**THE CONTRIBUTION OF SHORT-TERM MEMORY FOR SERIAL ORDER TO EARLY READING ACQUISITION: EVIDENCE FROM A LONGITUDINAL STUDY**

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Abstract

Early reading acquisition skills have been linked to verbal short-term memory (STM) capacity. However, the nature of this relationship remains controversial, since verbal STM, like reading acquisition, depends upon the complexity of underlying phonological processing skills. This longitudinal study addressed the relation between STM and reading decoding acquisition by distinguishing between STM for item and STM for order information, based on recent studies showing that STM for item information recruits underlying phonological representations, but not STM for order information. If there is a specific link between STM and reading decoding acquisition, STM for order information should be an independent predictor of reading decoding acquisition. Tasks maximizing STM for serial order or item information, measures of phonological abilities and reading tests were administered to children followed from kindergarten through 1st grade. We observed that order STM capacity but not item STM capacity predicted independent variance in reading decoding abilities one year later. These results highlight the specific role of STM for order in reading decoding acquisition, and argue for a causal role of order STM capacity in reading acquisition. Mechanisms relating STM for order information and reading acquisition will be discussed.

**Introduction**

Verbal short-term memory (STM) capacity, as measured by digit span or nonword repetition tasks, has been consistently linked to reading acquisition (de Jong & van der Leij, 1999; Dufva, Niemi, & Voeten, 2001; Gathercole & Baddeley, 1993; Gathercole, Willis, & Baddeley, 1991; Hansen & Bowey, 1994; Meyler & Breznitz, 1998; Muter & Snowling, 1998; Naslund & Schneider, 1991; Parrila, Kirby, & McQuarrie, 2004; Rohl & Pratt, 1995; Scarborough, 1998b; Sprugevica & Høien, 2003; Wagner et al., 1997). At the same time, the nature of this relationship remains controversial. Two contrasting accounts have been proposed, one linking STM capacity causally to reading acquisition (Gathercole & Baddeley, 1993; Molfese, Molfese, & Modgline, 2001), and the other one considering that STM capacity reflects a more general phonological processing factor which is also involved in literacy development (Muter & Snowling, 1998; Ramus et al., 2003; Wagner et al., 1997). The present study uses the distinction between the processing of item and order information in STM tasks in order to gain further understanding on the relationship between STM and reading acquisition, with a specific focus on the importance of serial order processing capacities for reading performance.

In typical STM tasks (i.e., immediate serial recall of word lists, nonword repetition), the subject has to simultaneously store the items and their order of presentation when repeating a list of nonword syllables, digits or words. First, recent research suggests that serial order and item information are represented in STM using distinct codes. A number of recent models assume that verbal item information is stored directly via temporary activation of the language network; in that sense, processing and storage of verbal item information depend very directly upon the availability and richness of underlying phonological and semantic representations (Brown, Vousden, McCormack, & Hulme, 1999; Burgess, N. & Hitch, 1999; Gupta, 2003; Henson, 1998). This is supported by many empirical studies showing that the psycholinguistic properties such as word frequency, lexicality, word imageability, and semantic content most reliably affect recall of item information, but not the order in which the items are recalled (e.g., Majerus & D'Argembeau, 2011; Nairne & Kelley, 2004; Saint-Aubin & Poirier, 1999). Patients presenting phonological or semantic language impairment also present poor item recall in STM tasks, but order recall can be strikingly preserved (for those items which are still correctly recalled) (Majerus, Norris, & Patterson, 2007). Neuroimaging studies also have shown greater activation of phonological and semantic processing areas in the bilateral temporal lobes during STM tasks focusing on item memory, as opposed to order memory (Majerus et al., 2010; Majerus, Poncelet, Van der Linden et al., 2006). On the other hand, order STM is considered to be processed by a specialized processing module, which encodes and reactivates the order of activation of representations in the language system via time-based, context-based or positional codes in a specific representational system (Brown et al., 1999; Burgess, N. & Hitch, 1999, 2006; Gupta, 2003; Henson, 1998). Functional neuroimaging studies have also shown that the retention of order information specifically activates non-linguistic neural networks centered on the right intraparietal sulcus (Majerus, Belayachi et al., 2008; Majerus et al., 2010; Majerus, Poncelet, Van der Linden et al., 2006).

Second, recent studies exploring the relation between item STM, order STM and language development have observed that serial order STM capacity is a critical determinant of vocabulary knowledge and acquisition, relative to item STM (Leclercq & Majerus, 2010; Majerus, Belayachi et al., 2008; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008). Majerus, Poncelet, Elsen et al. (2006) showed that measures maximizing serial order retention are a better predictor of new word learning capacity in monolingual adults than measures maximizing item STM. Similarly, a recent developmental study with children aged 4–6 years observed independent associations between STM tasks maximizing serial order or item recall and vocabulary development (Majerus, Poncelet, Greffe et al., 2006). The serial order STM processes have also been shown to be related to new word acquisition in bilingual speakers (Majerus, Belayachi et al., 2008). Finally, in a longitudinal study, Leclercq and Majerus (2010) further showed that order STM, but not item STM in children aged 4 years predicted their vocabulary knowledge one year later.

