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Phonological memory and vocabulary learning in children with focal lesions

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Abstract

Eleven children with early focal lesions were compared with 70 age-matched controls to assess their performance in repeating non-words, in learning new words, and in immediate serial recall, a triad of abilities that are believed to share a dependence on serial ordering mechanisms (e.g., Baddeley, Gathercole, & Papagno, 1998; Gupta, in press-a). Results for the experimental group were also compared with other assessments previously reported for the same children by MacWhinney, Feldman, Sacco, and Valdés-Pérez (2000). The children with brain injury showed substantial impairment relative to controls in the experimental tasks, in contrast with relatively unimpaired performance on measures of vocabulary and non-verbal intelligence. The relationships between word learning, non-word repetition, and immediate serial recall were similar to those observed in several other populations. These results support previous reports that there are persistent processing impairments following early brain injury, despite developmental plasticity. They also suggest that word learning, non-word repetition, and immediate serial recall may be relatively demanding tasks, and that their relationship is a fundamental aspect of the cognitive system.

1. Introduction

Learning the vocabulary of a native language is one of the most important developmental processes a child needs to undergo. A variety of evidence now suggests that human vocabulary acquisition processes and aspects of human verbal short-term memory may be related. In children, reliable correlations have been obtained between digit span, non-word repetition ability, and vocabulary achievement, even when other possible factors such as age and non-verbal intelligence have been factored out (e.g., Gathercole & Baddeley, 1989; Gathercole, Willis, Emslie, & Baddeley, 1992). Non-word repetition ability has been shown to be an excellent predictor of language learning ability in children learning English as a second language (Service, 1992; Service & Kohonen, 1995), and is also associated with more rapid learning of the phonology of new words by children in experimental tasks (Gathercole & Baddeley, 1990b; Gathercole, Hitch, Service, & Martin, 1997; Michas &

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Henry, 1994). In addition, similar relationships between these abilities appear to hold in adults (Gupta, in press-a; Papagno, Valentine, & Baddeley, 1991; Papagno & Vallar, 1992). Thus there is now a considerable body of evidence to suggest that word learning, immediate serial recall, and non-word repetition are a related triad of abilities (Baddeley et al., 1998; Gathercole & Baddeley, 1993). An emerging view of this relationship is that immediate serial recall and non-word repetition are both tasks that draw on the mechanisms of verbal short-term memory fairly directly, and that the learning of new words is also in some way supported by verbal short-term memory (e.g., Baddeley et al., 1998; Brown & Hulme, 1996; Gathercole, Service, Hitch, Adams, & Martin, 1999; see also Gupta (1996; Gupta & MacWhinney, 1997) for a related but somewhat different view).

The studies cited above provide evidence about the relationship between these abilities in normally developing children and in normal adults. This relationship has also been examined in children diagnosed as having specific language impairment (SLI) not attributable to neurological deficit. Although there is considerable debate over the nature of SLI (for review, see Bishop, 2000; Evans, 2001), it often involves difficulty in phonological processing (including the processing of novel phonological forms, as in non-word repetition), and in lexical learning (e.g., Bird, Bishop, & Freeman, 1995; Bishop, 2000; Windfuhr, Faragher, & Conti-Ramsden, 2002). What is relevant to the present discussion is that deficits in non-word repetition and word learning co-occur with difficulties in immediate serial recall (Gathercole & Baddeley, 1990a), suggesting that these abilities are related not only under normal language development but also under SLI. It also appears that there is a population of neuropsychologically impaired “pure STM” patients who exhibit selective deficits in immediate serial recall but in whom language production and comprehension is largely preserved (e.g., Shallice, 1988). Further investigation of their linguistic skills reveals, however, that these patients’ serial recall deficits are accompanied by deficits in non-word repetition and word learning ability (Baddeley, 1993; Baddeley, Papagno, & Vallar, 1988). Additionally, the co-occurrence of linguistic and verbal short-term memory deficits in adult aphasics has been noted by a number of investigators and interpreted as indicative of a functional relationship (e.g., N. Martin, Saffran, & Dell, 1996; Saffran, 1990), although other investigators have argued for a separation between verbal short-term memory buffers and linguistic representations (e.g., R. Martin & Lesch, 1996). Overall, however, the relationships between verbal short-term memory abilities and the linguistic processing of novel phonological forms appear to be a rather pervasive aspect of the human cognitive architecture, holding up as they do even under conditions of delayed linguistic development in children, and under neurological insult in adults.

