SERIAL ORDER SHORT-TERM MEMORY CAPACITIES AND SPECIFIC LANGUAGE IMPAIRMENT: NO EVIDENCE FOR A CAUSAL ASSOCIATION

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ABSTRACT

This study re-explored the nature of verbal STM deficits in children with specific language impairment (SLI), by distinguishing item and serial order STM processes. Recent studies have shown serial order STM capacity to be a critical determinant of language development, relative to item STM. In Experiment 1, 12 children with SLI, 12 age-matched children and 12 language-matched children were administered serial order recognition and reconstruction tasks. Experiment 2 assessed implicit serial learning abilities via a Hebb learning task. The SLI group showed impaired performance for the serial order reconstruction and recognition tasks, relative to language-matched and/or age-matched control groups. However, normal serial position effects were observed in all SLI children in the serial order reconstruction task, suggesting normal coding of serial position information. Similarly, performance on the Hebb serial learning task was at chronological age appropriate levels. Experiment 3 showed that the group differences observed for the serial order STM tasks in Experiment 1disappeared when the SLI group was compared to a mental age-matched control group. Experiment 4 showed similar performance levels in the SLI group and the mental age-matched control group for a nonword recognition task assessing item STM capacities. This study shows that children with SLI have no specific impairments for serial order and item STM components but that poorer general cognitive efficiency is related to functional limitations in verbal STM tasks. The data are in line with limited information processing accounts of SLI.

236 words

Key-words: short-term memory, serial order, lexical learning, specific language impairment

INTRODUCTION

Specific language impairment (SLI) has received considerable research interest during the past 20 years, yet the nature of this developmental language disorder is still poorly understood, at both cognitive and neurobiological levels. The aim of the present study is to explore one specific cognitive factor that has been causally linked to SLI, verbal short-term memory (STM). Although verbal STM, most often estimated by nonword repetition tasks in the SLI literature, seems to be very consistently impaired in children SLI, the reason for this impairment and its possible causal impact on the poor language development of children with SLI still remain an intensive matter of debate.

Verbal STM impairments as a causal factor of SLI

Verbal STM capacities, or at least the tasks used to measure this capacity, are very consistently impaired in SLI. Many studies, using most often nonword repetition tasks, have documented poor performance in children with SLI for these tasks, and this relative to both age and language matched control groups (e.g., Archibald and Gathercole, 2006ab; Gathercole and Baddeley, 1990; Gillam et al., 1998; Majerus et al., 2003; Montgomery, 2004). This deficit seems to be relatively specific since visuo-spatial STM is in general less impaired than verbal STM or not impaired at all relative to age matched control groups, although there is ongoing debate on this issue (Archibald and Gathercole, 2006ab; Bavin et al., 2005; Hick et al., 2005). Nonword repetition has also been shown to be a highly reliable diagnostic marker of SLI and is one of the most reliable measures when it comes to relate phenotypical markers of SLI to genetic correlates of SLI (see for example, Bishop, 2006; Conti-Ramsden et al., 2001; Gray, 2003; Newbury et al., 2005). In the light of these results, it has been argued that the SLI children's poor performance in nonword repetition tasks reflects poor verbal STM storage capacity, which is causally related to the poor lexical learning abilities that characterize many children with SLI (e.g., Gathercole and Baddeley, 1990; see also Newbury et al., 2005). This interpretation is also based on numerous studies showing strong correlations between vocabulary development and verbal STM performance in typically developing children as well as on studies showing that patients with verbal STM deficits have difficulties in acquiring new verbal information (e.g., Baddeley, 1993; Gathercole et al., 1997). This has led to a theoretical proposal suggesting that verbal short-term storage capacity is a critical building block of lexical learning. Following this perspective, the quality of the temporary representations in STM for new verbal information will determine the quality and speed of acquisition of a more stable long-term memory representation for this information (e.g., Baddeley et al., 1998).

However, this interpretation has been challenged given that nonword repetition is a highly multi-determined task measuring not only phonological STM capacity, but also a number of other processes such as phonological segmentation and access to sublexical phonological knowledge in order to ensure correct decoding (at input) and encoding (at output) of the unfamiliar phonological sequence. Hence, poor performance on nonword repetition tasks can also be considered to reflect poorly developed phonological representations and is itself determined by the language system, rather than determining language acquisition (e.g., Metsala, 1999; Chiat, 2001). A current series of theoretical discussion papers on nonword repetition highlight the concern these issues continue to raise (e.g., Gathercole, 2006). The aim of the present study is to further our understanding of the complex relationship between verbal STM and lexical language impairment in SLI by adopting an increasingly important distinction in the STM literature, the distinction between order and item information.

STM for Order vs. Item information

Most recent models of STM assume the existence of distinct mechanisms and capacities for the storage of serial order information and item information. Serial order information concerns the sequential order in which the different items of a list are presented. Item information concerns the phonological and semantic properties of the verbal stimuli themselves. A number of models assume that verbal item information is stored directly via activation of corresponding phonological and semantic levels of representations in the language system; in that sense, processing and storage of verbal item information depends very directly upon the quality of underlying phonological and semantic representations (e.g., Burgess and Hitch, 2006; Gupta, 2003; Martin and Saffran, 1992). On the other hand, processing and storage of order information is assumed to depend on a specialized STM system encoding the sequential order of appearance of the different items within a list, which also amounts to encoding the order of activation of corresponding language representations in the language system (e.g., Gupta, 2003).

