable estimate of performance for a given task than does a unique measure at a single time point. This also allowed to measure reliability estimates of the item and serial-order STM tasks. For the later correlation analyses with vocabulary knowledge, the scores obtained for both parts of the tasks were combined. More precisely, during Session 1, the child was administered the first part of the serial-order reconstruction task, the first part of the nonword repetition task, and the Raven's matrices. During Session 2, the child was administered the vocabulary knowledge task, the second part of the nonword repetition task, and the second part of the serial-order reconstruction task. These two sessions were administered in the same order at age 4 and at age 5.

Results

Valid data sets were obtained for 45 participants.[1] Descriptive statistics for the different tasks administered at ages 4 and 5 are shown in Table 1. A large range of performance, with no floor or ceiling effects, was observed for all tasks and the two test periods. Response accuracy increased with age in all tasks: A within-subjects *t* test showed a highly significant increase from age 4 to age 5 in vocabulary performances, $t(44) = 9.4$, $p < .001$; delayed

[1] Three participants had to be removed due to outlier performance at the vocabulary task, and the data from 12 other participants were excluded from analyses due to very poor test–retest reliability on the short-term memory tasks (their performance decreased sharply during the second session of the same time period, indicating fatigue or lack of collaboration; this was likely to be due to the fact that during the second session, the STM tasks were administered after the vocabulary task, which in some children took a very long amount of time as they failed to reach the stop criterion for the vocabulary task).

Table 1
Descriptive Statistics for the Different Measures Administered

Measure	*M*	*SD*	Range	Proportional score[a]	Skewness[b]	Kurtosis[c]
		Age 4				
Serial-order reconstruction (max. = 24)	5.76	2.1	2–10	.24	0.25	−0.80
Single nonword delayed repetition (max. = 30)	13.62	7.03	0–25	.45	−0.17	−1.04
EVIP	52.24	12.78	14–74		−0.39	0.49
RCPM (max. = 36)	12.82	3.47	3–20	.36	−0.44	0.73
		Age 5				
Serial-order reconstruction (max. = 24)	9.04	2.23	5–14	.38	0.24	−0.39
Single nonword delayed repetition (max. = 30)	20.96	5.3	9–30	.70	−0.55	−0.59
EVIP	68.20	12.41	42–92		−0.13	−0.52
RCPM (max. = 36)	17.80	3.62	11–30	.49	1.04	2.05

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
[a] Proportion of observed scores relative to maximal possible score. [b] 2 standard error skewness cutoff = 0.71. [c] 2 standard error Kurtosis cutoff = 1.39.

nonword repetition performances, $t(44) = 7.12$, $p < .001$; serial-order reconstruction performances, $t(44) = 11.67$, $p < .001$; and nonverbal reasoning scores, $t(44) = 7.68$, $p < .001$. The shapes of the distribution of the different tasks results were also evaluated: Skewness and kurtosis estimates remained within the recommended two standard error range (Tabachnick & Fidell, 1996) for every task except the nonverbal reasoning scores at age 5 (see Table 1).

In order to show that the item STM task actually minimized the serial-order STM processes, we performed an analysis of error types. As explained in the task description, the only order errors that could occur were inversions between the first and last consonant. At the same time, these inversions are relatively unlikely given that the first and final consonant will not be coded as two arbitrary and exchangeable serial positions, but they will be coded relative to long-term syllabic structure knowledge assuming an onset and a coda position. As predicted, we observed that only 0.4% of errors was due to an inversion of initial and final consonants.

Although performance levels in the item and serial-order STM tasks appear to differ slightly, differences in task difficulty are not likely to explain the specific pattern of correlations presented below. Performances in both tasks showed neither floor nor ceiling effects, with skewness estimates being comparable (no leftward skewness for the apparently more difficult serial-order STM measure) and remaining in the range of ±2 standard errors. Both tasks also showed similar sensitivity, as zero-order correlations between both STM measure and other variables of interest were of similar magnitude (see Table 2). Both measures also increased with age and correlated with age to a comparable degree.

Test–Retest Reliability

The STM tasks showed moderate to excellent test–retest reliability estimates, as reflected by the correlation of each participant's score on the first and second administration of the task (at the same age period)—serial-order reconstruction task: $r = .68$, $p < .001$; delayed single nonword repetition: $r = .79$, $p < .001$. The correlations between scores at age 4 and age 5 were also significant, except for the nonverbal reasoning task—serial-order reconstruction task: $r = .62$, $p < .001$; delayed single nonword repetition: $r = .40$, $p < .01$; receptive vocabulary: $r = .59$, $p < .001$; nonverbal reasoning: $r = .25$, *ns* (see Table 2).