Little is known, however, about the impact of early neurological injury on the development of these abilities. Previous studies of the development of language in children with early focal lesions suggest that there is a generally favorable prognosis for language acquisition that is nevertheless accompanied by selective deficits or delays, especially in the more complex aspects of language processing (e.g., Aram, Ekelman, Rose, & Whitaker, 1985; Aram, Ekelman, & Whitaker, 1986; Lenneberg, 1967; MacWhinney et al., 2000; Marchman, Miller, & Bates, 1991; Thal et al., 1991). No previous studies have specifically examined the impact of early lesions on vocabulary learning, non-word repetition, and immediate serial recall. Thus on the one hand, we might expect the plasticity of the developing brain to compensate for the insult, leaving little deficit in these abilities; on the other hand, perhaps these abilities would be among those manifesting delay and/or impairment.

The importance of this question lies in its implications for the nature of the processing that underlies these abilities. If these abilities are not significantly impacted by early injury, this would suggest that they are relatively easy tasks and/or that the functionality of the underlying mechanisms is relatively amenable to reorganization through developmental plasticity. If these abilities are significantly impacted by early injury, this would suggest that they are relatively demanding tasks and/or that the underlying processing functionality is not easily achieved through neural reorganization. Additionally, if the relationship between these abilities is indeed a fundamental aspect of cognition, then even following early injury, we would expect these relationships to be similar to those observed in the variety of populations cited above. Such a finding would have two possible interpretations. First, that the abilities are subserved by brain areas that are uniformly spared or damaged by lesions. Second, that they are logically and ecologically dependent: if an area were damaged that impacted one of these abilities, reorganization would occupy new territory for that ability and drag the other two with it. On the other hand, a finding that the relationships between these abilities do not hold following early brain injury would suggest that these abilities might have reorganized in ways that no longer shared processing components in the same manner, suggesting that their relationship might not be such a fundamental aspect of cognitive architecture.

The present work sought to shed light on these questions by administering tests of vocabulary learning, non-word repetition, and immediate serial recall to two groups of children aged 5–10. One group of 11 children had suffered perinatal brain injury that resulted in focal lesions. The lesions affected the left hemisphere in all 11 children in this group; in 9 of the cases, the right hemisphere was spared, while in 2 of the cases, the left hemisphere lesions were accompanied by smaller right hemisphere lesions. The second group of children consisted of normally developing age-matched controls. The experimental group of children were part of a large-scale investigation, other aspects of which were reported in MacWhinney et al. (2000). It was therefore possible to compare results from the present investigations with a broader profile of results that has been established for the same children.

2. Method

2.1. Participants

Experimental group—The participants were 11 children ages 5–10, who were recruited through referrals from local hospitals, rehabilitation centers, and previous research studies. All except one of this group (JL) also participated in the studies described in MacWhinney et al. (2000). Neurological information was available in the form of MRI scans for all children; neurological profiles are summarized in Table 1. Further information about the MRI scans, neurological profiles, and demographic characteristics is provided in MacWhinney et al. (2000).

Control group—Seventy children ranging in ages from 5 to 10 years were recruited to serve as controls. 10 of the children were aged 5, 11 were aged 6, 14 were aged 7, 13 were aged 8, 12 were aged 9, and 10 were aged 10. All of the control children were functioning at grade level. They were recruited from parochial and private schools in the greater Pittsburgh area, as well as from advertisements. They were tested either at their schools or in the Department of Psychology at Carnegie Mellon University. Parental consent was obtained for all participants.

2.2. Experimental measures

Immediate serial recall—One token of each of the digits *one* through *nine* spoken by a female native speaker of American English was recorded as digitized sound on an Apple PowerMacintosh computer. Random sequences of these tokens were generated, varying in length from two digits to eleven digits. Each digit sequence was presented auditorily under computer control. One trial consisted of presentation of one sequence of a particular length. For example, one trial at list length four consisted of auditory presentation of a sequence of four digits such as *three*, *eight*, *two*, and *five*.

There were 5 trials at each list length. Presentation of lists started with sequences of two digits. Participants were seated facing the screen. After presentation of each digit sequence, a rectangular answer box appeared on the screen, with a question mark in it. Participants were instructed to repeat the sequence orally as soon as the answer box appeared on the screen. The participant's response was typed in by the experimenter, and appeared in the answer box on the screen. The experimenter completed entering the response by pressing the carriage return key on the computer keyboard, which initiated auditory presentation of the next digit sequence. If a participant recalled in correct serial order three or more of the five sequences at a particular list length, the next higher list length was introduced. The longest list length for which a participant correctly recalled three or more sequences was taken as the measure of that participant's digit span.