This distinction is based on a number of empirical studies showing dissociations between STM capacities for the retention of item and order information in neuropsychological and neurodevelopmental populations (e.g., Majerus et al., 2007a), with deficits in item STM being strongly related to the integrity of underlying language representations (Majerus et al., 2007b). A series of experimental studies in adult participants have also shown that linguistic knowledge affects mainly item recall but much less order recall in immediate serial recall tasks (as for example when comparing recall for lists of words of high versus low lexical frequency; Nairne and Kelley, 2004).

Most importantly, some of these models, and most explicitly the model by Gupta (2003), assume that the capacity of serial order STM is crucial for vocabulary learning. Following Gupta (2003), the serial order STM system, interconnected to phonological levels of language representation, permits to refresh and 'replay' an unfamiliar phonological sequence that has been presented and hence increases the chances that the temporary phonological representation that has been created for the new phonological sequence will be eventually transformed into a stable long-term memory representation. This prediction is supported by recent developmental data, showing that tasks maximizing recall of order information (serial order reconstruction for sequences containing highly familiar items and varying only in their order of presentation across the different trials) and STM tasks maximizing recall of item information (delayed recall of single, short verbal items, each item being new at each trial) are independently related to vocabulary knowledge in children aged 4 to 6 years (Majerus et al., 2006a). Recent studies in monolingual and bilingual adults also showed that serial order STM measures are the most consistent predictors of new word learning as opposed to item STM (Majerus et al., 2008; Majerus et al., 2006b).

By adopting the item/serial order distinction for the study of STM impairments in SLI, we might get a clearer understanding of the possible causal nature of verbal STM deficits for the language impairments in SLI. If there is a causal relationship between verbal STM capacity and language development in SLI, then there should be specific serial order STM impairments in SLI, according to the model by Gupta (2003). Given that serial order STM capacities are supposed to be distinct from language processing components and are, as such, much less influenced by the quality of the language network (Burgess and Hitch, 2005; Gupta, 2003), the finding of a deficit for this type of STM tasks would permit more safely to conclude that there is a specific STM impairment that cannot simply be dismissed as reflecting access to poorly developed levels of language representations. This is not the case for item STM which, on the contrary, is supposed to depend more directly upon activation of the language network, and hence will be determined by the quality of the language system.

In SLI, the impact of language knowledge on serial recall performance has been investigated, showing a strong influence of lexical and semantic knowledge on STM performance (Mainela-Arnold and Evans, 2005; Majerus et al., 2003). Even nonword recall has been shown to be affected by sublexical knowledge about the phonological properties of word forms, in SLI children as it is in healthy control children (Majerus et al., 2003, Casalini et al., 2007). These studies confirm that STM performance in SLI strongly depends on the integrity of underlying language representations of the stimuli to-be-recalled. The aim of the present study is to focus specifically on serial order STM and to explore whether deficits can be observed in tasks maximizing serial order retention, but minimizing item retention and hence the impact of underlying language knowledge. Experiment 1 investigated SLI children's ability to reconstruct and recognize serial order information for verbal sequences using highly familiar item information. Experiment 2 assessed implicit serial order processing and learning abilities, by comparing SLI and control children's performance on a Hebb digit sequence learning experiment. The SLI children's performance was compared to that of two control groups: a first control group was matched on age to the SLI group, and a second group was matched on receptive vocabulary knowledge. Experiment 3 compared the SLI group to a mental age matched control group for the same tasks as those administered in Experiments 1 and 2, in order to assess the impact of potential differences in mental age between the SLI group and the chronological age matched control group on verbal STM performance. Finally, Experiment 4 assessed item STM capacities via a nonword item STM recognition task.

EXPERIMENT 1: SERIAL ORDER RECONSTRUCTION AND RECOGNITION

Contrary to STM tasks used in previous studies, confounding item and order information and using unfamiliar nonwords which are especially challenging at the level of sublexical phonological processing, the present experiments used items that were highly familiar and known in advance in order to minimize the influence of language capacities on STM performance. The first task was a serial order reconstruction task using highly familiar digit items. In order to further decrease item processing requirements, the items were known in advance: for sequences containing 4 items, the items were sampled from the digits 1-4; for sequences containing 5 items, the items were sampled from the digits 1-5, and so forth for subsequent sequence lengths. Only order of presentation of the items changed across trials of the same sequence lengths, putting maximal weight on serial order retention mechanisms. The second task was a serial order recognition paradigm and consisted also in the presentation of digit sequences of increasing length, with the digits being known in advance. The probe sequence consisted of the presentation of a sequence of the same length as the target sequence; negative trials were created by exchanging the serial position of two adjacent items; this task also maximized serial order processing requirements given that item information was exactly the same in target and probe sequences. Both serial order STM tasks were adaptations of previously published tasks and have been shown to be highly sensitive to serial order retention capacity, as opposed to item processing capacities (Majerus et al., 2006a; Majerus et al., 2008).