Hence, order STM capacity not only involves a language independent STM capacity, but at the same time, appears to be an important building block for the acquisition of new phonological representations. Gupta (2003) as well as Majerus, Poncelet, Greffe et al. (2006) have proposed that the temporary representation of the order of phonemes of a new word form will enable the refreshing of the new word form, by reactivating in correct order the new phonological and lexical representations that have been activated in the language system, facilitating long-term learning of the new word form for example via Hebbian adjustment of connection weights between phonemes and lexical nodes for new forms (Burgess, N. & Hitch, 1999; Hebb, 1961). In the context of the current study, we propose that this theoretical framework could also be extended to the acquisition of reading. STM for serial order information may be involved in early reading decoding processes which require the temporary storage in an ordered succession of the successive products of the letter-to-sound conversion processes, allowing the blending of successive phonemes into a word form. The repetition of this process may further foster the creation of new orthographic representations for irregular orthographic forms, as has been shown for the acquisition of new phonological representations.

In the light of these theoretical developments, the aim of the present study is to determine to what extent item and order STM capacities are involved in reading acquisition, and more precisely in the acquisition of decoding processes. Indeed, many authors argue that decoding processes are the central mechanism of reading acquisition, necessary for the acquisition of long-term orthographic knowledge and for reading progress more generally (Ehri, 1998; Share, 1995, 1999; Stanovich & Stanovich, 1995). As noted by Share (1995), “there can be no case of competent reading in absence of functional decoding” (p. 173). For these reasons, the present study focuses on the possible relationship between item and order STM capacities and decoding reading acquisition. On the one hand, we expect a close relation between item STM and reading decoding acquisition, since both item STM and reading decoding acquisition are considered to require access to phonological knowledge and representations (Gathercole, Frankish, Pickering, & Peaker, 1999; Hulme, 2002; Majerus, Van der Linden, Mulder, Meulemans, & Peters, 2004; Parrila et al., 2004; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004; Thorn & Frankish, 2005; Wagner & Torgesen, 1987); this finding would support the fact that verbal STM and reading both rely on the recruitment of a common pool of phonological representations and processes. If this is the case, the relation between item STM capacities and reading decoding abilities should disappear when these phonological processes are explicitly controlled for, for example via phonological awareness tasks which are typically used in studies on reading to measure phonological analysis and segmentation capacities (Hulme, 2002; Parrila et al., 2004; Schatschneider et al., 2004; Wagner & Torgesen, 1987). On the other hand, the observation of a specific relation between order STM and reading decoding acquisition would be very informative at the theoretical level, since this relation cannot be simply ascribed to the intervention of a common phonological processing factor, but could hint to a more causal role of STM in reading acquisition. Past studies on reading decoding acquisition and STM capacity typically have confounded item and order STM processes. Gathercole et al. (Gathercole & Baddeley, 1993; Gathercole, Willis, Emslie, & Baddeley, 1992) followed 80 children from 4 to 8 years of age. They observed nonword repetition performance, a STM measure involving the retention of both item and order STM, measured at the age 4 (when the children had not yet started reading instruction) to be a significant predictor of reading ability in tasks involving recoding strategies at age 8. Similar results were observed by Meyler and Breznitz (1998) and Molfese et al. (2001). Muter and Snowling (1998) also controlled for phonological awareness abilities and observed that verbal STM measures (nonword repetition) remained a significant predictor of later reading performance after accounting for variance due to phonological awareness abilities (phoneme deletion task). These results suggest that the relation between verbal STM and reading acquisition may reflect more than simply the common reliance on phonological processing abilities. However, as in other studies, item and order STM capacities, which allow us to address this question more directly, were not distinguished.

In the present study, we explored the relationship between reading decoding acquisition and verbal STM capacities by using a longitudinal design and verbal STM tasks specifically designed to maximize short-term retention processes for either serial order information or item information. The tasks used here to measure item and order STM capacities have already been successfully implemented in several studies exploring the relation between order STM and language capacities (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen et al., 2006; Majerus, Poncelet, Greffe et al., 2006). These tasks were administered to 74 children when they were in kindergarten. After the onset of reading instruction, one year later, decoding skills were assessed with a nonword reading task, considered as the benchmark measure of decoding processes (Share, 1995; Wagner & Torgesen, 1987).

Order STM was measured via a serial order STM reconstruction task(Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe et al., 2006). This task maximizes retention capacities for serial order information, while minimizing requirements for processing phonological, lexical, and semantic information. This task involves the auditory presentation of sequences of animal names, by increasing list length. At the end of the list, the children receive cards depicting the animals that have been presented and they have to reconstruct the order of presentation of the animals using the cards. Item retention abilities are minimized since item information is provided at recall, and only their serial order has to be reconstructed. Furthermore, the same animal names are repeatedly presented throughout the different STM lists, further reducing item processing and retention demands. Item STM was assessed via **a** single nonword delayed repetition task maximizing retention of item information by requiring the children to process, store, and repeat unfamiliar phonological patterns. In this task, a single nonword is presented and has to be recalled after a short, filled retention delay (Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe et al., 2006). To maximize processing requirements for item information, the items are new on each trial. In order to reduce serial order requirements, only a single item has to be maintained in each trial. Furthermore, all nonwords are short and have the same CVC syllabic structure further reducing processing requirement at the level of sequence information (i.e., the sequence structure was the same in each trial, only phoneme identity varied between trials). This last characteristic distinguishes the present task from most nonword repetition STM tasks, which typically use complex nonwords of increasing length and thus require item retention and syllable serial order retention processes at the same time.