Non-word repetition—We used 2-syllable, 3-syllable, and 4-syllable word forms taken from the Childrens' Test of Non-word Repetition (CNRep; Gathercole, Willis, Baddeley, & Emslie, 1994). This test was devised specifically for use with children, and formed the basis of the studies that first reported correlations between memory span, non-word repetition, and vocabulary ability in children (e.g., Gathercole & Baddeley, 1989; Gathercole, Willis, Emslie, & Baddeley, 1991b). However, we decided not to use the 5-syllable word forms in the CNRep, in view of the anomalous results reported at this non-word length (Gathercole et al., 1994). The nonwords in our adaptation of the CNRep were recorded as digitized sound on an Apple PowerMacintosh computer by a female native speaker of American English. Stimuli were presented by computer, and all participants listened to the stimuli on headphones. Each non-word was spoken twice, and participants were instructed to repeat every non-word stimulus after hearing it the second time. The experimenter rated each repetition as correct or incorrect. This scoring procedure was adopted in order to maintain consistency with the previous studies that documented correlations between non-word repetition, vocabulary, and immediate serial recall in children, both with normal language and SLI (e.g.,

Word learning—To obtain a measure of word learning ability, we presented participants with non-word–picture pairs. This was followed by cued recall, in which the picture served as the cue, and participants were asked to recall the non-word with which the picture had been paired during presentation. This was meant to approximate the task of word learning, in which the representation for a novel word form must be created and bound to a semantics or other contextual representation.

Participants were presented with non-words auditorily. Presentation of each non-word was accompanied by the picture of an unfamiliar object. There were nine nonword–picture pairs. The nine non-words consisted of three 2-syllable word forms, three 3-syllable word forms, and three 4-syllable word forms. Presentation was blocked in groups of three, so that participants would not have to learn all nine pairs in one trial. Stimulus pairs were chosen to minimize stimulus similarity for the stimuli at any given word length. However, it was difficult to ensure that all nine pairs were completely distinct from each other. For this reason, the blocking variable chosen was word length: within a block, stimulus pairs would be distinct and therefore non-confusable.

The non-word–picture pairs used are shown in Fig. 1. Each non-word was recorded as digitized sound on an Apple PowerMacintosh computer by a female native speaker of American English. All participants listened to the stimuli on headphones, with a uniform playback volume for all participants. The pictures were all of real but unfamiliar objects which participants were unlikely to know or have a name for. Unfamiliarity of the pictured objects was confirmed by informal pilot testing prior to the actual experiment.

The procedure for presentation was as follows. Each non-word–picture pair was presented under computer control. Each non-word was repeated twice. Participants were told that the word forms they heard were the “names” of the pictured objects, and that they were to learn these names. The picture appeared on the computer screen synchronously with onset of the first repetition of the non-word. The second repetition of the non-word occurred 1800 ms after onset of the first repetition. A fixation cross replaced the picture 1500 ms after onset of the second repetition of the non-word. Thus the picture was displayed on the screen for 3300 ms, during which the non-word was presented twice, auditorily. Participants were instructed to repeat the word form they had just heard, as soon as the fixation cross appeared on the screen. The fixation cross stayed on the screen for 1500 ms, at the end of which presentation of the next non-word–picture pair began. To make the task less difficult, especially for the younger children, it was decided to present the nine pairs in blocks of three. It was also decided to present the shortest non-words first, so that participants could begin the task with the easier 2-syllable words; again, this seemed particularly important for the younger children. For both of these reasons, presentation of the nonword–picture pairs was blocked by non-word length. Thus there were three non-word–picture pairs at each length (2-syllable, 3-syllable, and 4-syllable), and all the pairs of a particular length were presented in one block. This procedure had the further advantage of preventing participants from using non-word length as a recall aid. Presentation order of pairs within each block was random without replacement.

Cued recall followed presentation of the three stimulus pairs in each block. Participants were presented with pictures from the immediately preceding nonword–picture pairs, and were instructed to respond by saying the "name" of the pictured object out loud. Pictures were selected randomly without replacement, from the set of three pairs in each block. Each picture cue was displayed for 1500 ms, during which the participant was supposed to name it. The screen was masked for 1000 ms before presentation of the next picture cue. Presentation of pictures was controlled by the computer.

This procedure was repeated five times for each block of non-word–picture pairs. When the five cycles for one block of three non-word–picture pairs were complete, the next block of pairs was introduced.

