Journal of Experimental Child Psychology 103 (2009) 66–86

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Impact of auditory selective attention on verbal short-term memory and vocabulary development

Steve Majerus [a,b,*], Lucie Heiligenstein [a], Nathalie Gautherot [a], Martine Poncelet [a], Martial Van der Linden [a,c]

[a] Department of Cognitive Sciences, Center for Cognitive and Behavioral Neuroscience, Université de Liège, 4000 Liege, Belgium
[b] Fonds de la Recherche Scientifique (F.R.S.-FNRS), 1000 Bruxelles, Belgium
[c] Cognitive Psychopathology Unit, Université de Genève, CH-1205 Geneva, Switzerland

ARTICLE INFO

Article history:
Received 25 February 2008
Revised 4 July 2008
Available online 7 September 2008

Keywords:
Verbal short-term memory
Lexical development
Attention
Serial order

ABSTRACT

This study investigated the role of auditory selective attention capacities as a possible mediator of the well-established association between verbal short-term memory (STM) and vocabulary development. A total of 47 6- and 7-year-olds were administered verbal immediate serial recall and auditory attention tasks. Both task types probed processing of item and serial order information because recent studies have shown this distinction to be critical when exploring relations between STM and lexical development. Multiple regression and variance partitioning analyses highlighted two variables as determinants of vocabulary development: (a) a serial order processing variable shared by STM order recall and a selective attention task for sequence information and (b) an attentional variable shared by selective attention measures targeting item or sequence information. The current study highlights the need for integrative STM models, accounting for conjoined influences of attentional capacities and serial order processing capacities on STM performance and the establishment of the lexical language network.

Introduction

Over the past 20 years, a considerable literature has accumulated showing close relations between performance on verbal short-term memory (STM) measures and estimates of lexical development.

* Corresponding author. Address: Department of Cognitive Sciences, Center for Cognitive and Behavioral Neuroscience, Université de Liège, Boulevard du Rectorat, B33, 4000 Liege, Belgium. Fax: +32 43662808.
E-mail address: smajerus@ulg.ac.be (S. Majerus).

0022-0965/$ - see front matter
doi:10.1016/j.jecp.2008.07.004

However, the reason for this association remains uncertain, and a number of different interpretations have been proposed. The aim of the current study is to explore the respective role of serial order storage and auditory attention capacities for accounting for the association between performance on verbal STM measures and vocabulary development.

The main difficulty when interpreting the association between STM measures and vocabulary development is related to the difficulty of clearly understanding what verbal STM tasks actually measure. Typically, a verbal STM task requires immediate repetition of sequences of familiar or unfamiliar verbal information, the sequences containing either multiple items (e.g., word list immediate serial recall) or single items of variable length (e.g., multisyllabic nonword repetition). The most straightforward interpretation is to consider that verbal STM tasks reflect the capacity of a specialized verbal short-term storage system such as the phonological loop model proposed by Baddeley and Hitch (1974). In that view, the association between performance on STM tasks and vocabulary development reveals the importance of temporary phonological storage capacity for forming new long-term phonological lexical representations (e.g., Baddeley, Gathercole, & Papagno, 1998; Gathercole & Baddeley, 1989). In other words, verbal STM tasks are considered to measure verbal short-term storage capacity that is causally involved in lexical development. Longitudinal studies, showing that performance in nonword repetition tasks at 4 years of age predicts vocabulary knowledge at 5 years of age, are supportive of this assumption (Gathercole, Willis, Emslie, & Baddeley, 1992).

However, verbal STM tasks do not only reflect the capacity of a specialized STM system. A substantial body of research now shows that many verbal STM tasks are dependent on the quality and level of segmentation of lexical and sublexical phonological representations in the language system. For example, immediate serial recall tasks using word stimuli lead to higher performance levels than do tasks using nonwords, suggesting that lexical knowledge contributes to short-term recall, either indirectly via redintegration processes of the decayed STM trace during retrieval (e.g., Hulme, Maughan, & Brown, 1991; Schweickert, 1993) or directly via stabilizing feedback activation between language and STM systems at the moment of encoding (e.g., Baddeley et al., 1998; Martin, Lesch, & Bartha, 1999). Similarly, at the sublexical level, subtle knowledge about statistical properties of sound co-occurrences for the native language phonology leads to a recall advantage for nonwords containing frequent phonotactic patterns relative to nonwords with less frequent phonotactic patterns (Gathercole, Frankish, Pickering, & Peaker, 1999; Thorn & Frankish, 2005). The impact of lexical and sublexical phonological knowledge on STM performance seems to remain constant across development (Majerus & Van der Linden, 2003; Majerus, Van der Linden, Mulder, Meulemans, & Peters, 2004; Peters et al., 2007). Finally, functional neuroimaging studies also show that language-processing areas are actively recruited during verbal STM tasks (Collette et al., 2001; Fiebach, Friederici, Smith, & Swinney, 2007; Majerus, Poncelet, Van der Linden, Albouy, Salmon, Sterpenich, Vandewalle, Collette, & Maquet, 2006). This implies that traditional STM tasks reveal at least as much about language processing as they do about STM processing. Hence, the relation between performances on STM and vocabulary measures could simply imply that both measures reflect the level of development of the language system. This possibility is also raised by a subset of the results of the longitudinal study by Gathercole and colleagues (1992), who observed that vocabulary knowledge at 5 years of age predicts nonword repetition performance at 6 years of age.

There may, however, be a possibility to separate the intervention of STM and language processes in STM tasks by distinguishing between the different types of information to be maintained in these tasks. A number of studies have shown that language knowledge primarily affects processing and recall of item information, but less so recall of serial order information (e.g., Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 2005). Most recent STM models also consider that item information is partially stored via temporary activation of the language network, whereas serial order information is processed by a specialized STM system, although the exact implementation of this system varies between models (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Burgess & Hitch, 2006; Gupta, 2003). Majerus, Poncelet, Greffe, and Van der Linden (2006) implemented this distinction by designing STM tasks either to maximize processing and retention of serial order information while minimizing item processing requirement (e.g., immediate serial recall of word lists with the words being sampled from a closed set of highly predictable and familiar items) or to maximize item processing requirements while minimizing serial order processing requirements (e.g., delayed recall of single unfamiliar items such as nonwords challenging the sublexical phonological knowledge system). Using this procedure, the authors were able to show that "item" and "order" STM tasks independently predict vocabulary development in 4- to 6-year-olds. Similar results were obtained when predicting new word learning capacities in adults, with the serial order STM measures being the strongest and most consistent predictors (Majerus, Poncelet, Elsen, & Van der Linden, 2006; Majerus, Poncelet, Van der Linden, & Weekes, 2008). By assuming that order STM measures reflect specific serial order STM capacities that do not reflect underlying language knowledge, these results lend support to the position that verbal STM or at least some of its constituent processes may be causally involved in lexical development.

However, serial order retention and activation/decay of language representations are not the only factors determining verbal STM performance and thereby also the relationship between vocabulary development and verbal STM performance. When performing an auditory immediate serial recall task of word lists, a prerequisite cognitive capacity is the ability to selectively attend to the stimuli to be presented and to maintain attention toward the stimuli all along the encoding process. Auditory selective attention capacities are thus likely to also be an important determinant of verbal STM performance. Surprisingly, although the relation between attention and short-term storage has been explored extensively in the context of working memory tasks combining storage and processing (e.g., Baddeley & Logie, 1999; Barrouillet, Bernardin, & Camos, 2004; Engle, Kane, & Tuholski, 1999; Gavens & Barrouillet, 2004; Lovett, Reder, & Lebiere, 1999), the likely influence of auditory selective attention capacities on more basic, passive, short-term storage capacities has received considerably less interest. Yet irrespective of differing theoretical accounts on the relation between attention and temporary storage presented below, performing a passive STM task such as digit span recall without carefully orienting attention to the items being presented and to be recalled is likely to lead to relatively poor STM performance. A further hint for the importance of attention in STM tasks can be derived from the definitions of attentional capacity. For example, William James defined attention in the following way:

> Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others. (James, 1890/1950, pp. 403–404).