Moreover, each task performances (considering performances at age 4 and age 5) significantly correlated with age (see Table 3).

Table 2
Raw Correlations Between Tasks at Age 4 and Age 5

Task	1	2	3	4	5	6	7	8
Age 4								
1. Serial-order reconstruction	—	.52***	.48**	.32*	.62***	.18	.64***	.45**
2. Single nonword delayed repetition		—	.34*	.16	.51***	.40**	.50***	.24
3. EVIP			—	.08	.32*	.21	.59***	.16
4. RCPM				—	.15	.26	.25	.25
Age 5								
5. Serial-order reconstruction					—	.41**	.54***	.39**
6. Single nonword delayed repetition						—	.40**	.05
7. EVIP							—	.36*
8. RCPM								—

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3
Raw Correlations Between Tasks Performances (Both Ages) and Age

Task	Raw correlation with age
Serial-order reconstruction	.59***
Single nonword delayed repetition	.52***
EVIP	.54***
RCPM	.55***

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
*** $p < .001$.

Correlations Between Vocabulary and STM Measures at Ages 4 and 5

As can be seen in Table 2, raw correlation analyses showed a significant association between STM and vocabulary measures at each age period (serial-order reconstruction task at age 4: $r = .48$, $p < .01$; delayed nonword repetition task at age 4: $r = .34$, $p < .05$; serial-order reconstruction task at age 5: $r = .54$, $p < .001$; delayed nonword repetition task at age 5: $r = .40$, $p < .01$).

Multiple Regression Analyses

Next, we used multiple hierarchical regression analyses to examine the specific predictive power of the two experimental tasks, the single nonword delayed repetition task, and the serial-order reconstruction task, on vocabulary knowledge, after we controlled for differences at the level of age and nonverbal intellectual efficiency as estimated by Raven's matrices. For these analyses, we first considered the relationship between STM and vocabulary measures for the same time period (age 4 or age 5), before examining longitudinal associations (prediction of vocabulary scores at age 5 by STM measures at age 4).

At age 4, performances on the nonword repetition task and on the serial-order reconstruction task both accounted for a significant amount of the variance in vocabulary scores after control of age and Raven's matrices. However, as shown in Table 4, when we entered the serial-order reconstruction after the nonword repetition task in the regression analysis, the serial-order reconstruction task accounted for a further 13% of independent variance in vocabulary scores, while the nonword repetition task, when entered after the serial-order reconstruction task, did not predict any independent variance in vocabulary scores.

Table 5 shows the same pattern of predictions at age 5: While performance at both STM tasks explained a significant amount of variance of vocabulary knowledge, only the serial-order reconstruction task explained a further 7% of independent variance in vocabulary scores after introduction of the nonword delayed repetition task.

The next set of multiple regression analyses assessed the critical longitudinal associations between STM and vocabulary measures, by predicting vocabulary knowledge at age 5 by STM performances at age 4. Like Gathercole and Baddeley (1989), we controlled for initial differences in vocabulary knowledge by entering also vocabulary knowledge at age 4 in the regression analyses, before entering the STM measures at age 4. This allowed us to control for the part of variance in vocabulary scores at age 5 that could be shared by verbal STM measures and vocabulary knowledge at age 4. We observed that performances on both the serial-order reconstruction task and on the nonword delayed repetition task at age 4 accounted for significant parts of variance in vocabulary scores after we controlled for age, nonverbal reasoning, and initial vocabulary knowledge (nonword repetition accounted for 8% of variance and serial-order reconstruction accounted for 12% of variance). Furthermore, scores at the serial-order reconstruction task accounted for a further 7% of independent variance in vocabulary scores once the variance shared with nonword repetition abilities was removed, while the reverse was not true (see Table 6).