We further included measures of phonemic discrimination, phonological awareness and naming speed, in order to obtain an estimate of the quality and activation speed of phonological sublexical and lexical representations. These measures allowed us to control for the impact of phonological processes on the relationship between reading acquisition and item STM. As detailed earlier, we expect the association between item STM and reading decoding abilities to disappear when controlling for phonological processing abilities.

**Method**

**Participants**

Children were tested at the end of kindergarten (T1) and tested again 1 year later, at the end of 1st grade (T2), one year after the onset of reading instruction. At study onset, the sample consisted of 74 kindergarten children (mean age: 70 months; range: 62–81; 38 girls and 36 boys). The children were recruited in eight kindergarten and primary schools of the provinces of Liege and Namur, Belgium. All children came from families with middle-class socioeconomic background, as determined by their parents’ professional status. Letters were sent to the parents explaining the purpose of the study and asking for permission for children‘s participation. The parents were also asked to complete a questionnaire, allowing us to ensure that the children were native French speakers and that they presented no history of language, sensorimotor or neurological disorders. The children who did not meet these criteria were excluded. At T2, 66 of these children were tested again; of the initial sample four children had changed school and four children stayed in kindergarten for an additional year. Formal reading instruction started in Grade 1 and was based on phonics predominantly in all participating schools.

**Materials**

**Item STM task.** Item STM was assessed using a single nonword delayed repetition task (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen et al., 2006; Majerus, Poncelet, Greffe et al., 2006). This task was designed to maximize the processing demands of phonological item information while minimizing the contribution of serial order STM processes. The task consisted of 30 monosyllabic nonwords presented separately and the items were new on any trial. The stimuli had a CVC syllabic structure, and all were legal with respect to French phonotactic rules. The diphone frequencies of the CV segments (mean: 149; range: 3–524) and VC segments (mean: 129; range: 7–728) were nevertheless chosen to be low relative to the phonological structure of French, according to the database of French phonology by Tubach and Boë (1990) maximizing the processing demands of phonological item information. By contrast, order information retention was reduced for several reasons : (a) only a single item had to be retained; (b) all nonwords had the same monosyllabic consonant–vowel–consonant 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 -these permutations are however infrequent, Leclercq and Majerus (2010) only observed 0.4% of errors due to an inversion of initial and final consonants-; (c) nonwords were recalled after a filled delay which hindered sequential rehearsal of the to-be-stored information.The nonword stimuli were recorded by a female human voice and stored on a computer disk. The stimuli were presented via headphones. At the end of the stimulus, the children were instructed to continuously repeat the syllable “bla” during 3 seconds. Then the experimenter instructed the children to repeat the stimulus. The children additionally had to repeat the nonword once immediately after presentation to confirm that they had correctly perceived the item and were able to reproduce it accurately. However, no corrective feedback was given to the children. We determined the percentage of phonemes correctly repeated as dependent variable.

**Order STM task.** The retention of serial order information was assessed using a serial order reconstruction task, initially developed to explore the relation between order STM and vocabulary development (Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe et al., 2006). After the auditory presentation of sequences of animal names (*chat, chien, coq, lion, loup, ours, and singe* [cat, dog, cock, lion, wolf, bear, and monkey]), the children had to rearrange cards depicting the animals as a function of their order of presentation. This task was designed to maximize requirements for processing serial order information. Requirements for processing item information were minimized: (a) the seven stimuli had been selected for their high lexical frequency and their low age of acquisition (Majerus, Poncelet, Greffe et al., 2006) ensuring that they were highly familiar to the children; (b) the stimuli presented a monosyllabic structure minimizing phonological processing demands; (c) item were known in advance given that, for each length, the same animal names were selected to construct the sequences (for sequences of length 2, the cat and the lion were used; for sequences of length 3, the cat, the lion and the wolf were used, and so forth for the other sequence lengths); (d) finally, item information was fully available at recall because the cards representing the presented animals were given to the children who simply had to arrange them in correct serial position. These methodological precautions ensured the high sensitivity of this task to serial order information and minimized the processing demands for item information.The seven stimuli were used to form lists with lengths ranging from two to seven items, and there were four trials for each list length. All 24 trials were presented to each child. The sequences had been recorded by a female voice at a rate of one item per second, stored on computer disk and presented to the children via headphones. The trials were presented by increasing list length. At the end of each trial, the children were given cards (in alphabetical order) depicting the specific animals that had been presented in the trial. Thus, for list length 2, the children received two cards; for list length 3, the children received three cards; and so forth for subsequent list lengths. The children had to rearrange them according to their order of presentation, on a staircase with seven steps drawn on a sheet: they had to put the first item on the highest step, the second item on the second step, and so on. We determined the percentage of correctly placed items by pooling over all sequence lengths, as the dependent measure.

**Pre-reading letter knowledge.** The pre-reading level of the children at T1 was estimated via a letter identification task. The children were asked to name the different letters of the French alphabet. Items were written in lower case on individual cards and presented in random order. The total number of letters identified by the children was used as the dependent measure, with a maximum score of 26.

**Phonemic discrimination.** A minimal pair discrimination task was used to measure phoneme discrimination abilities. One hundred pairs of nonsense CCV or CCCV syllables were presented. Fifty pairs were identical (e.g., /fva-fva/) and 50 pairs differed in one phonetic feature (e.g., /*p*la-*b*la/) or contained phoneme transpositions (e.g., /*st*a-*ts*a/). All stimuli were recorded by a female native French speaker, stored on a computer disk and presented to the children in random order via high quality headphones, in two different sessions. There were at least 3 practice trials before each session. The dependent variable was the percentage of correct responses.