METHODS

Participants

The experimental group was comprised of 12 children (10 boys) diagnosed as presenting specific language impairment according to DSM-IV criteria (absence of sensory, neurological and psychiatric deficits; normal hearing status; no structural and functional impairments of the speech apparatus; normal non-verbal intelligence levels; clinical history of delayed language development interfering with social communication and scholastic achievement; performance at least < 1.5SD on at least one standardized test of expressive or receptive language assessment) ; the fulfilment of these criteria was determined via extensive language, neuropsychological, psychological and medical assessments. Half of the children were recruited from the university neuropediatric rehabilitation centre of Kremlin Bicètre (Paris) and the other children were recruited from a specialized school setting for children with SLI (Dysphasia, Paris). All children were French speakers from the Parisian area. They had a mean age of 8;4 years (range: 6;11 – 10 years). As shown in Table 1, they presented in average a 2-year delay between chronological age and lexical and syntactical ages, with a compromised verbal IQ (for those children where verbal IQ could be reliably assessed). The experimental group was matched to two groups of typically developing children from similar socio-economic background as the SLI group (see Table 1). A first group (N=12; 3 boys) was matched for chronological age (mean age: 8;7 years; $t(22)<1$, n.s.) but expectedly differed from the SLI group at the level of verbal (EVIP raw score; $t(22)=4.01$, $p<.001$) but not non-verbal (Raven's CPM matrices; $t(22)=1.69$, n.s.) measures. A second group (N=12; 6 boys) was comprised of younger typically developing children matched for lexical age, using the raw score on the EVIP receptive vocabulary scales ($t(22)<1$, n.s.). This group differed from the SLI group at the level of chronological age (mean age: 6;6 years; $t(22)=3.44$, $p<.01$); there was also a tendency for the SLI group to show higher performance on the Raven's CPM matrices relative to the lexical age matched control group (see Table 1), but this tendency was not significant ($t(22)<1$, n.s.). Finally, the SLI children differed from both groups on a standardized nonword repetition task (see Table 1; $t(22)=8.17$, $p<.001$ for SLI vs. age matched controls; $t(22)=3.08$, $p<.01$, for SLI vs. language matched controls), confirming previous studies showing that nonword repetition is impaired in SLI relative to both language and age-matched control groups (e.g., Gathercole and Baddeley, 1990). Informed consent had been obtained from all participating children and their parents.

< INSERT TABLE 1 ABOUT HERE >

Material and procedure

Serial order reconstruction task. This task consisted in the auditory presentation of lists of increasing length containing highly familiar digit items. The participants had to reconstruct the order of presentation of the items within the list by using cards on which the digits had been printed. The lists, containing 3 to 7 digits, were sampled from the digits 1-7. For list length 3, only the digits 1, 2 and 3 were used. For list length 4, only the digits 1, 2, 3 and 4 were used, and so on for other list lengths. This procedure ensured that items were known in advance, and that the participants only had to remember the position in which each item occurred. The lists had been recorded by a female voice and stored on computer disk, with a 500-ms inter-stimulus interval between each item in the list (mean item duration: 540 (±139) ms).

The sequences were presented auditorily via high quality loudspeakers connected to a PC that controlled stimulus presentation by running E-Prime software (version 1.0, Psychology Software Tools). They were presented by increasing length, with six trials for each sequence length. At the end of each trial, the participants were given cards (size: 5x5 cm) on which the digits presented during the trial were printed in black font. The number of cards corresponded to the number of digits presented and were presented in numerical order to the participants. The participants were requested to put the cards in the order of presentation. When they had finished, the cards were removed and the next list was presented. We determined the number of correct trials, by pooling over all sequence lengths.

Serial order recognition of digit sequences. This task also consisted in the presentation of a list of digits (containing 3 to 6 digits), followed by the presentation of the same digit list. The participants had to judge whether the order of the digits within the two lists was the same. The different lists had been recorded by a female human voice and stored on computer disk. Mean stimulus duration for the different words was 677 ($\pm$116) ms. Within each list, the words were separated by a 500-ms inter-stimulus interval. List presentation began with the shortest list length. There were 6 trials for each list length.

The different lists were presented using the same apparatus as for the previous task. The participants were told that they would hear two lists containing exactly the same digits, but that sometimes the position of two adjacent items would be exchanged in the second list compared to the first list. The end of the first list was signalled by the presentation of a brief tone (sinusoidal pure tone; 500 ms). This was then followed by the recognition trial. The recognition trial consisted of the presentation of a sequence containing exactly the same digits as the target sequence, but the serial position of two adjacent words within the list was exchanged in two-third of trials, with serial position exchanges occurring once in the primacy portion (first two positions), twice in the middle of the list (only for lists larger than 3 items), and once in the recency portion (last two positions)[1]. At the end of the recognition sequence, the participants had to judge whether the serial position of all digits in the recognition sequence matched those of digits of the target sequence, by pressing a green–coloured response button (for yes) or a red-coloured response button (for no). After the response, the words "new trial" appeared on the screen for 2500 ms, then the screen went white and the next list was presented. We computed the proportion of correct recognitions over the 24 trials.

[1] The reason for having more negative than positive trials was to be able to sample transpositions for the different list positions without unnecessarily increasing the length of the entire task. Pilot testing had indeed shown that, independently of sequence length, very few errors occurred on positive trials. Thus, including an equal number of positive and negative trials would have merely increased the duration of the task without increasing its sensitivity and informative value.

RESULTS

A first ANOVA assessed group effects on the serial order reconstruction task yielding a main effect of group, $F(2,33)=11.92$, $MSE=0.03$, $p<.001$ (see Table 2). Planned comparisons showed that the SLI group had significantly poorer performance than the age-matched ($F(1,33)=23.43$, $MSE=0.03$, $p_{one\text{-}tailed}<.001$) and the language matched ($F(1,33)=3.49$, $MSE=0.03$, $p_{one\text{-}tailed}<.05$) control groups. A similar analysis was performed for the serial order recognition task, yielding a marginally significant group effect, $F(2,33)=2.70$, $MSE=0.02$, $p=.08$. Planned comparisons revealed a significant disadvantage for the SLI group relative to the age-matched control group ($F(1,33)=3.18$, $MSE=0.02$, $p_{one\text{-}tailed}<.05$), but not relative to the language-matched control group ($F(1.33)<1$, n.s.). The latter null effect cannot be attributed to poor statistical power due to small sample size given that performance means were virtually identical between the SLI group and the language matched control group; assuming that the observed (non)difference is true for the general SLI population, there would still be no statistically meaningful effect with much larger sample sizes.