2.3. Standardized tests

As described in MacWhinney et al. (2000), a number of standardized measures were administered to each experimental participant: (1) The Leiter International Performance Scale (Leiter, 1979) is an untimed test that provides a culture-free, non-verbal means of assessing general intelligence based on primarily abstract concepts. This test has a norm of 100 and a standard deviation of 15. (2) The Peabody Picture Vocabulary Test-Revised (PPVT-R; Dunn & Dunn, 1981) is an untimed test of receptive vocabulary that measures a participant' s hearing vocabulary for Standard American English. The test has a mean of 100 and a standard deviation of 15. (3) The Clinical Evaluation of Language Fundamentals-Revised (CELF-R; Semel, Wiig, & Secord, 1987) is a standardized measure of language functioning that diagnoses language skill deficits in school-aged children, and consists of several subtests, for each of which norms are provided. Each subtest has a mean of 10 and standard deviation of 3. The CELFRS (Recalling Sentences) is an expressive test that assesses the ability to recall and reproduce sentence surface structure of varying length and syntactic complexity. The CELF-FS (Formulating Sentences) is an expressive test that assesses the ability to formulate simple, compound, and complex sentences from words provided by the examiner. The CELF-OD (Oral Directions) is a receptive test that assesses the ability to interpret, recall and execute oral directions of increasing length and complexity.

3. Results and discussion

The two questions of interest in the present study were, first, whether non-word repetition, immediate serial recall, and word learning in the experimental group would be significantly impacted by this group's early injury; and second, whether the relationships between these abilities would be similar to those observed in the variety of other populations described in the introduction. For ease of exposition, we begin with discussion of the first question, examining levels of performance in the three abilities, rather than their pattern of relationship. It is worth noting, however, that investigation of the second question will reveal a very strong relationship between the abilities, a point that may not be readily apparent from consideration of the levels of performance themselves, to which we now turn.

Scores on the three experimental tasks are shown in Table 2. The upper panel of the table shows performance on word learning. Each experimental group participant's raw score is

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shown, as well as the standardized score (*z*-score) with respect to the relevant age-matched control group. The middle panel shows the same information for the non-word repetition task, and the bottom panel provides this information for immediate serial recall.

The standardized scores show, for each measure, how many standard deviations from the age-matched control group mean each experimental group participant's performance lies. Each participant's performance on each test was evaluated in two ways. First, we examined whether the subject's *z*-score fell within ±1.645 of the control group mean. This corresponds to a 90% confidence interval around the control group mean; we used this (rather than a 95% interval) because we wished to identify those scores that fell in the lowest 5% of the distribution defined by control group performance. Second, we examined whether the participant's score fell within the actual range of scores obtained for the control subjects. Performance was considered to be unimpaired on a particular test if it met either of these criteria. Scores that failed both of these criteria were considered to be in the impaired range, and are marked with an asterisk in the Table.

As can be seen, the experimental group's performance exhibits impairment on several of the measures: of the 33 scores (comprised of 11 participants' scores on each of three measures), 19 fall within the impaired range. Of these, six are in word learning, seven are in non-word repetition, and six are in immediate serial recall. This provides preliminary indication that neurological insults in children do lead to deficits in performance on word learning, non-word repetition, and immediate serial recall, as they do in adults.

Fig. 2 plots these results and displays regression lines fitted to the control and experimental groups for each measure. For word learning, we see that the performance of the experimental group is substantially lower than that of the control group at all ages. However, scores improve with age in both groups. The overall trend with age is very similar for the two groups, with essentially parallel regression lines. Thus the experimental group's relative impairment in word learning appears to persist over this age range, and does not show improvement with respect to controls.

In non-word repetition, the experimental group's scores are substantially lower than the control group's at the younger ages, but show a much steeper improvement than those of the control group, catching up with control group performance at the older ages. The experimental group's impairment in non-word repetition thus appears to remit over this age range, as a result of markedly greater improvement in this ability than occurs in controls. This is also apparent from the regression lines, which converge at about age 10.

For immediate serial recall, the picture is very similar to that for word learning. The performance of the experimental group is substantially lower than that of the control group at all ages; scores improve with age in both groups, and the overall trend with age is very similar for the two groups, with almost parallel regression lines. Thus, as in word learning, the experimental group's impairment in immediate serial recall appears to persist over this age range, not showing improvement relative to controls. The results for immediate serial recall mirror those reported by MacWhinney et al. (2000) using a slightly different test of immediate serial recall.

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Thus the results suggest a fairly pervasive impairment in the experimental group's performance on word learning, non-word repetition, and immediate serial recall, although the impairment in non-word repetition remits by the end of the age range we examined. But do these results truly reflect impairment in the measures examined? Or are they rather merely a reflection of some generalized impairment in cognitive function? Further understanding of the present results can be obtained by comparing them with results reported by MacWhinney et al. (2000). That study obtained measures from the same experimental group on the standardized tests described earlier (Leiter, PPVT-R, and CELF), as well as on a number of reaction-time tasks designed specifically to test basic online skills relevant to language processing.