**Phonological awareness.** Phonological awareness abilities were assessed via a phoneme identification task, taken from the standardized language assessment battery *Nouvelles épreuves pour l’examen du langage* (New language Examination Battery, Chevrie-Muller & Plaza, 2001). Twelve bi-syllabic nonwords were presented. For 7 trials, the target phoneme was also the first syllable of the nonword (e.g., /y/ in /ytri/) and for 5 other trials, the target phoneme was part of the first syllable of the nonword (e.g., /a/ in /azly/). Each stimulus was presented once by the examiner. The children were asked to identify the initial vowel of the nonword. No corrective feedback was given. There were 2 practice trials before the test. The percentage of correct responses was used as the dependent variable.

**Rapid Automatized Naming (RAN).** A rapid automatic object naming task was designed to assess the speed of lexical access. This task involved two sets of objects (*maison*, *pomme*, *lit*, *feu,* *cadeau* [house, apple, bed, fire, present]; *sorcière*, *train*, *arbre*, *fourchette, grenouille* [witch, train, tree, fork, frog]) presented 10 times. For each set of object, the 50 items were presented horizontally on the screen of a computer. The children only saw 3 objects at once. The children had to name as quickly as possible the object presented in the center of the screen and indicated by an arrow. As soon as the children had named the object, the experimenter pressed on a key of the keyboard, the most rightward item was moved to the center of the screen and indicated by an arrow for naming, and so on for all other items. This successive presentation procedure decreased multiple object scanning processes while allowing the children to anticipate the following object. Total naming time was recorded, irrespective of response accuracy.

**Reading decoding.** To assess reading decoding abilities, the children were asked to read 32 nonwords varying in syllable structure (CV or VC versus CCV or VCC) and length (2 syllables versus 3 syllables). The nonwords were constructed by sampling from the letters taught during the first grade in the eight participating schools in this study (vowels /a, i, o, u/ and consonants /b, d, f, l, m, n, p, r, s, t, v/). The nonwords were presented by lists of 4, printed in lower-case on cards. The children were asked to read each list as accurately as possible. The percentage of nonwords correctly read was taken as a dependent measure.

**Nonverbal intelligence and vocabulary knowledge.** We also collected estimates of nonverbal intelligence and vocabulary knowledge to control for overall nonverbal and verbal abilities in our participants. Raven’s Colored Progressive Matrices (RCPM; Raven, Court, & Raven, 1998) were used as a measure of general nonverbal reasoning abilities. The raw scores were taken as the dependent measure. Receptive vocabulary knowledge was estimated using the EVIP scales (*Echelle de Vocabulaire en Images Peabody*) (Dunn, Thériault-Whalen, & Dunn, 1993), a French adaptation of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981). As a dependent variable, we used standardized vocabulary scores.

**Procedure**

At T1, all tests were administered, with the exception of the nonword reading task. The tasks were administered over two sessions, each lasting approximately 40 min. During the first session, the children were administered the RAN task, the item STM task, the vocabulary knowledge task and the phonological awareness task. The second session (2-3 days later) involved the administration of the letter knowledge task, followed by the order STM task, the phoneme discrimination task and the Raven’s matrices. The tests were given in the same fixed order for all participants. At T2, the nonword reading task was administered. Children were seen individually in their respective school, in a quiet room. Statistical analyses were performed using the STATISTICA 9 software package (StatSoft, Tulsa, Oklahoma, USA).

**Results**

Valid data sets were obtained for 50 participants[[1]](#footnote-1). Descriptive statistics for all variables measured at T1 and T2 are presented in Table 1. The distributional properties of the results for the different tasks were explored and one deviation from the expected normal distribution was observed. The letter knowledge score at T1 was skewed to the left, revealing a floor effect. This confirms that reading instruction had not yet started at kindergarten in the participating schools, and that only few children had some letter knowledge. After a log-transformation of this measure, skewness and kurtosis statistics were within the recommended two standard error range (Tabachnick & Fidell, 1996). Only the log-transformed score for letter knowledge was used in analyses. In order to check that the item STM task minimized serial order STM processes, we computed the number of order errors. As predicted, these inversions were very rare, only 0.55% of errors being due to inversions of the first and last consonant. Finally, we divided each STM task in two halves, by attributing all even trials to one half, and all uneven trials to the other half (split-half reliability). Highly reliability estimates were obtained for both STM measures: *r* = .75 for the order STM task and *r* = .72 for the item STM task.