This definition of attention describes a number of processes that are actually crucial when performing an STM task such as focalization and concentration of consciousness on the stimuli to be remembered.

Although many theoretical models have addressed the relation between attention and working memory performance, few have specifically targeted passive short-term storage tasks. For example, in the highly influential working memory model by Baddeley (1986), Baddeley (2000), verbal short-term storage capacity is supposed to be determined essentially by mnemonic factors such as decay of STM traces in a phonological short-term store and the refreshing of these traces via rehearsal strategies. Attentional factors intervene only via a third component, the central executive, allowing the intervention of task-specific controlled attentional processes as needed when information needs to be not only passively maintained in STM but also manipulated (e.g., backward digit recall) or when STM and non-STM tasks need to be performed concurrently (e.g., double task situations). In this framework, controlled attentional factors play an important role in working memory tasks but less so in passive verbal short-term storage tasks. Recent studies have shown that these controlled attentional factors play a role in verbal development. Gathercole and colleagues followed children from 5 to 8 years of age on a number of STM, working memory, and scholastic achievement measures. They observed that initial phonological STM scores were less consistently associated with later scholastic achievement (including vocabulary development) than were working memory measures that are more demanding at the level of controlled attentional processes according to the working memory model (Gathercole, Tiffany, Briscoe, Thorn, & ALSPAC Team, 2005). However, this does not inform us about the intervention of attentional processes in "passive" verbal STM tasks and how these might mediate the relationship between performance on these tasks and vocabulary development.

Cowan (1988), Cowan (1999) is one of the few authors addressing more directly the link between basic short-term storage capacity and attentional capacity. Cowan proposed that an essential factor limiting short-term storage capacity is indeed so-called focused attention capacity. In Cowan's embedded process framework, short-term storage for verbal information depends on temporary activation of corresponding long-term language representations and their maintenance in the focus of attention. In this sense, STM measures are basically attentional measures rather than reflecting a time-based mnemonic capacity. The tasks used by Cowan and colleagues to study these focused attention capacities are so-called scope of attention measures. In one variant of this task, auditory digit sequences are presented at a very fast pace (e.g., four digits per second) to prevent the application of rehearsal or any other strategy, and at some unpredictable time points the participants are then asked to recall any digits they can remember in forward order. Cowan, Nugent, Elliott, Ponomarev, and Saults (1999) showed that in these tasks, scope of attention is generally limited to four items in adults and increases with age in children. For Cowan and colleagues, this very basic, automatic attentional capacity is an important determinant of performance in STM tasks. This research group also observed that scope of attention tasks predict scholastic achievement and verbal intelligence measures (including vocabulary development) in school-age children and that the largest part of variance explained in these achievement measures was common variance shared by the scope of attention and STM measures (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Cowan et al., 2005). However, although these studies show the usefulness of a theoretical concept such as the scope of attention for exploring the relations between STM and verbal development, they do not yet directly address the problem of the auditory selective attention requirements that are involved in typical verbal STM measures such as immediate serial recall of word lists. With respect to the scope of attention tasks, it should be noted that standard immediate serial recall tasks differ from scope of attention measures in the sense that items are presented at much slower speed, enabling and requiring intentional sustained attentional encoding. Scope of attention tasks are not designed to account for these intentional attentional processes; rather, they are designed to explicitly circumvent these processes.

Hence, although auditory selective attention is very likely to be an important determinant of verbal STM performance, no study has yet directly addressed this issue. The aim of the current study was to explore the extent to which individual differences in performance on verbal immediate serial recall tasks is determined by individual differences in auditory selective attention capacities as needed during processing of item and order information in these STM tasks and the extent to which these attentional differences mediate the relationship between performance on verbal STM tasks and vocabulary development. As we have already described, typical immediate serial recall tasks require the child to encode verbal items as well as their order of presentation, to retain these different types of information for a short period of time, and to output retrieved order and item information. Although we have presented a number of studies suggesting that processing of item information requires the recruitment of language knowledge, whereas processing of serial order information reflects the intervention of a specialized STM system, attentional factors are also likely to influence item and order processing. Indeed, a necessary condition for accurate encoding of item and order information is that the child selectively directs his or her attention to the different items and their order of presentation. If attention is fading or distracted by internal thoughts or external stimulations, item and order information is likely to be encoded with lesser strength and vividness, resulting in poorer item and order processing and possibly poorer recall.

In the current study, we designed auditory selective tasks requiring attention to be directed to either order information or item information so as to obtain measures reflecting the precise auditory selective attentional demands associated with item and order processing during typical immediate serial recall tasks. Our main aim was to determine the extent to which the attentional demands associated with item and order encoding during verbal STM tasks explain individual differences in item and order STM capacity and possibly mediate the associations among item STM, order STM, and vocabulary development. In this respect, the choice of the auditory selective attention tasks was empirically driven rather than theoretically driven, with our main concern being to devise tasks that reflect as closely as possible the selective attention demands as they are involved during an immediate serial recall situation.

The current study

Verbal STM was assessed using an immediate serial recall task probing both item and order information based on previous studies (Majerus, Bastin, Poncelet, Van der Linden, Salmon, Collette, & Maquet, 2007; Majerus, Norris, & Patterson, 2007; Majerus, Van der Linden, Braissand, & Eliez, 2007; Majerus et al., 2006; Majerus et al., 2008; Poirier & Saint-Aubin, 1996; Majerus et al., 2006). Contrary to these previous studies that used separate tasks to probe item and order STM, we determined item and order recall performance by using a single immediate serial recall task of word lists and by computing the number of item and order errors occurring in that task. This procedure permits ensuring that any differential correlation patterns expected between vocabulary development and item and order STM performance are related to the different types of information to be recalled and not to any structural differences in task design for tasks specifically developed to maximize either serial order or item retention capacities.

The auditory selective attention tasks were designed to capture as closely as possible the attentional demands associated with item and order processing during verbal immediate serial recall while at the same time minimizing any temporary storage requirements. For both the STM and auditory selective attention tasks, auditory sequences of familiar items (animal names) were presented at identical presentation rates. For the STM tasks, the sequences were presented by increasing length and the children needed to reproduce each sequence immediately after presentation. For the item selective attention condition, the children heard a continuous sequence containing the same items as used in the STM task and were instructed to press a response button when a predefined target stimulus occurred. This condition captured attentional demands as involved during item processing in the immediate serial recall task by the fact that children needed to direct their attention to each item and to shift attention from one item to the next while analyzing the identity of the items. For the sequence selective attention condition, the children heard a continuous sequence that included only two or three items, with these items succeeding each other in variable order. The children were instructed to press a response button when the items appeared in a predefined order (e.g., target sequence = $I_a \rightarrow I_c \rightarrow I_b$, nontarget sequences = all other possible successions such as $I_b \rightarrow I_c \rightarrow I_a$ and $I_a \rightarrow I_a \rightarrow I_b$). This condition captured attentional demands as involved during order processing in the immediate serial recall task by the fact that children needed to constantly direct their attention to the order of appearance of the items and to update order information with any new incoming stimulus.