In a further analysis, we controlled for the possibility that correlation between serial-order STM performance at age 4 and vocabulary at age 5 are mediated by their common association with serial-order STM performance at age 5. In order to check this, we performed a rather conservative partial correlation analysis, further controlling for serial-order STM performance at age 5 (in addition to the control of initial differences in age, vocabulary knowledge, item STM performance, and nonverbal abilities). In that case, the partial correlation was no longer significant ($r = .25$, $p > .05$). However, this partial correlation is close to overparameterization, given our sample size. We therefore conducted a

Table 4
Hierarchical Regression Analyses Predicting Vocabulary Knowledge at Age 4 by Short-Term Serial-Order Reconstruction and Short-Term Nonword Delayed Repetition at Age 4 After Controlling for Age and Raven's Colored Progressive Matrices Scores

Variable	ΔR^2	B	$SE\ B$	β
Step 1. Age	.01	0.42	0.53	.12
Step 2. RPCM	.00	0.19	0.59	.05
Step 3. Nonword repetition	.11	0.61	0.27	.33*
Step 4. Serial-order reconstruction	.13	2.64	1.01	.43*
Step 3. Serial-order reconstruction	.22	3.03	0.88	.49**
Step 4. Nonword repetition	.01	0.39	0.29	.13

Note. RCPM = Raven's Colored Progressive Matrices.
* $p < .05$. ** $p < .01$.

Table 5
Hierarchical Regression Analyses Predicting Vocabulary Knowledge at Age 5 by Serial-Order Reconstruction Performances and Nonword Repetition Performances at Age 5 After Controlling for Age and Raven's Colored Progressive Matrices Scores

Variable	ΔR^2	B	$SE\ B$	β
Step 1. Age	.07	0.95	0.52	.27
Step 2. RPCM	.13	1.24	0.47	.36*
Step 3. Nonword repetition	.12	0.81	0.31	.35*
Step 4. Serial-order reconstruction	.07	1.81	0.84	.32*
Step 3. Serial-order reconstruction	.14	2.36	0.79	.42**
Step 4. Nonword repetition	.04	0.54	0.32	.23

Note. RCPM = Raven's Colored Progressive Matrices.
* $p < .05$. ** $p < .01$.

Table 6
Hierarchical Regression Analyses Predicting Vocabulary Development at Age 5 by Short-Term Serial-Order Reconstruction and Short-Term Nonword Delayed Repetition at Age 4 After Controlling for Age, Raven's Colored Progressive Matrices Scores, and Initial Vocabulary Knowledge

Variable	ΔR^2	*B*	*SE B*	β
Step 1. Age	.06	0.82	0.51	.24
Step 2. RPCM	.04	0.71	0.55	.19
Step 3. EVIP	.31	0.55	0.12	.56***
Step 4. Nonword repetition	.08	0.53	0.22	.29*
Step 5. Serial-order reconstruction	.07	2.03	0.84	.34*
Step 4. Serial-order reconstruction	.12	2.49	0.77	.42**
Step 5. Nonword repetition	.02	0.31	0.23	.17

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
* $p < .05$. ** $p < .01$. *** $p < .001$.

further correlation analysis in which we directly assessed the role of the association between age 4 and age 5 serial-order STM measures, while avoiding overparameterization. In this analysis, we controlled for serial-order STM performance at age 5 and vocabulary knowledge at age 4 (but without further controlling for initial differences in Raven, age, and item STM performance). In that case, the partial correlation between serial-order STM at age 4 and vocabulary at age 5 remained significant ($r = .33$, $p < .05$), ruling out the possibility that this correlation is only driven by the common association of serial-order STM performance at age 4 and vocabulary knowledge at age 5 with serial-order STM performance at age 5.

Moreover, in order to demonstrate that it is the serial-order STM task that predicts vocabulary development and not the reverse, we conducted a further set of regression analyses predicting serial-order STM at age 5 by vocabulary knowledge at age 4. Table 7 shows that vocabulary knowledge at age 4 was not a significant predictor of verbal STM development at age 5 once we controlled for initial differences in age, nonverbal reasoning, and serial-order STM performances.

A further set of analyses considered performance increase between age 4 and age 5, rather than absolute levels of performance at the different time points, reflecting more directly the developmental gain for the cognitive abilities of interest. We calculated difference scores by subtracting performance at age 4 from performance at age 5, as well as for the vocabulary and STM tasks of interest. Partial correlation analyses revealed that only the increase of performance on the serial-order reconstruction task, as measured by the number of correct positions recalled, predicted the increase in vocabulary knowledge after control of increase in Raven's matrices performances ($r = .34$, $p < .05$). In contrast, the performance increase in nonword repetition task did not predict the increase in vocabulary knowledge once we controlled for the increase in Raven's matrices performances ($r = .00$, $p = .98$). All of these regression analyses strengthen the interpretation of our results in terms of a specific predictive power of serial-order STM on vocabulary development 1 year later.