The first three rows of Table 3 summarize performance on the experimental measures in the present study, reproducing the *z*-scores from Table 2 in a format that facilitates identification of each child's profile of impairment. It is worth noting the wide prevalence of impairment on the experimental measures: 9 of 11 children were impaired on at least one of the measures, KAM and TID being the only exceptions. (The fact that not all the children were impaired on all the measures, and the fact that two of them were unimpaired on all three measures might appear to indicate a lack of relationship between these measures; however, as we shall see shortly, the measures are in fact strongly related.)

The remaining rows show performance on each of the standardized measures administered by MacWhinney et al. (2000), except for one child (JL), for whom these data were not available. To facilitate comparison with the experimental tasks, scores on each of the standardized tests have been converted to *z*-scores using the mean and standard deviation published for each standardized measure. As with the experimental measures, scores that fell in the lowest 5% (i.e., *z*-scores of lower than −1.645) were considered to be in the impaired range, and are indicated with an asterisk.

What is apparent is that the childrens' non-verbal intelligence and vocabulary (as measured by the Leiter and PPVT-R, respectively) are solidly within the normal range, with only one score on each measure falling in the impaired range, and with the mean *z*-scores being −.113 for the Leiter, and −.447 for the PPVT-R. This is a finding that MacWhinney et al. (2000) also noted for the larger group of 20 children. Thus the finding of substantial impairment on the present experimental tests of word learning, non-word repetition, and immediate serial recall is not simply a manifestation of generalized cognitive impairment; nor is it even a manifestation simply of generalized linguistic impairment, as gauged by the childrens' vocabularies.

MacWhinney et al. (2000) further noted that, in contrast to nearly normal performance on the Leiter and PPVT-R, the 20 experimental participants performed more poorly on the language processing tasks of the CELF. This trend can also be seen in the results for the present set of 10 children: the mean *z*-scores are −.800, −1.100, and −1.233 for the CELF-RS, CELF-OD, and CELF-FS, respectively. MacWhinney et al. (2000) also reported that the children with focal lesions were markedly slower than their respective control groups on the various reaction-time tasks. However, as the control group in the present study was different, and the reaction-time measures were not administered to them, no comparison can be made between the present experimental and control groups with regard to these measures.

MacWhinney et al. (2000) suggested that the CELF language processing tasks required more complex online processing than the Leiter and PPVT-R, with the CELFOD requiring a child to store, elaborate, and execute a complex plan to follow oral directions, and the CELFFS requiring the child to apply syntactic, semantic, and pragmatic abilities to compose a complex sentence structure based on the words provided. They suggested that the reaction-time tasks were also such as to reveal underlying processing deficits. To summarize their view, the performance of the experimental group as a whole reflects adequate language function and adequate overall cognitive function, but underlying processing deficits exist nevertheless, and are revealed by tasks that are more demanding. Task demands may arise from the complexity of the task, or from it being more constrained in its response requirements. The CELF tasks would be an example of both of these types of task demand: for instance, the CELF-OD is more complex than the Leiter or PPVT; it is also more constrained, requiring a very specific plan to be executed, whereas the Leiter allows greater flexibility in how the items are responded to. Task demand may also arise in the requirement for speeded processing, as in the reaction-time tasks. We could further imagine that part of what constitutes "complexity" may be a requirement to engage verbal short-term memory (see the description of the CELF tasks above). Set against this background, the present results suggest that word learning, non-word repetition, and immediate serial recall are relatively demanding tasks, eliciting performance that is substantially weaker than performance on the measures of general non-verbal intelligence and of vocabulary, and that is weaker even than performance on the subtasks of the CELF, as may be verified from examination of the mean *z*-scores in Table 3.

Overall, our results thus far answer the first question we wished to address, indicating that word learning, non-word repetition, and immediate serial recall do exhibit substantial impairment in children with early focal lesions, and that this impairment is not merely secondary to generalized cognitive impairment or to generalized linguistic impairment. They also provide insight into the nature of these abilities, suggesting that the underlying processing mechanisms may be relatively complex or demanding.