< INSERT TABLE 2 ABOUT HERE >

In order to obtain a more precise and qualitative view of serial position coding performance in the SLI sample, we re-analyzed the results of the serial order reconstruction task, by determining the presence or absence of typical serial position effects, i.e. primacy effects (better recall of first relative to middle positions) and recency effects (better recall of final relative to middle positions). This was done at an individual basis, by determining whether each SLI participant presented expected serial position effects. Due to differential levels of performance on this task, no direct comparison between the three groups was conducted given that any possible statistically significant interaction between group and serial position would be difficult to interpret: primacy and recency effects tend to be attenuated when performance approach ceiling or floor levels. For the individual serial position analyses in the SLI children, we retained for each participant the 6 trials of sequence length 5 and 6, where the 12 SLI children showed no marked floor or ceiling effects, and performed a repeated measures ANOVA on items, as a function of serial position. In order to increase the sensitivity of this analysis, we included the 6 trials of sequence length 5 and 6, and combined serial positions 3 and 4 for sequence length 6, by creating a new variable reflecting the mean performance of both positions. This yielded 12 trials with 5 serial positions to be analyzed at an item-level for each individual participant. The results of these analyses are presented in Figure 1. As shown in Figure 1, each of the twelve children showed significant serial position effects, with normal U-shaped serial position curves, showing primacy and recency effects in all SLI participants except for an attenuated primacy effect in subject SLI_8. Primacy effects were also generally more prolonged than recency effects.

< INSERT FIGURE 1 ABOUT HERE >

The results show that children with SLI have reduced performance levels in tasks necessitating the retention of serial order information, at least relative to chronological age matched typically developing children. These difficulties were most obvious for the most challenging serial order STM task, the serial order reconstruction task, where the entire sequence information had to be reconstructed at recall. Poor performance on this task cannot be attributed to speech output difficulties, given that at output, the children reconstructed the original order of the sequence by using cards on which the digits were printed. No overt oral production was needed. Performance was less impaired on the serial order recognition task.

This task was probably less sensitive than the serial order reconstruction task given that during yes-no recognition judgments, correct performance might still be achieved if order information has only been partially retained; if the partial sequence that has been retained contains the serial order positions that are exchanged in the probe sequence, then the child can correctly reject the probe sequence even if he/she would not be able to reconstruct the order information of the entire sequence.

Although this experiment shows that children with SLI present reduced performance in STM tasks specifically designed to probe serial order retention capacities, this does not necessarily mean that children with SLI have specific difficulties in processing serial order information. Indeed, individual item-analyses showed normal serial position effects in each SLI participant, suggesting that SLI children code serial information following primacy and recency gradients as expected by any STM model of normal serial order processing (e.g., Henson, 1998; Burgess and Hitch, 1998; Page and Norris, 1998). Our data also reproduce the classical pattern of prolonged primacy effects versus smaller last-item recency effects, as typically observed in immediate serial recall tasks (e.g., Henson, 1998).

The next experiment further explored serial order processing abilities in children with SLI, by determining their ability to incidentally process and learn new sequence information.

EXPERIMENT 2: IMPLICIT SERIAL ORDER LEARNING

The Hebb learning paradigm consists in the presentation of supraspan digit lists, with one particular list repeated every third trial (the participants are not aware of this repetition) (Hebb, 1961). The repetition of a given list every third trial generally leads to a progressive increase of recall performance, as a result of long-term learning of the repeated sequence. Given that the same items (digits) are presented repeatedly, but by exchanging their serial position trial after trial (except for every third trial were the positions remain the same), this paradigm is a test of the ability to incidentally detect regularities in sequentially presented information, and to learn these regularities. Hence, this paradigm allows the assessment of the ability to implicitly and automatically detect, code and learn serial order information. We used this paradigm in order to assess basic serial order processing abilities in children with SLI. A further reason for exploring the Hebb learning effect in this language impaired population is that some theoretical models consider that learning of new verbal sequences (i.e., new word forms) relies, at least partially, on Hebb-like learning mechanisms at the phonemic and syllabic level of language representations (see for example, Burgess and Hitch, 2005). Burgess and Hitch (1999, 2006) proposed a connectionist architecture of both short-term and long-term verbal learning, where Hebb learning reflects the interaction between STM and long-term memory. In their model, STM is achieved via updating and decay of short-term connection weights between language processing nodes (for item information) and context nodes (allowing the encoding of serial order / temporal information). Hebb learning uses exactly the same representational substrate of item and context nodes, but the updating of connection weights is in this case governed by a more cumulative and longer-lasting association than the short-term updating of connection weights in the STM situation. Hence Hebb learning and immediate serial recall will share a number of effects: they are both sensitive to grouping and rhythm effects of the information to be recalled (Burgess and Hitch, 2005; Bower and Winzenz, 1969; Page et al., 2006). However, contrary to immediate serial recall, Hebb learning is insensitive to phonemic similarity and articulatory suppression, the latter effects arising from the intervention of short-term connections between the different constituent elements of the model (Burgess and Hitch, 1999, 2006).

METHODS

Participants

The participants were the same as in the previous experiment.

Material and procedure

The material consisted in 24 digit sequences, the digits being sampled from the digits 1-9. Digit-position associations for every third sequence were always identical, while the digit-position associations for all other sequences varied randomly. All sequences were recorded by a female voice, digitized and stored on computer disk in order to ensure standardized presentation of repeated and non-repeated sequences. The digits were presented at the rate of one digit per second.