However, the possibility remains that verbal STM abilities at age 4 are also predictive of general cognitive attainment at age 5, and not only of vocabulary development (see, e.g., Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009). For this reason, we conducted a further set of regression analyses by predicting performance on Raven's matrices by the STM measures. We observed that performance at the nonword delayed repetition task at age 4 did not independently predict variance in Raven's scores 1 year later (see Table 8). However, serial-order reconstruction performance at age 4 remained a significant predictor of Raven's matrices scores 1 year later, predicting 10% of independent variance, after control of initial differences in age, vocabulary knowledge, Raven's matrices scores, and nonword delayed repetition performance. Nevertheless, performance increase in the serial-order STM task did not predict performance increase in the nonverbal intelligence task between age 4 and age 5 after control of vocabulary increase ($r = .07$, $p = .67$).

Discussion

This longitudinal study used the distinction between item and order information for achieving a more detailed understanding of the relationship between verbal STM and vocabulary development. The longitudinal design allowed us to assess the predictive power of the verbal STM performance at the age of 4 on vocabulary achievement 1 year later. Results demonstrated that serial-order STM capacities, as measured by a serial-order reconstruction task,

Table 7
Hierarchical Regression Analyses Predicting Short-Term Memory for Serial-Order Development at Age 5 by Vocabulary Knowledge at Age 4 After Controlling for Age, Raven's Colored Progressive Matrices Scores and Initial Short-Term Memory for Serial-Order Performances

Variable	ΔR^2	*B*	*SE B*	β
Step 1. Age	.04	0.12	0.09	.19
Step 2. RCPM	.01	0.07	0.10	.11
Step 3. Serial-order reconstruction	.35	0.66	0.14	.63***
Step 4. EVIP	.00	0.00	0.02	.02

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
*** $p < .001$.

Table 8
Hierarchical Regression Analyses Predicting Nonverbal Reasoning Development at Age 5 by Verbal Short-Term Memory Abilities at Age 4 After Controlling for Initial Differences in Age, Vocabulary Development, and Nonverbal Reasoning

Variable	ΔR^2	*B*	*SE B*	β
Step 1. Age	.00	0.06	0.15	.06
Step 2. EVIP	.03	0.04	0.04	.16
Step 3. RCPM	.06	0.25	0.16	.24
Step 4. Nonword repetition	.03	0.09	0.08	.18
Step 5. Serial-order reconstruction	.10	0.73	0.32	.43*
Step 4. Serial-order reconstruction	.13	0.75	0.29	.44*
Step 5. Nonword repetition	.00	0.01	0.09	.03

Note. EVIP = French version of Peabody Picture Vocabulary Test; RCPM = Raven's Colored Progressive Matrices.
* $p < .05$.

are the strongest independent predictor of vocabulary knowledge 1 year later, even when initial differences in vocabulary knowledge and item STM capacities are controlled. By contrast, item STM did not independently predict vocabulary development when serial-order STM abilities were controlled. We also observed that serial-order STM capacities were independently correlated with nonverbal reasoning capacities 1 year later.

A Longitudinal Prediction of Vocabulary Knowledge by Serial-Order STM Performance: Evidence for a Determinant Influence?

On the one hand, the present data corroborate the already vast literature, showing very consistent relations between verbal STM capacity and vocabulary development (e.g., Gathercole & Adams, 1993, 1994; Gathercole & Baddeley, 1989; Gathercole et al., 1992; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Michas & Henry, 1994). On the other hand, this study goes well beyond the conclusions of previous studies that suggest that verbal STM is a "critical building block" (Baddeley et al., 1998) in vocabulary development. Our results herald a more nuanced interpretation of the relationship between verbal STM performances and vocabulary development, by distinguishing between item STM and serial-order STM capacities and their independent associations with vocabulary knowledge. We observed a specific association between serial-order STM abilities at age 4 and vocabulary development at age 5, while this was not the case for item STM capacities. The distinct associations observed between these two STM abilities and vocabulary knowledge corroborate the dissociation already observed between item and serial-order STM capacities and vocabulary development or new-word learning performances in previous studies using transversal study designs (e.g., Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden et al., 2006; Majerus et al., 2008) and support the theoretical proposal suggesting that (at least partially) distinct cognitive processes underlie the processing and storage of item and order information (e.g., Brown et al., 2000; Burgess & Hitch, 1992, 1999; Gupta, 2003; Gupta & MacWhinney, 1997).