This leads to the second question we wished to address: is the relationship between word learning, nonword repetition, and immediate serial recall similar to that observed in normally developing children, which is also observed in children with specific language impairment, and in normal and neurologically impaired adults? To examine this issue, we determined correlations between these abilities in the experimental and control groups, and compared these with correlations that have previously been reported for normally developing children. Table 4 shows the patterns of correlation, both simple and partial, between these abilities in the experimental and control groups, and also summarizes developmental results for normally developing children (e.g., Gathercole et al., 1994).

Let us first consider correlations in the control group. The simple correlations were somewhat higher than those reported by Gathercole et al. (1994). Correlations were therefore examined with age partialled out. These partialled correlations were lower than the simple correlations, but remained significant, and were for the most part similar to those reported in the literature. It should be noted that the partial correlations previously reported factored out age and non-verbal intelligence, whereas the partial correlations we report for our control group were after factoring out only age, as no measure of non-verbal intelligence was administered to this group. This may be one reason why the partial correlations remained somewhat higher than those previously reported.

Turning to correlations for the experimental group, it can be seen that the simple correlations are highly significant; however, they are very much higher than in either the present control group or the reported developmental results. To further examine these results, we partialled out age and non-verbal intelligence (as measured by the Leiter), thus making the partial correlations comparable with those previously reported. (For comparison with the control group, each correlation is also shown with only age partialled out). As shown, the partial correlations between digit span and non-word repetition, and between digit span and word learning remained significant even with both age and non-verbal intelligence partialled. However, the partial correlation between word learning and non-word repetition was marginally non-significant ($p = :067$), a result that is consistent with results reported for 8-year-olds (as shown in the Table), and with findings in normal adult populations (Gupta, in press-a). The partial correlations remained of greater magnitude than those previously reported.

It is important to keep in mind, however, that it is not the magnitudes of correlations in themselves that should be of primary interest, but rather the overall pattern of correlations between the measures. This is because there are a number of differences in the way that the various measures were determined in previous studies as compared with the present study. First, the previously reported developmental studies reported vocabulary measures, whereas the present results incorporate a measure of word learning performance. (It should be noted, however, that Gathercole et al. (1997) examined relationships between digit span, non-word repetition, and performance in a simulated word learning task with 5-year-olds, and found patterns of correlation similar to the developmental results summarized above.) Second, the measures of non-word repetition were different, being based on the CNRep for the children aged 4, 5, and 8 years (Gathercole, Willis, & Baddeley, 1991a; Gathercole et al., 1992; Gathercole et al., 1994), and in the present study, but being based on repetition of pairs of non-words for the 13-year-olds (Gathercole et al., 1999). These various differences indicate that we should not expect to find identical correlations; the more significant finding is that the pattern of simple and partial correlations between the three measures is similar to that obtained in normal development. Correlations in the control group are mostly within the range of developmental correlations that have previously been reported; and correlations in the experimental group remain significant even when age and non-verbal intelligence are partialled out, as they do in normally developing children.

Overall, therefore, the present results address the second question we raised: it appears that despite the brain injuries suffered by the experimental group, the pattern of relationships between word learning, nonword repetition, and immediate serial recall are maintained, and are similar to those that have been reported in other populations.

4. General discussion

The studies described here provide new information, both about the impact of early brain injury on word learning, non-word repetition, and immediate serial recall, and about the pattern of preservation and impairment of behavioral abilities in children following early brain injury.

Regarding the investigation of word learning, nonword repetition, and immediate serial recall, the first question we addressed was whether these abilities are significantly impacted by early injury. The results indicate that these abilities do exhibit substantial impairment in children with early focal lesions, and that this impairment is not merely secondary to generalized cognitive impairment or to generalized linguistic impairment. They also provide insight into the nature of these abilities, suggesting that the underlying processing mechanisms may be relatively complex. Furthermore, the finding of impairment across a wide variety of lesions suggests that this triad of abilities places demands on a distributed neural system that is likely to be impacted by almost any cortical injury.

The second question we addressed was whether the relationships between these abilities would be similar to those observed in a variety of other populations, including normally developing children, children with specific language impairment, normal adults, and adults with neurological injury. The results suggest that the relationships between digit span, non-word repetition, and word learning are similar to those observed in the other populations, even under conditions of early brain injury. We noted in the introduction that such a finding might indicate either that the brain regions underlying these abilities had been uniformly damaged by lesions, or that these abilities are logically and ecologically dependent, a possibility that is entirely consistent with current thinking about the phonological loop (e.g., Baddeley et al., 1998). Given that the lesions in the present experimental group were widely varied, it seems very unlikely that the brain areas subserving immediate serial recall, non-word repetition, and word learning were uniformly impaired across the group. We therefore suggest that the results are best interpreted as indicating that this triad of abilities is functionally related, and thus as providing further evidence that the relationship between these abilities is indeed a fundamental aspect of cognition.