For both attentional tasks, STM requirements were minimized because the target information was constantly cued via the display of a picture of the target animals or a picture of the target animal sequence. Therefore, to equate the STM and auditory selective attention tasks at the level of response production, the same pictures that cued the target response in the attention tasks were also used for response production in the immediate serial recall task. The children needed to reconstruct the auditory sequence by selecting the corresponding pictures from a larger set of pictures and putting them in correct order. So, both the attention and STM tasks required the matching of auditory and visual information. In this way, it was also ensured that similar response selection, inhibition, and monitoring processes were involved in both STM and attention tasks. During response production in the STM task, the target pictures needed to be selected in accordance to the auditory–verbal STM representation, and selection of other pictures needed to be inhibited; in the attention task, a response needed to be made when an auditory stimulus corresponding to the target picture occurred, whereas response selection for the other names needed to be inhibited.

These tasks were administered to a group of 6- and 7-year-olds. Pilot testing had shown that this was the youngest age group for whom the attentional measures used in this study could be applied in a reliable way. Furthermore, we aimed to explore the relations among vocabulary development, STM, and attention at the youngest possible age, where the association between STM capacity and vocabulary development is most robust (Gathercole, Service, Hitch, Adams, & Martin, 1999). We were interested in determining the extent to which the relationship between performance on the STM measures and vocabulary development was mediated by auditory selective attention measures and whether this mediation depended on the type of information (item vs. order) to be attended to. We first computed correlation analyses to establish the strength of association between the different measures. Next, hierarchical multiple regression and variance partitioning methods were used to determine independent and shared contributions of the STM and selective attention measures on vocabulary scores. In line with the vast majority of previous studies examining relations between verbal STM and vocabulary development (e.g., Avons, Wragg, Cupples, & Lovegrove, 1998; Bowey, 1996; Gathercole & Adams, 1994; Gathercole & Baddeley, 1989; Gathercole, Willis, & Baddeley, 1991; Gathercole et al., 1992), we controlled for individual differences in general cognitive efficiency and their impact on correlation analyses by partialing out performance on a test of nonverbal intellectual efficiency, Progressive Coloured Matrices (Raven, Court, & Raven, 1998). However, we should note that by doing so, we might also remove the influence of variables of interest in this study, such as selective attention capacities, that are likely to support performance in the Raven's matrices task, as they will in any task requiring attention to be selectively directed and focused on information processing as a function of task requirements. Therefore, we first report partial correlation analyses controlling for performance on Raven's matrices, in line with current practice. The variance decomposition analyses will then directly consider the impact of STM and attentional capacities on vocabulary performance and Raven's matrices performances.

Method

Participants

A total of 47 children participated in this study. Their mean age was 82 months (*SD* = 5.5). The children were selected from second-grade-level classes in the suburban area of Liege, Belgium (*n* = 37), and Besançon, France (*n* = 10).[1] Parental consent was obtained for each child. Parents were also administered a questionnaire ensuring that the children's native language was French, that they had no history of neurological disorders or neurodevelopmental delay, that auditory and visual acuity were normal, and that the children had normal language development and no learning difficulties. The children lived in families with a middle-class socioeconomic background. The children were seen in their respective schools.

Material and procedure

Verbal STM (animal race task)

This STM task, first validated by Majerus et al. (2006), was adapted to measure conjointly item and order STM performance. The stimuli consisted of seven monosyllabic animal names: *chien, chat, loup, ours, lion, coq,* and *singe* (dog, cat, wolf, bear, lion, cock, and monkey, respectively). The mean age of acquisition for the seven names was 1 year 8 months (range = 13–24 months) (Alario & Ferrand, 1999; Ferrand & Alario, 1998). The mean lexical frequency, based on a database derived from texts of schoolbooks and general books for children of primary school age, was very high (mean lexical frequency = 50,631, range = 16,423–90,926 [source: *Novlex* by Lambert & Chesnet, 2001]). These selection parameters ensured that all items were equally familiar to the children. These seven stimuli were used to form lists with a length ranging from two to six items, with two trials for each list length. For each list, the items were randomly selected from the pool of seven items, and no item could occur twice in the same list. The individual items were recorded by a female voice and stored on a computer disk. The mean duration of the items was 549 ms (range = 371–696). The different prerecorded items were used to assemble 10 stimulus lists. Within the lists, the items were presented at a rate of one item per second.

The stimuli were presented by increasing list length, beginning with a list length of two items. All trials were presented to each child. The stimulus lists were presented via headphones connected to a portable PC. The experimenter activated the presentation of each stimulus list. After the auditory presentation of the list of animal names, each child was given seven cards with dimensions of 6.5 $\times$ 6.5

[1] No significant differences in performance levels were observed for the tasks used here as a function of area of origin of the children.

cm. The seven cards depicted the seven possible animals that could occur in each sequence. The child then needed to select the cards that had been presented and to arrange these cards (given in alphabetical order) following the order of presentation of the auditory sequence by putting them on a 50×50-cm cardboard sheet on which a staircase-like figure with six steps was depicted. This procedure ensured that the child could make both item and serial order errors. The child needed to put the first animal on the list at the highest step, the second animal at the second-highest step, and so forth for the subsequent trials. However, the child could begin order reconstruction at any serial position. For list lengths smaller than six items, the steps not needed were covered by a blank sheet. The experimenter wrote down the order in which the child had reordered the cards, removed the cards, and activated the auditory presentation of the next list. The child was told the following story for task description:

> Every year, the animals from all over the world gather to have a huge race. This year, seven animals are participating: a dog, a cat, a lion, a bear, a wolf, a monkey, and a cock [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. On other times, there are big races with six animals. Through the headphones, you will hear someone announce the animals' 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 that participated in the race 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?

The child was informed when the list length increased. To measure both item and order retention capacities, we determined the number of errors within each list, separated the errors as a function of error type (item errors [omissions and confusions, i.e., an animal not presented has been selected] versus order errors [a target animal is reconstructed in the wrong serial position]) and then computed the total number of item and order errors by pooling over the four sequence lengths (maximum possible number of errors = 36 per error type, discarding the first two trials that were practice trials).

Auditory selective attention for items and sequences

Item and sequence selective attention tasks were designed, with the participants needing to detect target auditory items and target auditory sequences, respectively. The auditory stimuli were sampled from the same seven animal name recordings as those used in the STM task. The stimuli were presented at a rate of one stimulus per second.

For the item selective attention condition, picture representations of the two or three target animals were displayed on a computer screen throughout the entire task to permanently cue the target stimuli and to minimize STM load as much as possible. The children needed to press a response button as quickly as possible when detecting a target stimulus in the auditory stimulus stream. There were four trials: two trials with two targets and two trials with three targets. In each trial, 90 stimuli were presented, with 20–22 occurrences of target stimuli (for trials with two possible targets) or 30–36 occurrences of target stimuli (for trials with three possible targets). The distractor stimuli were sampled from the remaining four or five nontarget animal names.

For the sequence selective attention condition, the task design was very similar with the exception that the picture representations of the target stimuli on the computer screen were spatially organized from the top left corner to the bottom right corner to signal their sequential organization. The children needed to detect the target sequence, starting with the animal displayed at the highest and most leftward position and finishing with the animal at the lowest and most rightward position, in the auditory stream. As for the previous condition, the visual display of the sequence remained throughout the entire trial to minimize any STM load. A major difference between the item and sequence conditions was that in the sequence condition each trial was constructed by sampling repeatedly from the same two or three names of which the target sequence was made. This ensured that the children focused only on the order of succession of the items without needing to pay special attention to the nature of the items because the same two or three items always occurred. The number of target sequences ranged between 10 and 12 for each trial and sequence length. Although the number of motor responses to be made was two or three times smaller than it was in the item selective attention trials, this procedure ensured that the amount of information to be processed was in fact the same in each condition. For the two-item sequences, the order of two items needed to be correctly detected to give a response, and for the three-item sequences the order of three items needed to be processed to give a response. Hence, given that a total of 90 stimuli were presented in each trial, as for the item condition, the number of items to be processed was the same in both the item and order conditions despite a differing number of actual motor responses to be made. For each trial in both conditions, the different stimuli were presented in a pseudo-random order.