It is interesting that the main outcome of results of the present study, using a single-item delayed repetition task as an estimation of item STM capacity, echoes those of other previous studies using relatively different estimates of item STM. Majerus et al. (2009) adapted the animal race task to simultaneously measure item- and order-retention capacities based on item-recognition and order-reconstruction procedures: In place of giving the children only the cards used in a specific trial, they gave the children the seven possible cards at each trial. Children first had to select the animals present in the sequence among the seven possible cards (item selection) and then arrange them following their presentation order (order processing). Like the present and other previous studies, a significant correlation between serial-order STM estimates and vocabulary knowledge was observed after Majerus et al. (2009) partialled out the influence of item STM estimates, but the reverse was not true. In another study (Majerus, Poncelet, Elsen, & van der Linden, 2006), item-retention capacities were assessed via a rhyme probe recognition task, in which adult participants had to judge whether a probe word rhymed with one of the words in the memory list; serial-order retention capacities were assessed by a digit serial-order reconstruction task. Again, performances on the serial-order reconstruction task, but not on the rhyme probe recognition task, correlated significantly with an estimate of vocabulary learning performance (word–nonword paired associate learning). Finally, a more recent study explored the association between item STM, serial-order STM, and second-language lexical proficiency, using a single-item recall task similar to the one used in the present study, and yielding again very comparable results: Only the serial-order STM task, but not the item STM task, was independently associated with foreign language vocabulary learning (Majerus et al., 2008). The converging evidence from these different studies suggests that single-item delayed repetition and item probe recognition tasks are both valid and reliable measures of item STM capacity, as opposed to serial-order STM capacity.

While previous studies were able to show that serial-order and item STM are independently associated with vocabulary knowledge, these transversal studies did not permit us to conclude the real directionality of these associations. The longitudinal design used here enables us to go one step further, by directly testing the direction of these associations, in the sense that performance for a given STM ability at a given age predicts or does not predict later vocabulary development. A follow-up of the same cohort of children over a 1-year period enabled us to observe that serial-order STM capacities predict the later vocabulary knowledge, whatever the initial level of vocabulary knowledge. Despite using a more powerful design compared to transversal study designs and despite controlling for the influence of initial differences in age, nonverbal reasoning capacity and vocabulary knowledge, we must, however, acknowledge that we cannot rule out the existence of a third, noncontrolled, ability that might mediate the observed longitudinal relationship. Although the serial-order STM task requires storage of serial-order information, this task is also challenging at the level of selective attention capacities directed toward the processing of serial-order information as well as at the level of sequential rehearsal. More generally, our results strongly support the theoretical proposal assuming a specific causal role for serial-order processing, storage, and/or rehearsal abilities in vocabulary development, as opposed to item processing abilities (e.g., Gupta, 2003; Gupta & MacWhinney, 1997; Majerus et al., 2009).

Vocabulary acquisition is a complex process in which phonological, semantic, and morphosyntactic, as well as mnemonic, factors interact. Furthermore, the weight of these different factors might change as a function of lexical age. We observed that from age 4 to age 5, serial-order STM capacity but not item STM capacity predicted vocabulary development. However, we might have observed different results when studying younger children. Many studies have shown that the availability of accurate phonological representations is a major constraint on vocabulary development in earlier stages of lexical acquisition (Friedrich & Friederici, 2005; Jarrold, Thorn, & Stephens, 2009; Tsao, Liu, & Kuhl, 2004). Hence item STM, assumed to be supported by access to sublexical phonological representations, could be a stronger determinant of lexical development during these earlier developmental stages. The current results suggest that the maturation of serial-order STM processes from age 4 to age 5 is an important predictor of later vocabulary development. What is the precise meaning of this association? The developmental increase of serial-order STM capacity has been related to improved positional coding abilities and/or improved distinctiveness of the temporal cues associated with the encoding and retrieval of neighboring items in the sequence to learn (Brown, Vousden, McCormack, & Hulme, 1999; McCormack, Brown, Vousden, & Henson, 2000). This enhanced STM capacity for positional information will enable the child listener to encode and replay more efficiently the string of phonemes defining a new word form, as already explained. Relative to earlier lexical stages, the repertoire of phonemes will be quite established at age 4 and age 5, and hence learning new word forms will mainly depend on learning new sequential arrangements of the finite set of phonemes and syllables defining a natural language. This enhanced sequential positional coding ability could thus explain the specific association observed between serial-order STM capacity and vocabulary development in children ages 4 and 5. An alternative interpretation could be related to the increasing load of morphosyntactic cues on lexical development. Older children are likely to learn more and more from morphosyntactic context, either in learning new abstract words or in learning the derivative of more frequent words (Anglin, 1993). An accurate morphosyntactic analysis of a sentence context requires the parsing and segmentation of the sentence constituents, with a likely involvement of serial-order segmentation and retention capacities. The observed prediction of lexical development by serial-order STM capacity could thus also be linked to the increasing impact of morphosyntactic analyses and their sequential processing requirements on lexical development. Future studies might pay further interest to the link between serial-order STM, morphosyntactic processing, and vocabulary development.