What is the nature of this relationship? One hypothesis about its functional nature comes from recent work that examined syllable serial position effects in repetition of individual polysyllablic non-words, and obtained significant primacy and recency effects much like the serial position effects obtained in immediate serial recall of lists of verbal items (Gupta, in press-b). This suggests that the functional relationship between non-word repetition and immediate serial recall may be (at least in part) that both rely on computation of the serial order of a sequence of elements: a sequence of lexical items, in the case of a list, and a sequence of sublexical items (syllables) in the case of a non-word (Gupta, in press-b; see also Gupta, in press-a for discussion of underlying computational mechanisms). A plausible explanation of the relationship between nonword repetition and word learning can be given in terms of the fact that every known word was once a non-word to the learner, so that greater facility in processing nonwords would be expected to lead to greater facility in eventually learning them; this hypothesis is discussed in other recent work that considers the relationship between non-word repetition, word learning, and procedural and declarative memory systems (Gupta & Cohen, 2002; Gupta & Dell, 1999).

It is also important to keep in mind that the mechanisms of verbal short-term memory do not operate independently of linguistic representations or the lexical system. A variety of evidence now indicates, for instance, that long-term linguistic knowledge significantly impacts performance in immediate serial recall as well as in non-word repetition (e.g., Gathercole, 1995; Hulme, Maughan, & Brown, 1991). Gupta (1995, 1996; Gupta & MacWhinney, 1997) developed a computational model of verbal short-term memory and lexical processing that offers an account of how performance of verbal short-term memory tasks such as immediate serial recall involves lexical processing mechanisms. This work incorporates a simple model of lexical processing, and a sequence memory that encodes the serial order of word forms as they are presented to the lexical system. The sequence memory is a specialized short-term store, corresponding roughly to the working memory model's phonological store, but with the important difference that it is not a buffer into which items are entered; rather, it takes snapshots of the activation of linguistic representations as they occur in sequence in the lexical system (Gupta, 1995; Gupta & MacWhinney, 1997). This model offers an account of word learning, nonword repetition, and immediate serial recall, providing a concretization of the notion that verbal short-term memory is intrinsically linked to lexical processing mechanisms.

Additionally, the model suggests that all three abilities depend crucially on the strength of long-term phonological knowledge in the lexical system. Thus the mechanisms of verbal short-term memory may themselves draw on aspect of the linguistic system, rather than consisting of an isolated verbal short-term memory buffer that stores or temporarily maintains traces derived from a completely separate lexical system. That is, although one aspect of the functional relationship between these abilities is that they share a dependence on the serial ordering mechanisms of the sequence memory or phonological store, they are also related in depending on the fundamentals of lexical processing. A similar point has been made by Gathercole et al. (1997), who noted that the "phonological store" on which immediate serial recall, non-word repetition, and word learning rely is perhaps better conceived of as a system whose performance depends on both a specialized short-term sequence memory and the activation of representations in the lexical system.

Finally, the present study provides new information about the prognosis for development following early brain injury. The overall pattern of impairment in word learning, non-word repetition, and immediate serial recall confirms suggestions from previous studies that despite developmental plasticity, there are processing deficits following early brain injury. What is encouraging, however, is the success that these children achieve in acquiring a thoroughly adequate functional use of language, as MacWhinney et al. (2000) also noted. One seeming paradox is the experimental group's lack of impairment on the vocabulary measure, given their impairment in learning new words. One possible explanation of this is that the word learning task that was administered taps into the core cognitive processes of word learning; however, as noted by MacWhinney et al. (2000), word learning is highly overdetermined, for instance, by well-structured parental input, good educational support, and nurturant family environments, and it is reasonable to suppose that the present experimental group benefits from some of these, so as to achieve normal control of language when measured in overall functional terms such as vocabulary level. In this connection, the finding of remission of deficits in non-word repetition is encouraging, suggesting that the prognosis even for online processing may be favorable. It would be valuable to obtain information about the time course of such abilities beyond the age range we examined, into the teenage years.