To avoid children becoming confused about task instructions, the four trials for each selective attention condition were presented in blocks by starting with the item selective attention condition and by starting with two-item trials. The target stimuli changed for each trial.

The auditory stimuli were presented via high-quality headphones connected to a PC that controlled auditory and visual stimulus presentation as well as button press responses using E-Prime 1.0 software (Psychology Software Tools, Pittsburgh, PA, USA). To make task instructions as concrete as possible, and to increase task compliance, the task was introduced by a story. For the item selective attention condition, the children were told the following:

> Each year, cats, dogs, cocks, lions, wolves, bear, and monkeys from all over the country come together for a big fair. They adore to have a ride on a very beautiful merry-go-round. Through the headphones I have put around your head, somebody will tell you each time the animals have completed a ride. Your task is to press on this button each time [Animal 1], [Animal 2], or [Animal 3] has completed a ride, that is, when you hear the name of one of these animals. In order to help you remember what animals you have to respond to, you also see a picture of them on this screen here. Okay? Let's do some examples.

For the sequence selective attention condition, the task instructions were as follows:

> We will now slightly change the merry-go-round game. On this magnificent merry-go-round, there is a very beautiful and large horse with two (three) seats placed one behind the other. [Animal 1] and [Animal 2] (and [Animal 3]) want each to get on the first seat. They are struggling to get the first seat even when the merry-go-round is running. In the headphones, somebody will tell you how the animals are changing seats. Your task is to press on this button each time [Animal 1] is seated first and [Animal 2] is seated behind (and [Animal 3] is seated last). In order to help you remember in what order the animals are to be seated, they are shown on this screen in their correct places. Okay? Let's do some examples.

For both the order and item conditions, there were 10 practice trials before the start of each experimental trial. The practice trials could be repeated if necessary.

Both response accuracy and reaction times were collected. However, only results for response accuracy are presented here given that we were interested in comparing the performance on the attention and STM tasks while keeping to comparable response parameters (accuracy of pointing responses in both cases). d' scores were computed for each trial, enabling us to obtain a summary score taking into account both hit and false alarm responses (Macmillan & Creelman, 1991). For the analyses reported in the Results section, mean d' scores for sequence and item conditions were used by computing a mean d' score over the four item selective attention trials and a mean d' score over the four sequence selective trials.

Receptive vocabulary knowledge

Vocabulary knowledge was estimated using the EVIP scales (Dunn, Thériault-Whalen, & Dunn, 1993), a French adaptation of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981). As a dependent variable, we used raw vocabulary scores.

Nonverbal intelligence

Raven's Progressive Coloured Matrices (Raven et al., 1998) were administered to control for general intellectual efficiency. Raw scores were used in the analyses presented in the Results section.

Task order

The different tasks were presented to the children in two sessions, each lasting approximately 40 min. During the first session, the vocabulary and attentional tasks were administered. To avoid fatigue effects for the attentional tasks, after each two trials of the attentional task, parts of the vocabulary task were presented. The second session (1–2 days later) involved the administration of the verbal STM task, followed by Raven's matrices.

Results

Descriptive statistics are shown in Table 1. For the STM measure, an extended range of order and item errors was observed, with order errors tending to be slightly more frequent. For the auditory attention tasks, a large range of performance was observed for both item- and sequence-focused conditions, with d' scores ranging from 0.62 to 3.19. No floor effects were observed because the lowest d' scores reflected performance well above chance levels (chance level d' score = .00). Task difficulty for the item and sequence selective attention conditions was balanced given the similar mean and range values for d' scores in both conditions. This was confirmed by a repeated-measures analysis of variance (ANOVA) showing no statistically significant difference between performance in both conditions, $F(1, 46) = 2.93$, $MSE = 0.13$, $p > .05$. The large range of performance in the STM and attention tasks suggests that both tasks present satisfactory sensitivity and allow us to explore the effect of interindividual differences in the STM and attention tasks on vocabulary development.

Correlation analyses

All correlations presented in the following sections are partial correlations controlling for the effect of age if not otherwise specified. A first set of correlation analyses assessed the overall relationship between the vocabulary measure and the different predictor measures. As shown in Table 2, signifi-

Table 1
Descriptive statistics (means and ranges) for all tasks

	Mean and range
EVIP (raw score)	85.94 (62–123)
Raven's matrices (raw score)	20.72 (12–31)
Short-term memory	
Order errors (proportion)	.34 (.08–.64)
Item errors (proportion)	.16 (.06–.44)
Auditory attention tasks	
Target: sequences (d' score)	2.05 (0.98–3.19)
Target: items (d' score)	1.92 (0.62–2.94)

Note. Ranges are in parentheses.

Table 2
Raw correlations between vocabulary knowledge and the different predictor tasks

	EVIP
Raven's matrices (raw score)	.57[a]
Short-term memory	
Order error proportions	−.48[a]
Item error proportions	−.42[a]
Auditory attention tasks	
Sequence d' scores	.56[a]
Item d' scores	.49[a]

[a] $p < .01$ (significant after Bonferroni corrections for multiple comparisons).

cant correlations were observed for all predictor measures, with the highest association being observed with Raven's matrices as well as with the sequence selective attention measure. A next set of analyses assessed the intercorrelations among the different predictor tasks (see Table 3). Performance on Raven's matrices was correlated with all STM and attention measures, although the correlation with the item selective attention condition was no longer significant after application of Bonferroni corrections for multiple comparisons. Order STM recall did not correlate with item STM recall or with the item selective attention condition; however, there was a significant correlation with the sequence selective attention condition. The item STM recall measure correlated with both the item and sequence selective attention measures. Finally, the item and sequence selective attention conditions were highly intercorrelated. On the one hand, this analysis shows information type-specific correlations; order errors in the STM task correlate with performance on the sequence selective attention task but not with item errors in the STM task or with performance on the item selective attention task. On the other hand, all other intercorrelations among the different predictor tasks were significant, suggesting that item STM, item selective attention, sequence selective attention, and Raven's matrices measure at least partially overlapping capacities.

The next analysis assessed independent relationships between vocabulary knowledge and the different predictor measures via partial correlation analyses. We were interested in the independent contribution of each predictor (item and order STM measures as well as item and sequence selective attention measures) relative to the other predictors (after control of chronological age and Raven's matrices). When entering the item recall measure as the predictor measure of vocabulary knowledge, the correlation was already nonsignificant after partialling out performance on Raven's matrices. When entering the order recall measure as a predictor measure, the relationship with vocabulary knowledge remained significant when partialling out the influence of Raven's matrices, item recall, and item selective attention (Table 4). This replicates our earlier findings showing a selective relationship between order retention measures and lexical learning (Majerus et al., 2006; Majerus et al., 2006; Majerus et al., 2008). However, when partialling out performance on the sequence selective attention

Table 3
Raw correlations among the different predictor tasks

	Order (STM)	Item (STM)	Order (attention)	Item (attention)
Raven's matrices	−.48[b]	−.45[b]	.57[b]	.37[a]
Order (STM)		.19	−.42[b]	−.08
Item (STM)			−.54[b]	−.43[b]
Order (attention)				.61[b]

[a] $p < .05$.
[b] $p < .01$ (significant after Bonferroni corrections for multiple comparisons).