< INSERT TABLE 1 ABOUT HERE >

**Correlation analyses**

A first set of analyses assessed the intercorrelations among the predictor variables taken at T1. As can be seen in Table 2, the two STM tasks correlated significantly, *r* = .30, *p* < .05. Moreover, the item STM task also correlated with nonverbal intelligence, *r* = .28, *p* < .05) and phonological awareness, *r* = .37, *p* < .01, while the order STM task showed a significant correlation with nonverbal intelligence, *r* = .48, *p* < .001, and vocabulary knowledge, *r* = .30, *p* < .05. This analysis suggests that item STM and phonological awareness processes are at least partly related to a common component, in agreement with the hypothesis of a dependence of item STM on underlying phonological representations. By contrast, as expected, no correlations were observed between order STM and phonological processing measures. Also note the correlation between the order STM measure and vocabulary knowledge which is in agreement with the theoretical models discussed earlier and considering that order STM is a critical building block for lexical learning. On the other hand, one may argue that if item STM depends on the quality and development of language representations, then we should also have observed strong correlations between our item STM measure and the other phonological measures as well as the vocabulary measure. As already noted, item STM capacity only correlated with the phonological awareness measure. The absence of a correlation between the item STM measure, and language measures such as vocabulary knowledge, RAN and phoneme discrimination is however consistent with our hypotheses because the language representations activated in these tasks stem from different linguistic levels. Given that the nonword item STM task used here requires access to sublexical phonological processes while the vocabulary task measures access to lexico-semantic representations, they reflect access to distinct levels of language representations. The same reason may also explain the absence of correlation between the item STM task and the RAN task, the latter assessing speed of access to lexical rather than sublexical phonological representations. Finally, the phoneme discrimination task assesses perceptual-phonetic rather than phonological processes (Morais et al., 1987). The status of these tasks in the context of the present study will be further discussed in the General Discussion.

< INSERT TABLE 2 ABOUT HERE >

We have conducted partial correlations between order STM, item STM and phonological awareness measures after control for nonverbal intelligence and vocabulary knowledge. The correlation between item STM and phonological awareness measures remained significant, *r* = .32, *p* < .05, while the correlation between the two STM tasks disappeared, *r* = .16, *ns*. Again, these analyses support the association between item STM and phonological abilities as well as the independence of order STM from phonological abilities.

A next set of raw correlation analyses assessed the overall relationship between the different predictor variables (measures taken at T1) and decoding reading performance one year later (nonword reading measure taken at T2). No significant correlation was noted for vocabulary knowledge*, r* = .17, *ns*, letter knowledge, *r* = .26, *ns*, and phoneme discrimination, *r* = .21, *ns*, measures. By contrast, significant correlations were observed for nonverbal intelligence, *r* = .40, *p* < .01, phonological awareness, *r* = .46, *p* < .001, item STM, *r* = .46, *p* < .001, and order STM, *r* = .49, *p* < .001, measures. As expected, not only phonological awareness and item STM but also order STM measures predicted reading performance.

**Multiple Regression Analyses**

The relative predictive value of T1 order STM, item STM and phonological awareness measures on T2 reading scores was determined via a set of multiple regression analysis. We first determined among the STM and phonological awareness measures at T1, which one was the strongest predictor of nonword reading performance at T2. Nonverbal intellectual efficiency and vocabulary knowledge were respectively entered in the regression at steps 1 and 2. Phonological awareness, item and order STM variables were entered in alternating order at steps 4, 5 or 6 to assess their relative importance in the prediction of nonword reading ability. As can be seen in Table 3, the regression model accounted for a significant proportion of variance in nonword reading at T2, *R*² = .43, *p* < .001. Phonological awareness and order STM task both explained a significant and unique amount of variance in nonword reading, whereas item STM did not account for significant unique variance in the regression analysis[[2]](#footnote-2). The fact that item STM measure was not an independent predictor of reading performance can largely be explained by its correlation with the phonological awareness measure. As shown in Table 3, the proportion of nonword reading variance predicted by the item STM measure dropped about 45% after the introduction of the phonological awareness task while this proportion only decreased about 18% after the introduction of the order STM measure in the regression equation. Of course, the item STM isn’t only a phonological task. The item STM task remains a STM measure and thus shares some general processes with the order STM task, such as attentional processes. Majerus et al. (2009) showed that the item and order STM tasks used here both draw upon auditory selective attention capacities.

< INSERT TABLE 3 ABOUT HERE >

Pre-reading level may influence the relationship between phonological awareness, order STM and nonword reading, even if in the preceding analyses, there was no significant correlation between pre-reading letter knowledge and later nonword reading ability. Nevertheless, in a last set of multiple hierarchical regression analyses, we checked whether phonological awareness and order STM measures remained independent predictors of reading abilities after controlling for initial differences in letter knowledge. Nonverbal intelligence, vocabulary and initial letter knowledge were respectively entered in the regression at steps 1, 2 and 3. Phonological awareness and order STM variables were entered in alternating order at steps 4 or 5. The results are displayed in Table 4. The regression model accounts for a significant proportion of variance in nonword reading at T2, *R*² = .44, *p* < .001. Performance in both phonological awareness and order STM tasks still accounted for significant portions of variance in nonword reading after controlling for nonverbal reasoning, vocabulary as well as for initial letter knowledge (phonological awareness accounted for 11% of independent variance and order STM also accounted for 11% of independent variance). Furthermore, both phonological awareness and order STM capacities predicted significant variance in reading performance when entered last into the regression equation, as in the previous analyses.

< INSERT TABLE 4 ABOUT HERE >

**Discussion**

The present study used the distinction between STM for item information and STM for order information to further our understanding of the relationship between verbal STM and reading acquisition. Using a longitudinal design, we observed that both order STM and item STM capacities at kindergarten predicted reading abilities one year later. At the same time, only order STM remained an independent predictor of reading abilities when controlling for phonological abilities. This is in line with our predictions that item STM abilities, but not order STM abilities, are strongly dependent upon the level of development of phonological representations and processes.