For each child, sequences of a length exceeding his/her digit span by one unit were presented in order to guarantee the same level of difficulty for sequence learning in each child. In order to quantify Hebb learning we determined the proportion of correct digits recalled in correct position for repeated versus unrepeated sequences, by pooling over the different trials for the two conditions (repeated/unrepeated).

RESULTS

A mixed ANOVA explored group-related differences in the size of the Hebb learning effect. This analysis revealed no significant group effect, $F(2,33)=1.14$, n.s., a large effect of list condition with a strong advantage for repeated lists, $F(1,33)=35.33$, $p<.0001$ and no interaction effect, $F(2,33)<1$, n.s. (see Table 3). In order to determine the variability of the size of the Hebb effect as a function of group more closely, we calculated the size of the Hebb effect by subtracting performance on unrepeated trials from performance on repeated trials. As shown in Figure 2, the mean size of the Hebb effect was very similar in the three groups, ranging from .12 in the age-matched control group to .18 in the SLI group. An ANOVA on the size of the Hebb effect confirmed the preceding results, by showing an absence of the group effect, $F(2,33)<1$, n.s. However, we should note that the Hebb effect was not present or reversed in some participants: this was true for two participants of the SLI group (Hebb effect: -.13, -.06), two participants in the CA group (Hebb effect: -.11, -.20) and two participants in the VA group (Hebb effect: -.13, .01). Hence, although there was some variability with respect to the presence and the size of the Hebb effect, the majority of participants in all three groups showed similar-sized Hebb effects. These results suggest that basic serial order detection and learning mechanisms, as assessed by the Hebb learning paradigm, are preserved in children with SLI.

< INSERT TABLE 3 AND FIGURE 2 ABOUT HERE >

EXPERIMENT 3 : SERIAL ORDER RECONSTRUCTION, RECOGNITION AND LEARNING IN CHILDREN WITH SLI AND THE CONTROL OF NON-VERBAL MENTAL AGE

The two previous experiments suggest that basic serial order processing abilities are intact in children with SLI, as evidenced by qualitatively normal serial position curves in the serial order reconstruction task, and normal serial order learning capacities in the Hebb learning task. Yet, SLI children’s performance was poorer than that of chronological and language matched control children, especially for the most challenging serial order reconstruction task. However, at the present stage, we cannot rule out that the observed differences are related to differences in general cognitive abilities. Indeed, the age-matched control group and the SLI group were not perfectly matched with respect to non-verbal cognitive capacities, as estimated by Raven’s matrices. The age-matched control group obtained a raw score of 29.42 while the SLI group obtained a raw score of 25.75. Although this difference might appear minimal and was not statistically reliable, the age-matched control group's performance corresponds to age appropriate performance with a mean percentile score of 56 while the mean percentile score for the SLI group was only 38 (Raven et al., 1998). A similar remark concerns the language-matched control group, with a lower raw score (23.67) relative to the SLI group, but a much higher age-corrected score (percentile 61). Hence, the SLI group shows also a mild delay with respect to non-verbal cognitive functioning. The aim of this third experiment was to control for non-verbal mental age effects by comparing the SLI group's performance on the serial order STM and learning experiments used in the previous experiments, relative to a control group of typically developing children with a similar chronological age and non-verbal cognitive abilities as assessed by Raven's matrices. A second aim was to complement the individual analyses of serial position effects in the SLI group reported in Experiment 1 by between-group analyses, comparing primacy and recency effects in the serial order reconstruction task directly between the SLI group and the Raven's matched control group.

METHODS

Participants

The SLI group was comprised of the same children as those in the other experiments. The Raven's matched control group was selected by administering the Raven's matrices to a total of 28 typically developing children in the same age range as the SLI children and by selecting from this group twelve children (6 boys) that were most closely matched at the level of both chronological age and Raven's matrices to the SLI children. As shown in Table 1, both groups had identical chronological age ($t(22)<1$, n.s.) and identical performance on Raven's matrices ($t(22)<1$, n.s.). Furthermore, percentile scores for Raven's matrices were also perfectly matched (SLI group: 38.75; Raven-matched group: 38.33; $t(22)<1$, n.s.), both groups showing identical lower average performance. As expected, both groups significantly differed at the level of receptive vocabulary knowledge ($t(22)=3.92$, $p<.001$) and nonword repetition performance ($t(22)=6.97$, $p<.001$), confirming the importance and specificity of language and nonword repetition impairments in the SLI group.

Material and procedure

The same serial order reconstruction, serial order recognition and Hebb learning tasks as described in Experiments 1 and 2 were administered to the Raven-matched group and compared to the performance obtained in the SLI group in Experiments 1 and 2.

RESULTS

A first ANOVA assessed group effects on the serial order reconstruction task showing no significant effect of group, $F(1,22)=1.51$, $MSE=0.03$, $p=.23$ (see Table 2). A further analysis compared serial position effects in both groups, by restricting the analysis to list lengths 5 and 6, and by combining serial positions 3 and 4 for list length 6, following exactly the same procedure as in Experiment 1, except that this time we assessed group effects for these positions rather than exploring the presence or absence of primacy and recency effects at an individual basis. Direct group comparisons of serial position effects were possible in Experiment 3 given that, contrary to Experiment 1 and 2, levels of performance were much closer in both groups and hence any possible group by serial position interaction could be interpreted more reliably. A mixed repeated measures ANOVA revealed a main effect of serial position, $F(4,88)=36.35$, $MSE=.01$, $p<.0001$, but no group effect, $F(1,22)=2.18$, $MSE=.20$, $p=.15$ nor any group by serial position interaction effect, $F(4,88)<1$, $MSE=.01$, n.s. As shown in Figure 3, nearly identical U-shaped serial position curves were observed for both the SLI group and the Raven-matched group, the only difference being a slightly lower level of performance in the SLI group for all serial positions.