Table 4
Independent associations between vocabulary knowledge and the different predictor measures

	EVIP
Item recall (Raven's matrices)	−.22
Order recall (Raven's matrices)	−.29[a]
Order recall (Raven's matrices, item recall)	−.31[a]
Order recall (Raven's matrices, sequence detection)	−.24
Order recall (Raven's matrices, item detection)	−.36[b]
Sequence detection (Raven's matrices)	.35[a]
Sequence detection (Raven's matrices, item detection)	.20
Sequence detection (Raven's matrices, order recall)	.31[a]
Item detection (Raven's matrices)	.37[b]
Item detection (Raven's matrices, sequence detection)	.23
Item detection (Raven's matrices, item recall)	.32[a]

Note. Variables partialed out are in parentheses. In all analyses, chronological age was controlled.
[a] $p < .05$ (significant after application of Bonferroni corrections for multiple comparisons).
[b] $p < .01$ (significant after application of Bonferroni corrections for multiple comparisons).

measure (in addition to performance on Raven's matrices), the correlation between order recall and vocabulary knowledge decreased and became nonsignificant. For the sequence selective attention measure, a significant correlation with vocabulary knowledge subsisted after partialling out performance on Raven's matrices and order recall, but the correlation became nonsignificant when partialling out performance on the item selective attention task and Raven's matrices. Similar findings were obtained for the item selective attention task as a predictor measure; a significant correlation with vocabulary knowledge was observed when partialling out performance on Raven's matrices and item recall but not when partialling out performance on the sequence selective attention condition and Raven's matrices.

The fact that the serial order STM measure was specifically associated with vocabulary knowledge relative to the item STM measure, and the fact that this relation was diminished when partialling out sequence selective attention but not when partialling out item selective attention, pleads for a specific importance of serial order processing abilities in vocabulary development. On the other hand, the fact that the sequence selective attention task remained an independent predictor of vocabulary development after controlling for order recall performance, and that the correlation between the sequence selective attention task and vocabulary development fell to nonsignificant levels when partialling out performance on the item selective attention task, also suggests that general[2] selective attention capacities are associated with vocabulary development.

Variance partitioning

Two main findings can be retained from the preceding analyses. First, there is a specific contribution of serial order processing capacities to vocabulary development. Second, there is a specific relation between auditory selective attention capacities and vocabulary development. In the following multiple regression and variance partitioning analyses, we tried to determine the relative importance of these different predictors for the explanation of vocabulary knowledge by determining the portions of common and independent variance in vocabulary scores explained by the different predictors (order recall, item recall, item selective attention, and sequence selective attention).

To determine the influence of selective attention measures on vocabulary development as clearly as possible, we did not include performance on Raven's matrices here given that this task might already require selective attention capacities, as noted earlier. Raven's matrices require the participant to orient his or her attention toward analyzing the figures that are presented and to maintain this attention until the problem posed by the matrices is solved. Hence, this task also requires selective attention. Furthermore, some form of serial processing may also be involved, given that sequential mental operations are necessary to solve the logical problems in Raven's matrices. An additional statistical problem is the high correlation of Raven's matrices with all other regressors, creating a problem of nonorthogonality between predictor measures and potentially leading to biased results when entering these measures as regressors in the same regression model. Therefore, we decided not to include the Raven's matrices measure in the multiple regression analyses used to perform variance partitioning. However, we directly addressed the problems raised here by performing a second set of multiple regression analyses with Raven's matrices as the dependent measure, allowing us to determine the contribution of selective attention and STM capacities to Raven's matrices performance.

We used the following general procedure for variance partitioning. We entered the predictor measures in all possible orders in multiple regression analyses on vocabulary scores, enabling us to calculate independent and common portions of variance explained by the different predictors, on the basis of the increase of R^2 values between a regression model with predictors a and b and a second regression model with predictors a, b, and c. The increase of R^2 for the second model relative to the first model reflects the amount of independent variance in vocabulary scores explained by predictor c. The common variance explained by predictors a and b can then be found by adding R^2 values for predictors a and b, when a and b are introduced in separate regression models, and by subtracting from this sum

[2] General selective attention capacities refer here to attentional capacities that appear to be common to attentional processing of those types of information distinguished in the current study (i.e., order vs. item). We do not intend here to extend the term *general* to other types of information not investigated in the current study (e.g., verbal vs. visual).

the R^2 value when *a* and *b* are introduced simultaneously in a regression model. For sake of clarity, variance partitioning was done for two different models, each containing three predictors, rather than by using a single model with all four predictors; variance partitioning with four predictors considerably increases the number of common and partially common variance portions (11 shared portions vs. 4 shared portions in a three-variable model), making interpretation of results very complex. The two models of interest contained the order STM recall measure and the two attentional measures or the item recall measure and the two attentional measures.

The results of the variance partitioning procedure for vocabulary scores are displayed in Fig. 1. The model predicting vocabulary scores using the attention measures and the order STM recall measure shows that a large portion of variance is predicted in common by the order recall and the sequence selective attention measure. A further large part of variance is independent variance predicted by

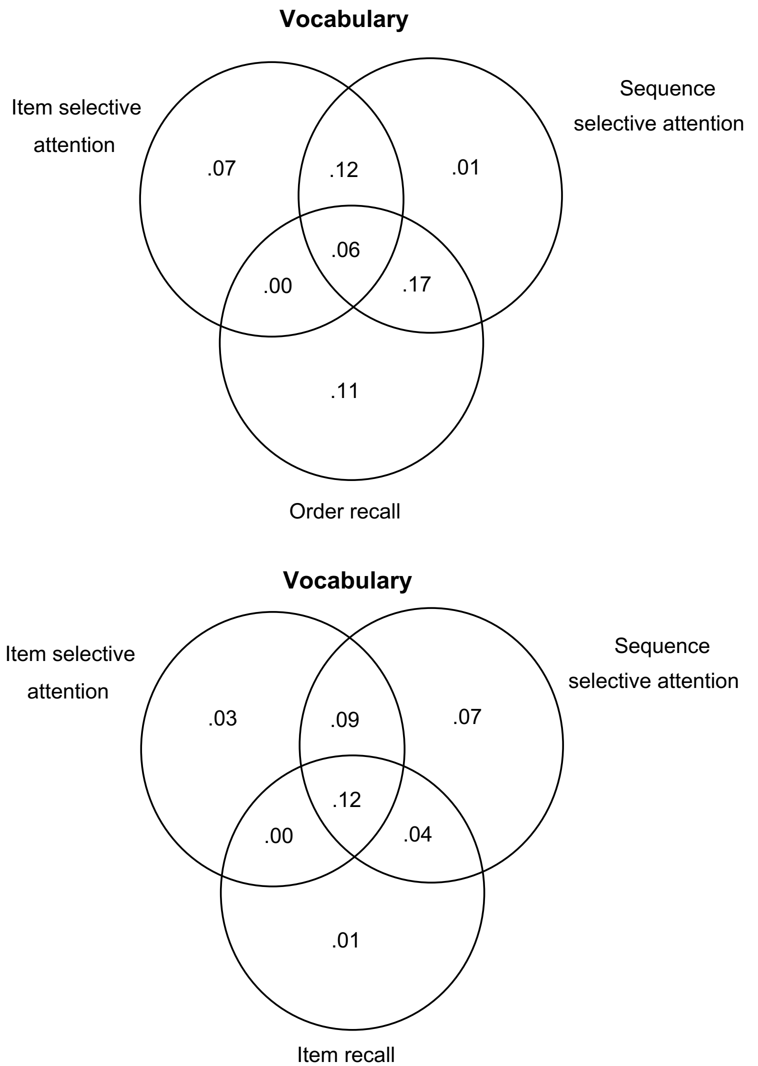

Fig. 1. Variance decomposition of vocabulary knowledge as a function of order STM, item STM, item selective attention, and order selective attention measures after controlling for chronological age.