**The relationship between phonological processes, item STM and reading abilities**

Before discussing the relationship between item STM and reading abilities and its likely mediation by a phonological processing factor, we first discuss the evidence we have for an association of phonological processes and reading abilities. In agreement with previous findings, we observed that our phonemic awareness measure was a robust predictor of reading ability (Kirby, Parrila, & Pfeiffer, 2003; Muter & Diethelm, 2001; Muter & Snowling, 1998; Parrila et al., 2004; Passenger, Stuart, & Terrell, 2000; Schatschneider et al., 2004). Phonemic awareness is considered to help beginning readers to realize that spoken words are composed of segments at the phonemic level, in order to understand that – at least for alphabetic writing systems – the most basic phonemes correspond to written symbols such as letters or letter groups (Morais, Alegria, & Content, 1987). The ability to segment spoken words into their most elementary units will thus facilitate the use of grapho-phonemic correspondences.

In our study, the kindergarten phonemic awareness measure explained significant unique variance in nonword reading ability at 1st grade even after controlling for initial letter knowledge. Only a small number of studies have attempted to control for pre-reading level when examining associations between phonological awareness and reading (de Jong & van der Leij, 1999; Muter & Diethelm, 2001; Muter & Snowling, 1998; Rohl & Pratt, 1995). It is important to control for this factor since letter knowledge has been shown to influence the development of phonological awareness (Burgess, S. & Lonigan, 1998; Johnston, Anderson, & Holligan, 1996). In longitudinal studies, Castles and Coltheart (2004) argued that “pre-existing literacy skills may artificially inflate phonological awareness scores measured at time 1, because orthographic information can be used to assist performance. These inflated phonological scores may then be associated with higher reading scores at time 2 and beyond, not because the phonological skills were good predictors, but because the orthographic skills were (pp.85).”

On the other hand, we observed no association between the RAN task, measuring speed of phonological word form access and later reading ability. Other studies have observed such an association (Bowers, 1995; de Jong & van der Leij, 1999; Parrila et al., 2004; Scarborough, 1998b; Wolf, Bowers, & Biddle, 2000). There are a number of differences between these studies and the present study which may underlie these contrasting findings. Previous studies have shown that speeded naming tasks using alphanumeric stimuli (digits or letters) are more robust predictors of reading abilities than speeded naming tasks for colors or objects, the latter being used in the present study (de Jong & van der Leij, 2002; Lervag, Braten, & Hulme, 2009; Savage & Frederickson, 2005). In particular, Savage and Frederickson (2005) showed that RAN of pictures, unlike RAN of digits, was not significantly correlated with nonword reading (*r* = .15 and *r* = .39 respectively). We chose objects for speeded naming because children at kindergarten do not yet perfectly know letters and digit names, and hence speed of lexical access will be difficult to assess if the lexical representations cannot be properly accessed. As already noted in the Results section, the same reason may also apply for the absence of correlation we observed between the nonword item STM task and the RAN task. A second possible reason for the divergent results may be related to the measure of nonword reading capacity we used in the present study. Bowers (1995) suggested that naming speed is more important for the development of reading speed than for word reading accuracy. In the results we report, we only considered reading accuracy; although we also collected reading latencies, the distribution of reading times was too skewed to be included in the parametric analyses used here.

Similarly, the phonemic discrimination measure did not correlate with later reading achievement. The misperception of phonemes may prevent the development of well-specified phonological representations and consequently may result in phonological deficits and reading difficulties. In this view, Mody, Studdert-Kennedy and Brady (1997) observed that poor readers show significantly inferior performance to typical readers in perceptual discrimination of phonemes. However, the implication of phonemic discrimination capacity in reading acquisition remains controversial. In a meta-analysis, Scarborough (1998a) observed that in many longitudinal studies, speech discrimination, measured before children received any formal reading instruction, did not appear to be a useful predictor of subsequent reading achievement. As already noted before, speech discrimination measures are considered to measure perceptual-phonetic processes, that is the analyses of the acoustic properties of the stimuli (i.e., formant frequency, voice-onset time, formant transitions), without necessarily activating the more abstract phonological representations needed for associating graphemes and phonemes (e.g., Morais et al., 1987).

 In sum, as in previous studies, we observed phonological awareness measures to provide the most robust estimate of phonological processes that are determinant for reading acquisition. As furthermore predicted, the relationship between item STM and later reading abilities appeared to be mediated by these phonological processes, since the correlation between item STM and reading abilities was diminished significantly after controlling for phonological awareness abilities. As noted in the Introduction, a number of models assume that verbal item information is stored directly via temporary activation of the language network; in that sense, processing and storage of verbal item information depend directly upon the quality of underlying phonological and semantic representations (Brown et al., 1999; Burgess, N. & Hitch, 1999; Gupta, 2003; Henson, 1998). The correlation observed in the present article between a nonword item STM task and phonological awareness is in agreement with this hypothesis. Indeed, several studies suggest that phonological awareness abilities reflect the integrity and level of segmentation of underlying phonological representations (Fowler, 1991; Griffiths & Snowling, 2002; Metsala, 1997; Snowling, 1998; Wagner, Torgesen, & Rashotte, 1994). Furthermore, the item STM task used in the present study required careful attention to the nonword phonological input, as well as further segmentation of the input in order to ensure accurate encoding and subsequent recall of the phonemes of the target nonword. These sublexical phonological processes supporting single nonword repetition are very similar to those involved in phonological awareness tasks (see also Gathercole, 2006, for an extensive review and discussion of the interdependency of nonword repetition tasks and phonological processing).