< INSERT FIGURE 3 ABOUT HERE >

Next, we assessed group effects for the serial order recognition task, revealing again no significant group effect, F(1,22)<1, MSE=0.03, n.s. Finally, the SLI group and the Raven-matched control group were compared on the Hebb learning task. A mixed repeated measures ANOVA showed a main effect of Hebb list repetition, F(1,22)=31.50, MSE=.01, p<.0001, but no group effect, F(1,22)<1, MSE=.04, n.s., nor any group by Hebb list interaction, F(1,22)<1, MSE=.01, n.s. As shown in Figure 2, the size of the Hebb learning effect was quite comparable in the SLI and the Raven-matched control group, F(1,22)<1, MSE=.02, n.s.

The results of Experiment 3 confirm the main conclusions of Experiments 1 and 2, by showing that basic serial order processing abilities, as measured by serial order reconstruction, serial order recognition and serial order learning tasks are preserved in SLI. However Experiment 3further shows that this preservation is not only observable via the presence of normal serial position effects in STM tasks and normal serial order learning effects in the Hebb learning task, but that quantitative performance levels in these tasks can also be preserved, at least relative to a group with normal language development but lower average general cognitive efficiency like the SLI group. Yet, nonword repetition performance is still severely impaired in the SLI group relative to the Raven-matched control group. The three experiments show that the poor performance in nonword repetition cannot be explained by difficulties in serial order retention and processing. However, children with SLI might have difficulties in retaining phonological information at the item level; the retention of precise phonological item information (i.e., which phonemes have been presented) is at least as important as the retention of order information (i.e., in which order the phonemes were presented) for accurate nonword repetition, as mentioned in the Introduction section. The last experiment investigated to what extent children with SLI have difficulties in retaining phonological information at the item level.

EXPERIMENT 4: PHONOLOGICAL ITEM STM IN SLI

Experiment 4 assessed item STM retention capacities by probing recognition for short nonword lists. Nonword stimuli were chosen in order to maximize the recruitment of temporary phonological representations while minimizing the support of long-term lexical and semantic language knowledge, which has been shown to determine item retention capacities to a much greater extent than serial order retention capacities (e.g., Nairne and Kelley, 2004). A recognition task was chosen rather than a verbal recall task in order to be able to assess phonological item STM performance while removing any confounding factors related to potential phonological output difficulties. Furthermore, short monosyllabic nonwords were used in order to diminish the impact of perceptual language processing abilities such as prosodic and coarticulatory phonological analysis (see also Archibald and Gathercole, 2007a, and the discussion of linguistic and non-linguistic requirements for processing monosyllabic *versus* multisyllabic nonwords in the Discussion section). The task consisted in the presentation of short nonword lists, followed by individual probe nonwords; negative probes differed from the target nonword by a single phoneme, requiring very detailed item STM traces in order to permit a correct rejection. A yes/no recognition judgment had to be made after each individual probe nonword. Serial order processing demands at the item level were minimized given that no serial order information had to be retained and recognized. Serial order processing demands at the phoneme level were also diminished by the fact that the nonwords had all the same monosyllabic CVC structure and hence no complex and long phoneme sequences had to be retained. The task was an adaptation of a similar task used in a previous study investigating item and order STM capacities in children presenting a chromosome 22q11.2 microdeletion (Majerus et al., 2007a).

METHODS

Participants

The participants were the same as in Experiment 3.

Materials and procedure

Nonword item recognition task. CVC nonwords were presented in lists of two to five nonwords. The negative probe nonwords differed from the target by the initial consonant only. Diphone frequency of the target and negative probe nonwords was similar, so that negative probes could not be rejected on the basis of different degrees of phonological familiarity for the target and the probe nonwords. The mean diphone frequency for CV diphones was 190.34 (range: 2-1164) for target nonwords and 200.70 (range: 2-1399) for negative probe nonwords, according to the database of French phonology by Tubach and Boë (1990). Each target list (containing either 2, 3 or 4 nonwords) was followed by the presentation of an equal number of positive and negative probe items, the number of positive probe items being further equal to the number of items in the target list. Hence a target list of four items was followed by four positive and four negative probe items, presented in random order. The nonwords had been recorded by a female human voice and stored on computer disk. Their mean duration was 696 ($\pm$96) ms. The different lists were presented auditorily, via high quality loudspeakers connected to a PC running E-Prime software. The nonword lists were presented by increasing length, starting at the shortest list length. There were four trials for each list length. When starting a new trial, the words “new trial” appeared on the screen. Then the screen went white and a target nonword list was presented. At the end of the nonword list, a 500-ms pure tone was presented, followed by the probe nonwords. After each probe nonword, the participant had to judge whether it had occurred in the target list or not, by pressing a green-coloured response button (for “yes” response) or a red-coloured response button (for “no”). We computed the proportion of correct recognitions over a total of 112 probes (pooling over all trials and trial lengths).

RESULTS

A simple ANOVA assessed the group effect for response accuracy in the nonword item recognition task showing no significant group effect, $F(1,22)=2.24$, $MSE=.006$, $p=.15$. Although there was a tendency for lower performance levels in the SLI group relative to the Raven-matched control group ($mean_{SLI}$: .60, SD_{SLI}: .05; $mean_{Raven\text{-}matched\ group}$: .65, $SD_{Raven\text{-}matched\ group}$: .09), the mild difference in performance levels (less than .06 SD) for this very challenging phonological item recognition task is in striking contrast to the much larger difference in performance (more than 2 SDs) for the equally challenging nonword repetition task. The present results suggest that phonological item STM capacity for simple nonword lists are not disproportionately impaired in children with SLI and hence cannot explain the severe difficulties observed during complex nonword repetition.