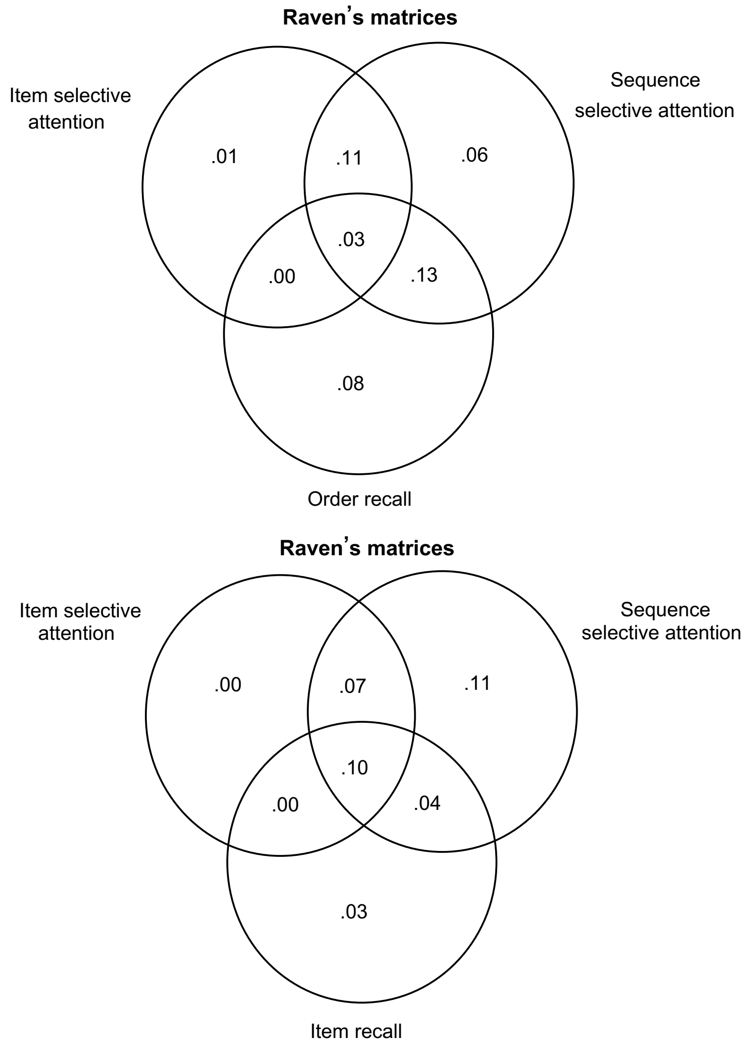

Fig. 2. Variance decomposition of Raven's matrices scores as a function of order STM, item STM, item selective attention, and order selective attention measures after controlling for chronological age.

the order recall measure only. Both the item and sequence selective attention measures explain 12% of common variance in vocabulary scores that are not shared with the order recall measure. Only 6% of variance is explained in common by all three predictors. Echoing the previous partial correlation analyses, this analysis shows, on the one hand, a general contribution of serial order processing abilities (common variance shared by the sequence selective attention measure and the order recall measure) and, on the other, a general selective attention contribution shared by the item and sequence selective attention tasks. Sequence selective attention makes an additional contribution to vocabulary knowledge relative to item selective attention, but with this contribution being shared with serial order processing abilities of the order STM measure. Finally, contrary to the previous partial correlation analyses (controlling for the influence of Raven's matrices scores), the order STM measure remained a robust independent predictor of vocabulary development after controlling for sequence selective attention capacities. The second model, predicting vocabulary scores by the item STM measure and both attentional measures, shows that the largest part of explained variance was common variance shared by all three predictor measures, suggesting that the relation between vocabulary development and item STM is largely mediated by the capacities measured by the selective attention measures. At the same time, the attentional measures made an additional independent contribution to vocabulary scores relative to the item recall task.

The final analyses directly considered the associations among the order STM measure, the selective attention measures, and Raven's matrices. When performing variance partitioning on performance on Raven's matrices, a strikingly similar pattern of results emerged relative to the variance partitioning analysis on vocabulary scores (see Fig. 2). For the model that included the order STM measure, a relatively small part of variance in Raven's matrices was shared variance explained by all three predictor measures. A more substantial part of variance was explained in common by the order STM and the sequence selective attention measures. An additional part of shared variance was explained in common by the item and sequence selective attention measures. In other words, the Raven's matrices measure behaved much like the vocabulary measure regarding the relations with order STM, item selective attention measures, and order selective attention measures. The same was observed for the model that included the item STM measure; as for variance partitioning of vocabulary knowledge, the largest part of variance in Raven's matrices was shared variance explained by the item STM and the two attentional measures, with additional independent contributions of the attentional measures especially for the sequence selective attention measure. Hence, the inclusion of Raven's matrices as a predictor of vocabulary knowledge is likely to lead to an underestimation of the impact of order STM and selective attention capacities on vocabulary development because these factors appear to be associated with Raven's matrices to the same extent. Importantly, the possibility that attentional and STM measures are associated with Raven's matrices only because they depend on general factors measured by Raven's matrices does not fit the current data. Indeed, the part of Raven's matrices variance explained in common by the STM and attentional predictor measures was relatively small, at least for the model that included the order STM measure. The distinct pattern of association between Raven's matrices and serial order processing variables, on the one hand, and between Raven's matrices and general selective attention variables, on the other, suggests that these associations do not arise from the intervention of a single general factor only.

Discussion

This study explored the nature of the relation between performance on verbal STM tasks and vocabulary development in 6- and 7-year-olds by assessing the extent to which this relation is influenced by item or sequence selective attentional capacities as required during auditory encoding of item and order information in STM tasks. For sake of clarity, we first summarize the main results before providing a detailed discussion of their implications. Partial correlation analyses, controlling for the influence of general intellectual efficiency as measured by Raven's matrices, showed that the order but not the item recall STM measure was independently associated with vocabulary development. Furthermore, this association became nonsignificant when sequence but not item selective attentional capacities were partialled out. The relationship between sequence selective attention and vocabulary development became nonsignificant after controlling for item selective attentional capacities. Variance decomposition analysis of vocabulary scores showed that the largest portion of explained variance was shared variance explained by the item and order selective attention tasks, on the one hand, and shared variance explained by the order recall measure and the order selective attention task, on the other. Hence, two main variables predicting vocabulary knowledge emerged: (a) serial order processing capacities shared between an order STM recall measure and a sequence selective attention measure and (b) selective attention capacities shared between the item and the sequence selective attention measures as well as the item recall measure. However, the variance decomposition analysis also showed that a substantial portion of independent variance in vocabulary scores was predicted by the order recall measure alone. A second variance decomposition analysis of vocabulary scores included the item recall measure and showed that the largest portion of variance was explained in common by the two attentional measures and the item recall measure. Overall, these results suggest that attentional factors as well as STM factors determine vocabulary development; the association between order STM and vocabulary is affected, but not completely eliminated, by sequence selective attentional capacities, whereas the relation between item STM and vocabulary appears to be affected by general selective attention capacities. A further noticeable finding was obtained when decomposing variance of Raven's matrices scores instead of vocabulary scores, revealing a relatively similar pattern of variance prediction by attentional variables and serial order processing variables as compared with the variance decomposition pattern for vocabulary scores.