**Order STM as a specific determinant of reading acquisition**

While item STM abilities are strongly related to linguistic processing abilities, this is not the case for order STM abilities, as shown by the present study as well as a large body of previous research (Majerus & D'Argembeau, 2011; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 1999). Recent theoretical models of STM also consider that order information is stored via a specialized, non-linguistic processing module (Brown et al., 1999; Burgess, N. & Hitch, 2006; Henson, 1998). Yet, we observed a robust prediction of later reading decoding abilities by order STM abilities at kindergarten after controlling for phonological awareness as well as general verbal and non-verbal intellectual efficiency at kindergarten. A similar finding was recently observed by Nithart et al. (2011), showing a significant intercorrelation between order STM capacity and reading decoding ability in 7-year-old children.

Contrary to previous studies on the same issue, the present data unambiguously show that the frequently observed association between verbal STM capacities and reading decoding abilities cannot be dismissed as reflecting only the common reliance on a phonological processing factor, but that there is a more fundamental association between core STM abilities and reading decoding acquisition. As shown by the present study, these core STM processes reside in the abilities that allow the maintenance of a temporary representation of sequence information. Order STM capacities have already been shown to be determinant for the acquisition of new phonological representations, by allowing the temporary storage and refreshment of the ordered sequence of phonemes that defines a new word form (Gupta, 2003; Jarrold, Thorn, & Stephens, 2009; Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen et al., 2006; Majerus, Poncelet, Greffe et al., 2006; Mosse & Jarrold, 2008). The present study shows that this mechanism can be extended to the acquisition of reading abilities. When reading new word forms, the beginning reader must associate multiple graphemes to corresponding phonemes, and temporarily store the sequence of sounds coded by the letters while blending these sounds into a phonological word form for read out. The successive products of the letter-to-sound conversion processes need to be stored in an ordered succession when blending the successive phonemes into a word form, thus requiring the critical intervention of order STM processes. Gathercole and colleagues (Gathercole & Baddeley, 1993; Gathercole et al., 1992) suggested that verbal STM may be used to temporarily store the successive phonological products when mapping phonology to orthography on a grapheme-by-phoneme basis. Their study design however did not allow for the identification of the core STM processes that explain this association. Our results are also supported by a growing body of research in reading impaired children and adults. Several authors have observed serial order retention deficits in poor readers (Mason, Katz, & Wicklund, 1975), in a case of developmental surface dysgraphia (Romani, Ward, & Olson, 1999) and in dyslexic children (Nithart et al., 2009), even if these studies did not explicitly distinguish between item and order STM processes. Martinez Perez, Majerus and Poncelet (2011) used specific tasks maximizing STM for serial order or item information and observed an important impairment of order STM capacities in dyslexic adults. The present finding that STM for order information plays a specific role in reading decoding acquisition has potential implications for reading and STM assessment. For early identification of children at risk for reading difficulties it may be useful to include tasks of order STM, in addition to standard phonological awareness measures (Bishop & League, 2006). Order STM capacities could also serve as a locus for intervention in order to put at-risk children in a better starting position for reading acquisition. However, further studies are needed to investigate whether the training of order STM processes actually reduces the probability of reading difficulties in these children. In the same way, it could be interesting to explore if intervention based on order STM capacities could improve reading decoding performance in children with dyslexia.

Besides the specific contribution of order STM in reading decoding processes, order STM capacity could also be important for the acquisition of new long-term orthographic representations. As already noted, during the acquisition of new phonological word forms, the order of phonemes defining a new word will be stored in order STM. This temporary sequence representation will then allow the ordered and repeated reactivation of the phonemes of the new word form, increasing the probability that the new phoneme sequence will be associated with a new lexical node, leading to the formation of a corresponding long-term phonological representation (Gupta, 2003; Jarrold et al., 2009; Leclercq & Majerus, 2010; Majerus, Poncelet et al., 2008). With respect to reading acquisition, a similar serial reactivation process could increase the probability that a new written word form is transformed in a stable long-term orthographic representation connected to its corresponding phonological representation; once these connections are stabilized, they can then be used for direct orthography-to-phonology mapping. This means that order STM would be involved especially during the first stages of the creation of new long-term orthographic representations. This also means that order STM processes would not be directly required anymore when children use the direct mapping reading procedure. However, the present study design uses a nonword reading task and hence does not permit to confirm or contradict this hypothesis. In order to test this hypothesis for word reading ability, future research should employ orthographic learning tasks such as those used by Shahar-Yames and Share (2008), enabling us to determine whether learning speed for acquiring orthographic representations is predicted by order STM capacity. Another limitation of the present study was the sample size. For correlation analyses, a sample size of 50 participants is a rather modest one and we cannot rule out that some of the non-significant correlations in the present study, such as between vocabulary or letter knowledge and reading performance, may have been significant with a larger sample. At the same time, we should note that the association between vocabulary and reading acquisition is not a constant one, and this association has been reported to be non-significant also in studies with much higher numbers of participants (Gathercole et al., 1992; Schatschneider et al., 2004; respectively 80 and 384 children) This inconsistency of results is probably related to the nature of reading tasks used, with vocabulary knowledge contributing to real word reading and reading comprehension rather than to decoding processes (Muter et al., 2004; Naslund & Schneider, 1991; Nation & Snowling, 2004)*.*

**Conclusions**

By using serial order STM tasks that minimize the recruitment of phonological processes, we were able to measure core STM processes independently of the contribution of phonological knowledge. We show that these core STM processes are a robust predictor of early reading acquisition, providing new evidence for a determining role of verbal STM capacity in reading development. Future studies will need to address the precise mechanisms that are responsible for the strong association between order STM processes and later reading abilities that have been documented in this study.