DISCUSSION

This study explored STM and implicit learning abilities for serial order information in children with SLI. Experiment 1 showed poor performance in reconstruction and recognition STM tasks maximizing the recruitment of serial order retention capacities, relative to language-matched and/or age-matched control groups. At the same time, all children showed significant serial position effects conforming to expected patterns (marked primacy and recency effects). Experiment 2, exploring implicit serial order processing and learning abilities via a Hebb learning paradigm, showed preserved serial order learning abilities, relative to both control groups. Experiment 3, comparing the SLI group to a non-verbal mental age-matched control group for the same serial order STM and learning tasks as in Experiments 1 and 2 showed similar performance in all tasks, and this for both overall performance levels and serial position and learning effects. Finally, Experiment 4 investigated phonological item STM capacities, revealing a small but non-significant decrement in performance in the SLI group relative to a mental-age matched control group.

What causes poor verbal STM performance in SLI?

As noted in the Introduction, consistently impaired performance is observed for nonword repetition tasks in children with SLI (e.g., Archibald and Gathercole, 2006ab; Gathercole and Baddeley, 1990). This has been taken as evidence for a phonological STM impairment in children with SLI, possibly underlying their difficulties in language development. The present study is consistent with these previous studies, in the sense that very poor performance was observed in nonword repetition tasks, irrespective of the control group the SLI group was compared to. However, the theoretical significance of impaired nonword repetition for SLI is more difficult to grasp due to the fact that nonword repetition is a highly multifaceted task, confounding item and serial order STM components, as well as the influence of phonological input and output language processing capacities. The principal aim of the present study was to assess serial order STM performance in SLI since serial order STM measures, relative to item STM measures, have been shown to be much less influenced by language knowledge (e.g., Majerus et al., 2008; Nairne and Kelley, 2004; Poirier and Saint-Aubin, 1996). Furthermore, theoretical and empirical data suggest that serial order STM capacity, rather than item STM capacity, is critical for learning new verbal sequences (e.g., Gupta, 2003; Majerus et al., 2006ab, 2008). Hence, our rationale was that if deficient STM is one of the underlying causes of SLI, a specific deficit should be observed for serial order STM processes. The present study however provides no evidence for specific deficits in short-term retention and learning of serial order information. Although relative to a chronological age-matched control group, performance was significantly lower for serial order STM tasks in the SLI group, this deficit was not specific since group differences disappeared when comparing the SLI group to a chronological *and* mental-age matched control group. Furthermore, at the qualitative level, the SLI children showed expected serial position effects during short-term serial order reconstruction and expected Hebb learning effects on a serial order implicit learning task, showing that SLI children are able to process, maintain and learn serial order information. In an additional experiment, we targeted item STM capacities, revealing again no specific deficit, as shown by unimpaired performance on a very challenging nonword item recognition task. These results suggest that, when considered separately, both serial order and item STM capacities appear to be at mental-age appropriate levels in SLI.

Despite this pattern of results, our SLI group was very severely impaired in a nonword repetition task, even relative to a mental-age matched control group (see also Archibald and Gathercole, 2007a, for similar findings). Since this deficit cannot be related to deficits in serial order and input item STM capacities, it is likely that other components also involved in nonword repetition such as output (articulatory) phonological language processes could be impaired and underlie poor nonword repetition performance. An alternative possibility is that children with SLI have no difficulty in individual STM processes *per se*, as suggested by the present study, but that they are impaired when different STM processes and language processing requirements have to be combined, which is clearly the case in nonword repetition tasks (see Gathercole, 2006 and related discussion papers for an extensive discussion of these issues). A similar interpretation has been provided by Gillam et al. (1998) when they observed traditional serial position effects in SLI children for an auditory verbal STM task with direct oral recall but not for a visually presented verbal STM task requiring a pointing response; the authors concluded that the difficulties in their SLI group arose from the need to combine multiple mental operations (visual-to-verbal recoding at input; verbal-to-picture recoding at output) in the visually presented verbal pointing STM task. Related results can also be found in another study by Gillam and colleagues where they observed a higher sensitivity to suffix effects[2] in SLI children, but only under the most strict scoring procedure requiring accurate recall for both order *and* item information; performance was preserved in the SLI group when recall was scored at only the item or at only the sequence level (Gillam et al., 1995). Finally, Archibald and Gathercole (2007a) observed that children with SLI were impaired to a greater extent for the repetition of single multisyllabic nonwords (i.e., the typical procedure used for nonword repetition tasks in the SLI literature) than for serial recall of lists containing the same syllables as those the multisyllabic nonwords were made of but where the syllables were separated by a pause, contrary to multisyllabic nonword repetition condition. The authors suggested that multisyllabic nonword repetition requires additional processes to STM maintenance, such as prosodic analysis, coarticulatoray input and output analysis and fine-grained temporal analysis, and that children with SLI are also impaired for these processes or, as we suggest, that they are impaired in combining all these processes in a STM situation. All these interpretations in terms of difficulties in rapid and simultaneous processing of multiple information are also in accordance with recent results showing that children with or without language development difficulties can be best differentiated by STM tasks which are very challenging with respect to the requirements to combine or manipulate information held in

[2] The suffix effect in verbal STM tasks refers to the situation where recall of the final list item is disrupted by the presentation of unrelated verbal information after the last item.