Role of short-term memory and selective attention in vocabulary development in 6- and 7-year-olds

On the one hand, the current data support the existence of a specific link between verbal STM capacity and vocabulary development by showing that STM capacity remains a significant predictor of vocabulary development after the influence of general selective attention. This was true for the order recall measure but not for the item recall measure, whose relation with vocabulary development was mediated by these attentional factors. The current data reproduce previous findings that already highlighted the selective importance of serial order storage capacities for vocabulary learning in children and adults (Majerus et al., 2006; Majerus et al., 2006; Majerus et al., 2008). However, although these studies used separate tasks to measure item and serial order STM capacities, the new finding of the current study is to show that the same type of specific association between serial order STM and vocabulary learning can be obtained by estimating item and order STM capacities on the basis of item and order errors produced in a single task. Recent theoretical models consider that the ability to temporarily store sequence information allows the reactivation and the ordered replay of a new unfamiliar phonological sequence, increasing the probability that this temporary verbal information is eventually transformed into a more stable long-term representation (e.g., Burgess & Hitch, 1999; Burgess & Hitch, 2006; Gupta, 2003). The storage of item information is considered to rely mainly on temporary activation of the language system, and in that sense it recruits language knowledge rather than serial order STM mechanisms.

Although the current data are in agreement with these theoretical models, they add a significant dimension by highlighting the role that selective attention processes exert on the relation between order and item STM processes and vocabulary development. We observed that a substantial part of variance in vocabulary scores was predicted in common by the order recall measure and the sequence selective attention measure; this part of variance was not shared with the item selective attention measure. This suggests that the processes measured in common by the STM and sequence selective attention measures (i.e., processing of serial order information) are predictive of vocabulary development and not only short-term storage of serial order information. However, the relation between order STM and vocabulary development, although partially mediated by this serial order processing variable, cannot be reduced only to that variable given that STM order recall remained a robust predictor of vocabulary development after controlling for sequence selective attention capacity, as revealed by the variance partitioning analysis. On the other hand, a significant part of variance in vocabulary scores was explained in common by the item and sequence selective attention measures; this part of variance was not shared with the order STM measure, but it was shared with the item STM measure. Hence, a general auditory selective attention variable also emerged from the findings as a strong predictor of vocabulary development. Most important, the latter results suggest that item STM is dependent not only on temporary language activation, as has been suggested, but also on selective attention processes. These processes possibly ensure that the activated language representations remain in a conscious and active format available for performing the STM task.

As already noted in the Introduction, a number of STM models have incorporated attentional factors, although these models do not explicitly account for the distinction between item and order information. Cowan (1988), Cowan (1999) considered that STM capacity is constrained by scope of attention capacity, that is, the amount of information that can be held in an active and conscious format at one time. The working memory model by Baddeley (1986), Baddeley (2000) considered that controlled attentional capacities intervene in temporary storage tasks, but essentially only when the stored information must be manipulated or maintained while performing a secondary task. In the current study, we adopted an empirical position by designing attentional tasks to reflect selective attention as they are recruited during encoding in STM. These tasks are to some extent more similar to controlled attention tasks given that information must be consciously attended to and guarded against interference coming from distracting stimuli. At the level of results, however, our findings are closer to Cowan's position in the sense that they show that attentional processes are involved during a STM recall task where stored information has simply to be output in the same order as during presentation, and hence no working memory-type manipulation is required. Another theoretical position that could capture these findings is the position proposed by Engle and colleagues (1999), who considered that STM results from activated long-term memory maintained in an active format and controlled attention. They considered that this applies equally to short-term and working memory-type tasks based on a recent meta-analysis showing that simple and complex span tasks appear to rely on the same basic processes (Unsworth & Engle, 2007). More detailed implications for theoretical models of STM are discussed in the next section.

Implications for STM models and their relation to vocabulary development

The current results shed a more complex light on the relations between verbal STM and vocabulary development than do most of previous studies and theoretical models on which they are based. The vast majority of past studies aimed at demonstrating that there is a relationship between verbal STM performance and vocabulary development and included mainly only those tasks necessary to show that there is such a relationship, for example, vocabulary and verbal STM tasks (e.g., Gathercole et al., 1992). Sometimes these studies also used other language tasks, such as phonological awareness tasks, or more refined verbal STM tasks distinguishing item and serial order processes, to be able to disentangle the complex relationships among vocabulary development, verbal STM capacity, and language knowledge necessary to perform verbal STM tasks (e.g., Bowey, 1996; Gathercole et al., 1991; Majerus et al., 2006). As we have noted, general factors were typically measured by estimates of nonverbal intelligence such as Raven's matrices, and variance explained by these factors was then discarded because it was considered to be of no interest and because the theoretical models used were not designed to take these factors into account. The theoretical question underlying these studies essentially concerned the degree of specificity of the association between a phonological short-term storage component (e.g., the phonological store [Baddeley et al., 1998]) and the phonological lexicon. More recent models have refined this view by considering the STM component as a serial order processing device linked to lexical and sublexical networks of language representation and determining long-term learning of phonogical sequences within these networks (e.g., Brown et al., 2000; Burgess & Hitch, 2006; Gupta, 2003). These models relegate attentional and other general factors to nuisance variables that the researcher merely wants to control but not take into account at a theoretical and explanatory level.

On the other hand, attentional models of STM, such as the embedded process framework by Cowan (1999), consider that limitations in scope of attention are a major limiting factor of STM capacity. STM is considered to reflect a portion of activated long-term memory that is attenuated to and maintained by focused attentional capacities (Cowan, 1999). However, the tasks used in the current study are very different from scope of attention tasks and are more similar to controlled attention tasks. In this sense, they could be considered to depend on central executive components as assumed by the working memory model (Baddeley, 1986; Baddeley, 2000) but also by Cowan (1988), Cowan (1999). Cowan (1988) proposed that these central executive components interact with the focus (scope) of attention and allow increasing functional capacity of the latter component. Hence, Cowan's position allows the influence of controlled attentional capacity in passive STM tasks, as strongly suggested by our results, whereas the working memory framework preferentially limits the intervention of this capacity to storage and processing tasks. Our results are also in line with the position by Engle and colleagues (1999), considering short-term and working memory as resulting from controlled attention and activated long-term memory. However, none of these frameworks explicitly considers separate capacities for attending to item and sequence information, although this distinction seems to be critical as evidenced by the current study.

Our data argue for the development of integrated frameworks of STM attention processing, considering interactions among selective attention capacities, serial order processing capacities, and language activation as well as their relationship with lexical learning capacities. An outline for such a framework is presented in Fig. 3 based on an earlier framework developed by Majerus (in press). The earlier framework contained sublexical, lexical, and semantic language processing systems, connected to an STM system, specifically processing and maintaining serial order information; an attentional modulator system was also included, focusing attention on the language processing systems to the serial order STM system or both as a function of task requirements. For example, during verbal item STM tasks, attention would be directed mainly to the language system where item information is processed, whereas during serial order STM tasks attention would be directed mainly toward the serial order STM system. This was based on earlier studies showing that serial order and item STM capacities are partially distinct, with verbal item STM capacities depending to a large extent on the activation of corresponding representations in the language system (Majerus et al., 2006; Majerus et al., 2006; Majerus et al., 2008; Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996). Functional neuroimaging studies had also shown distinct fronto–parieto–cerebellar and fronto–temporal networks for the processing of order and item information during STM tasks (Majerus, Poncelet, Van der Linden, et al., 2006). At the same time, functional neuroimaging studies had shown that left intraparietal regions were activated in common independent of the type of information to be retained (e.g., item vs. order, verbal vs. visual), suggesting the existence of common, and possibly attentional, processes underlying any type of STM task (Majerus, Bastin, et al., 2007; Majerus, Poncelet, Van der Linden, et al., 2006). The current study confirms the existence of general selective attention capacities underlying performance in so-called passive STM tasks. It further suggests that the previously observed relation between lexical learning and serial order STM measures is not specific to maintenance of serial order information per se but is partially mediated by a more general serial order processing variable.