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Table 1

*Means, Standard Deviations and Ranges for T1 and T2 variables (n = 50)*

 *M* *SD* Range

T1 - Kindergarten

RCPM (max = 36) 19. 8 2.9 15-27

RCPM (percentile) 47.8 22.0 13-94

EVIP (standardized score) 100.3 8.9 83-120

Letter knowledge (log score) 0.89 0.32 0-1.4

Phonological discrimination (proportion) 78.9 10.8 58-95

Phonological awareness (proportion) 55.2 24.2 8-91

RAN (second) 40.6 7.5 28-58

Item STM (proportion) 76.9 9.7 54-97

Order STM (proportion) 52.4 8.7 30-71

T2 - 1st Grade

Nonword reading (proportion) 81.5 12.9 44-100

*Note*. RCPM = Raven’s Colored Progressive Matrices; EVIP = French version of Peabody Picture Vocabulary Test.

Table 2

*Raw correlations among the variables at T1 (n = 50)*

 1 2 3 4 5 6 7 8

1. RCPM \_ .12 .13 .19 .21 -.21 .28\* .48\*\*\*

2. EVIP \_ .19 .14 .10 -.33\* .20 .30\*

3. Letter knowledge \_ .20 .38\*\* -.22 .05 .12

4. Phonological discrimination \_ .57\*\*\* -.38\*\* .22 .24

5. Phonological awareness \_ -.28\* .37\*\* .15

6. RAN \_ -.01 -.14

7. Item STM \_ .30\*

8. Order STM \_

*Note*. RCPM = Raven’s Colored Progressive Matrices; EVIP = French version of Peabody Picture Vocabulary Test.

\**p* < .05 \*\**p* < .01 \*\*\**p* < .001

Table 3

*Hierarchical multiple regression analyses of phonological awareness, item STM and order STM variables at T1 on nonword reading abilities at T2, after controlling for nonverbal intelligence and vocabulary knowledge*

Predictor Δ*R*² adjusted Δ*R*² β

1. RCPM .14 .12 .38\*\*

2. EVIP .01 .01 .11

3. Item STM .11 .10 .33\*\*

4. Order STM .09 .07 .32\*

5. Phonological awareness .08 .07 .31\*

3. Phonological awareness .14 .12 .38\*\*

4. Item STM .06 .05 .27\*

5. Order STM .08 .07 .31\*

3. Order STM .11 .10 .33\*\*

4. Item STM .09 .07 .32\*

5. Phonological awareness .08 .07 .31\*

3. Order STM .11 .10 .33\*\*

4. Phonological awareness .13 .11 .36\*\*

5. Item STM .04 .03 .22

*Note*. RCPM = Raven’s Colored Progressive Matrices; EVIP = French version of Peabody Picture Vocabulary Test. The betas (β) reported here are those obtained when introducing the predictor of interest at Step T, and the other predictors at Step T-1, and hence reflect the independent contribution of the predictor of interest after all the other predictors.

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

Table 4

*Hierarchical multiple regression analyses of phonological awareness and order STM variables on nonword reading abilities at T2, after controlling for nonverbal intelligence, vocabulary knowledge and pre-reading level*

Predictor Δ*R*² adjusted Δ*R*² β

1. RCPM .14 .12 .38\*\*

2. EVIP .01 .01 .11

3. Letter knowledge .05 .03 .19

4. Phonological awareness .12 .11 .36\*\*

5. Order STM .11 .10 .35\*\*

4. Order STM .12 .11 .37\*\*

5. Phonological awareness .11 .10 .34\*\*

*Note*. RCPM = Raven’s Colored Progressive Matrices; EVIP = French version of Peabody Picture Vocabulary Test. The betas (β) reported here are those obtained when introducing the predictor of interest at Step T, and the other predictors at Step T-1, and hence reflect the independent contribution of the predictor of interest after all the other predictors.

\*\**p* < .01

1. Three participants were excluded due to their very poor performance at the nonverbal intelligence task, and the data from an entire classroom (13 participants) had to be removed from analyses due to reading instruction failure in this school (most children were unable to decode nonwords correctly at T2, due to a change in teaching staff and type of reading instruction). [↑](#footnote-ref-1)
2. In order to determine whether a potential difference in difficulty for the order and item STM tasks may explain the fact that only the order STM measure remained a significant predictor of nonword reading performance when entered last into the regression analysis, we recalibrated our measures to achieve similar identical success rates. This was obtained by discarding list length 7 of the order STM task. This resulted in a performance increase from 52.4% to 72.0% for the order STM task (76.8% for the item STM task). We then recomputed all our regression analyses and obtained the same results as for the original measures: phonological awareness and order STM remained significant and independent predictors of nonword reading and item STM did not independently predict reading performance when entered last into the regression equation, as in the initial analyses. [↑](#footnote-ref-2)