STM, i.e. working memory tasks, rather than by ‘simple’ storage tasks (Gathercole et al., 2005). The fact that more general limitations in non-linguistic cognitive abilities could underlie poor performance in STM tasks is also illustrated in the present study by the fact that differences in performance levels on serial order STM tasks disappeared when the SLI group was compared to a control group perfectly matched for mental age. This also means that higher level cognitive abilities, as estimated by Raven’s matrices, were not perfectly in line with chronological age in our SLI sample, and this is also generally true in other studies on SLI (e.g., Bishop and MacArthur, 2005; Archibald and Gathercole, 2007ab).

Other studies, focusing more directly on non-linguistic cognitive abilities in SLI, have documented limitations for general cognitive processes, such as processing speed. They have also shown that these limitations are related to performance levels in verbal STM and language processing tasks (Fazio, 1998; Kail, 1994; Lahey and Edwards, 1996; Miller et al., 2001; Montgomery, 2004; Schul et al., 2004; Windsor and Hwang, 1999). For example, Fazio (1998) showed that preschool children with SLI have similar performance levels to chronological age and language matched control groups for memorizing sequences of verbal or non-verbal information when the presentation rate of the stimuli is slow; however, performance declines when the stimuli are presented at faster rates, and this for both verbal and non-verbal sequences. Studies in typically developing children have also shown that output speed (the rate at which items are produced during STM recall) is an important factor affecting immediate serial recall performance (Cowan et al., 1999). A very recent study has obtained further findings supporting the existence of a link between processing speed limitations and memory impairments in SLI: Archibald and Gathercole (2007a) observed that estimates of STM capacity alone cannot account for the poor performance of SLI children in complex span working memory tasks, but that slowed processing speed is a likely contributing factor. More generally, these studies can be related to the earlier studies by Tallal and colleagues, showing that children with SLI have poor capacity for discriminating verbal as well as visual information presented at very fast presentation rates (e.g., Tallal and Stark, 1981; Tallal et al., 1981).

Finally, we should note that, although not being a primary cause of SLI, the (non-specific) functional limitations observed for retaining serial order information in STM tasks, relative to chronological age-matched controls, are likely to have a negative impact on further lexical development in SLI, in agreement with recent data suggesting that serial order STM capacity is a critical determinant of lexical learning (e.g., Burgess and Hitch, 2005, 2006; Gupta, 2003; Majerus et al., 2006ab, 2008).

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Table 1. General language and intelligence measures for the SLI group as well as verbal and non-verbal matching variables for all groups (means and standard deviations).

	SLI group	Age-matched group (Experiments 1, 2)	Language-matched group (Experiments 1, 2)	Raven-matched group (Experiments 3, 4)
Age	100.75 (13.07)	102.91 (12.98)	78.92 (17.71)	100.5 (12.85)
Lexical Age[1]	75.75 (26.67)	/	/	/
Syntactical Age[2]	72.17 (18.80)	/	/	/
Verbal IQ[3]	70.57 (12.35)	/	/	/
Performance IQ[4]	97.50 (9.01)	/	/	/
EVIP raw score	77.08 (24.64)	110.33 (14.71)	80.25 (15.57)	112.58 (19.43)
Nonword repetition[5]	.22 (.09)	.50 (.08)	.38 (.15)	.58 (.15)
Raven's CPM raw score	25.75 (5.71)	29.42 (4.87)	23.67 (5.63)	26.17 (3.86)

[1] Lexical age derived from the EVIP (Dunn et al., 1993) or TVAPII (Deltour and Hupkens, 1980) receptive vocabulary scales

[2] Syntactical age derived from the ECOSSE (Lecocq, 1996), O-52 (Khomsi, 1987) or ELO (Khomsi, 2001) morpho-syntactic comprehension scales

[3] Verbal IQ derived from the Wechsler Intelligence Scales for Children (WISC-III) or Wechsler Pre-scholar and Primary School Intelligence scales (WPPSI-III); the mean verbal IQ reported here is based on only 8 children of the SLI group, no reliable verbal IQ estimates could be obtained for the other four children due to their language difficulties

[4] Performance IQ derived from the Wechsler Intelligence Scales for Children (WISC-III) or Wechsler Pre-scholar and Primary School Intelligence scales (WPPSI-III) , reported mean based on all children of the SLI group

[5] Standardized single nonword repetition task by Poncelet and Van der Linden (2003); proportion of items correctly recalled

Table 2. Means and standard deviations for performance on the different STM tasks (proportion of correct performance).

	SLI group	Age-matched group (Experiments 1, 2)	Language-matched group (Experiments 1, 2)	Raven-matched group (Experiments 3, 4)
Serial order recall	.44 (.18)	.79 (.17)	.58 (.18)	.52 (.15)
Serial order recognition	.72 (.15)	.83 (.13)	.70 (.16)	.75 (.11)

Table 3. Means and standard deviations for performance on the Hebb learning experiment .

	SLI group	Age-matched control group	Language-matched group	Raven-matched group
Proportion of items correctly recalled				
Non-repeated lists	.58 (.15)	.55 (.17)	.63 (.15)	.62 (.10)
Repeated lists	.76 (.25)	.67 (.21)	.80 (.17)	.77 (.12)

FIGURE LEGENDS

Figure 1. Serial position curves for each SLI participant

Figure 2. Mean size (and type-error) of the Hebb learning effect as function of group for Experiments 2 and 3.

Figure 3. Serial position curves for the SLI group and the Raven-matched control group in Experiment 3.