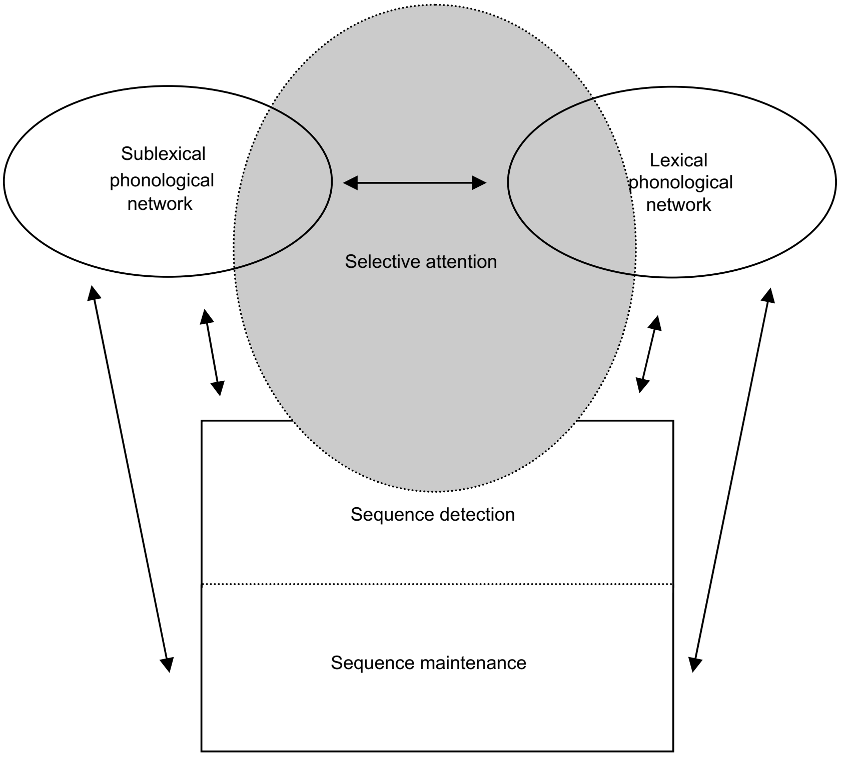

Fig. 3. Integrated framework of serial order STM, language knowledge, and selective attention. See text for further details.

For this reason, the revised framework presented here proposes a two-component sequence processor, with one component being involved in sequence detection and processing, shared by sequence selective attention and serial order STM measures, and a second component being more specifically involved in sequence maintenance during STM situations. Both the sequence detection and maintenance components interact with lexical and sublexical language processing components, accounting for the shared variance explained by both components in vocabulary scores in the current study but also accounting for the specific variance explained solely by the serial order STM measure in vocabulary scores. At another level, there is, as in our earlier framework, an attentional modulator directing selective attention to the language network, to the sequence detection system, or to both depending on task requirements. According to our results, the serial order maintenance component does not interact with these selective attention capacities. Further studies will need to validate this type of model and the specific interactive links that have been proposed based on the empirical data observed in the current study.

Role of short-term memory and selective attention in other cognitive abilities

A further noticeable finding of the current study is that the observed pattern of results is not specific to vocabulary development because very similar associations were observed between the different STM and attentional measures and Raven's matrices scores. This pattern of association was not just a general association, where all STM and attentional measures would have predicted a common portion of variance in Raven's matrices scores; in that case, this association could have merely meant that this association was driven by a general maturational factor measured by Raven's matrices and all predictor variables. Rather, selective attention variables and serial order processing variables were distinctly associated with performance on Raven's matrices, suggesting a specific relation between these variables and performance on Raven's matrices. As we have already mentioned, solving the logical problems included in the Raven's matrices task requires selective attention toward the matrices and problem solving as well as maintenance of these selective attention processes until the problem is solved. This also possibly involves some form of serial order processing in the sense that logical mental operations must be performed in an organized logical sequence. Although the association between general cognitive efficiency as measured by Raven's matrices and more complex working memory capacity is well established in the literature, the interpretation of this association is difficult given that these working memory tasks themselves require the intervention of multiple and complex cognitive processes just like reasoning tasks (e.g., Bühner, Krumm, Ziegler, & Plücken, 2006; Salthouse & Pink, 2008). The current study suggests that the isolation of some of the constituent processes involved in simple STM tasks already permits us to explain a significant portion of variance in Raven's matrices performance, suggesting that performance on reasoning tasks is determined by the same selective attention and serial order processing requirements as is performance on simple verbal STM tasks.

It follows that similar relationships could in principle be observed among STM, selective attention, and any other cognitive tasks implicating selective attention as well as processing and maintenance of sequentially organized information or processing steps. Mental calculation is an interesting candidate for this hypothesis given that mental calculation tasks require at least (a) selective attention directed to the input information and to the results generated at different processing steps and (b) sequential organization of the different processing steps. There is indeed an abundant literature showing close associations between verbal STM/working memory tasks and different mental arithmetic tasks (e.g., Fürst & Hitch, 2000; Hitch, 1978; Imbo, Vandierendonck, & Vergauwe, 2007). Similarly, performance on STM tasks is associated with learning of arithmetic processes such as number transcoding (Camos, 2008). Future studies will need to show the extent to which this association between STM/working memory tasks and mental arithmetic tasks is mediated by serial order processing, maintenance, and selective attention capacities, as was shown for vocabulary development and mental reasoning tasks in the current study.

A further general implication of the current findings is that using Raven's matrices as a control measure of general processes when studying the relationship between verbal STM and the development of cognitive abilities such as vocabulary development and mental arithmetic might in fact mask the factors of interest that are measured by STM tasks and that drive development of these cognitive abilities. For the purpose of illustration, we reviewed previously published studies on the association between vocabulary knowledge and verbal STM performance. Most studies used Raven's matrices with the aim to factor out "general" processes. However, the part of variance in vocabulary scores explained by the STM tasks in these cases was relatively small, with a mean of 6% (range = 2–17 based on the following studies: Avons et al., 1998; Bowey, 1996; Gathercole et al., 1991; Majerus et al., 2006). In the current study, STM and attentional variables predicted a total of 54% of variance in vocabulary scores (after controlling for age) for the model that included the order STM measure, and they predicted a total of 37% of variance for the model that included the item STM measure. At the same time, the same models also predicted 42 and 35% of variance in Raven's matrices scores, respectively. The largest part of vocabulary variance was in fact explained by the different attentional measures used in our study, suggesting that selective attention is strongly associated with vocabulary development and Raven's matrices and that this contribution might have been masked in previous studies via the use of Raven's matrices as a control task to be factored out.

Conclusions

Although many studies have shown specific relations between verbal STM tasks and lexical learning, the part of variance explained by verbal STM tasks in lexical knowledge and learning measures is typically small, raising the question of the existence of other factors codetermining lexical learning. The current study showed that general selective attention factors as well as serial order detection and maintenance capacities explain a substantial portion of variance in vocabulary knowledge of 6- and 7-year-olds. Our results suggest that selective attention, serial order processing, and serial order storage capacities conjointly and interactively determine vocabulary development. Furthermore, our results indicate that this association is not specific to vocabulary development but that the same selective attention, serial order processing, and maintenance capacities also determine other cognitive abilities such as reasoning.

Acknowledgments

Steve Majerus is a research associate funded by the Fund of Scientific Research F.R.S.-FNRS, Belgium. This study was also supported by an Inter-University Attraction Pole (IUAP) grant from the Belgian Federal Science Policy administration (grant IUAP P6/29). We thank all of the children, parents, and teachers for their collaboration and their time devoted to this study.

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