Serial-Order STM Capacities, Vocabulary Development, and Nonverbal Intelligence

A further result of this study is that serial-order STM capacities were also predictive of later nonverbal reasoning abilities, as assessed by Raven's Colored Progressive Matrices. Even if this association is not as robust as the one linking serial STM memory and vocabulary knowledge (serial-order STM performance increase did not predict Raven's matrices performance increase), this result deserves some further discussion. We should note that these data are in line with another recent study (Majerus et al., 2009) showing that a substantial amount of variance in both vocabulary and Raven's matrices scores in 6- to-7-year-old children was explained commonly by a serial-order STM measure and a selective attention task for sequence information but not item information. These results suggest that a common sequential processing ability may be recruited in both serial-order STM and sequential selective attentional tasks, and that this ability might also be associated with other cognitive tasks than lexical knowledge. Sequential processing could possibly be a general capacity playing a role in various cognitive capacities, such as deductive reasoning. These reasoning processes require that the different intermediate steps of the reasoning products are maintained and successively updated before reaching a final solution to the problem.

Recent neuroimaging studies corroborate the idea that a common sequential ability might underlie the serial processing required in different tasks. For example, common right fronto-parieto-cerebellar networks were shown to subtend the short-term serial-order processing of both verbal and visuospatial information, suggesting that the processing of serial-order information could be a more general, amodal capacity, intervening in any tasks necessitating the processing of spatially or temporally organized information (Majerus, Bastin, et al., 2007; Majerus, Poncelet, Van der Linden, et al., 2006). Behavioral studies are also in line with these findings, by showing quite similar position curves during verbal and visuospatial STM serial-order reconstruction tasks (Smyth, Dennis, & Hitch, 2005). It is thus possible that the sequential processing abilities recruited in serial-order STM tasks play a role in language development, but also in other cognitive domains in which sequential processing is an important factor such as logical deduction and reasoning.

At the same time, the more precise role of serial-order STM capacities in vocabulary learning and nonverbal reasoning tasks might nevertheless differ. As we have shown, serial-order STM performance was a good unique predictor for vocabulary development at age 4, age 5, and from age 4 to age 5, when we controlled for initial differences in age, vocabulary knowledge and even nonverbal reasoning. Moreover, the specific performance increase in serial STM performance between age 4 and age 5 predicted the increase in vocabulary knowledge after control of increase in Raven's matrices performances. In contrast, performance increase in serial-order STM did not predict nonverbal intelligence increase between age 4 and age 5 after control of vocabulary increase. It seems thus that if serial-order processing capacities are also linked with other cognitive capacities, they are specifically crucial to vocabulary acquisition. As discussed above, the impact of serial-order processing capacities on vocabulary development may be explained by various factors, but following the theoretical framework the present study relies on (Gupta, 2003), the specificity of serial-order STM for vocabulary acquisition resides in the ability to replay and rehearse a new phoneme sequence defining a new word form. The ordered repetition of this sequence will lead to the construction of a more stable long-term lexical representation, via Hebbian adjustment of long-term connection weights between the different lexical and sublexical levels of representation for the new word form. Other cognitive tasks, such as Raven's matrices, also involve the processing of sequence information, in the form of logical sequences that have to be formed, and their result has to be checked with respect to the expected result. Here, serial-order STM may be involved in the creation of new logical sequences, and in hypothesis testing with respect to the validity of these different logical sequences relative to the expected result. Hence, the possible role of serial-order STM processes is not exactly the same in the Raven's matrices task (generation of new logical sequences) relative to the vocabulary task (reproduction of perceived sequences); this might explain why the serial-order STM also predicted performance on Raven's matrices but independently so relative to performance on the vocabulary task (and vice versa).

Conclusions

This study highlights the specific role played by serial-order STM in vocabulary development by demonstrating a longitudinal association between serial-order STM capacities at age 4 and vocabulary development at age 5. These results strengthen the hypothesis of serial-order STM capacity as a determinant factor underlying the learning of new verbal sequences.

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