More speculatively, the present results may also offer some insight into patterns of cognitive impairment following brain injury more generally, and even regarding developmental language disorders. In the case of early lesions, there is a real possibility for remission of deficits as a result of developmental neural plasticity. It is therefore reasonable to conclude that those abilities that remain relatively more impaired are the ones that are either more demanding, or less amenable to neural reorganization, or both. To the extent that the present results indicate that word learning, non-word repetition, and immediate serial recall are relatively demanding tasks, as we have suggested, they may offer insight into the frequent cooccurrence of impairments in verbal short-term memory and in processing novel phonological material, in adult aphasic populations as well as in children with specific language impairment. Such impairments may reflect the breakdown of more demanding cognitive tasks under conditions of impairment to the underlying processing abilities, and indeed, this view has been advanced both in the case of aphasia (e.g., Martin et al., 1996), and in the case of specific language impairment (e.g., Merzenich et al., 1996; Tallal et al., 1996), where this view has led to the development of apparently successful treatments. If this is the case, then further investigation of these issues might have a bearing on programs of remediation following brain injury.

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Fig. 1.
Non-word–picture pairs used in word learning task.

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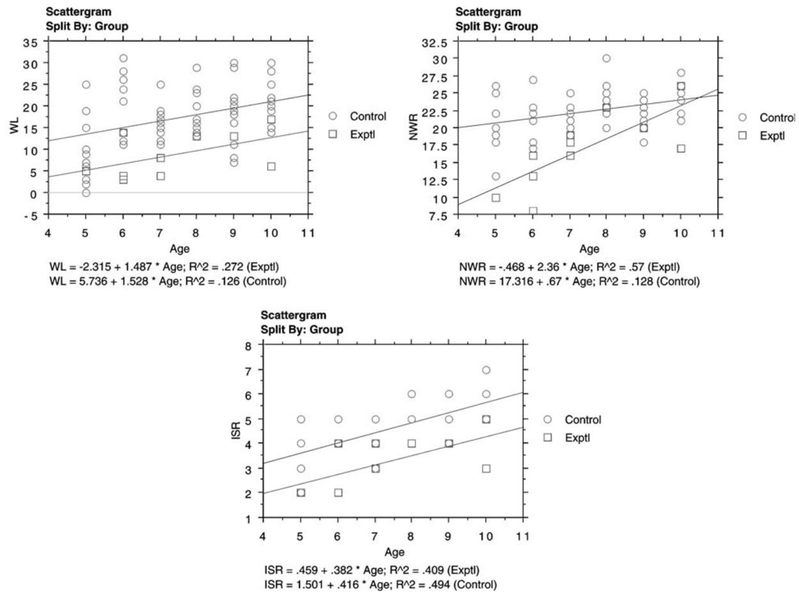

Fig. 2.

Regression lines for word learning (WL), non-word repetition (NWR), and immediate serial recall (ISR), for experimental and control groups.

Table 1

Neurological profiles of children in the experimental group, as reported in MacWhinney et al. (2000), except for JL

Code	Age	Description of lesion
STEW	5	Tissue loss along the left central sulcus involving the posterior left frontal cortex and anterior left parietal area
ELS	6	Small lesion in the left parietal white matter
JL	6	Right hemiparesis, with damage to left frontal cortical tissue
JOR	6	Damage to left dorsolateral prefrontal cortex and nearby areas, including Broca’s area; enlarged left ventricle
DUP	7	Enlargement of both lateral ventricles, L>R. Reduction in white matter in left periventricular region, in the areas anterior and posterior to the ventricle
RYB	7	Left lateral inferior frontal loss, affecting Broca’s area and dorsolateral prefrontal cortex; enlargement of left lateral ventricle, probable compensation for volume loss
MAM	7	Enlargement of left ventricle centrally with thinning of left white matter (corona radiata, centrum semiovale, and corpus callosum)
DAC	8	Enlargement of the left lateral ventricle engulfing most of parietal and much of occipital lobe. A thin parietal mantle remains, along with a somewhat larger occipital mantle. Some enlargement of right lateral ventricle
KAM	10	Left lateral/posterior/inferior frontal loss, adjacent to insula, sparing motor strip; left lateral/anterior parietal loss and some loss of the left insula
DES	10	Enlargement of the left ventricle. White matter loss underneath the entire left cortex, with some retrograde white matter loss
TID	10	Enlargement of the left lateral ventricle into posterior cortical areas

Gathercole & Baddeley, 1989, 1990a), which employed a simple binary scoring criterion for non-word repetition, and did not further analyze childrens’ errors.

Table 2

Performance on experimental measures: Word learning, nonword repetition, and immediate serial recall

		Control group		Participant	
Participant	**Age**	**Mean**	***SD***	**Raw score**	***z*-Score**
Word learning					
STEW	5	9.600	7.947	5.000	−0.579
ELS	6	20.273	8.101	14.000	−0.774
JL	6	20.273	8.101	4.000	*−2.009
JOR	6	20.273	8.101	3.000	*−2.132
DUP	7	15.500	3.798	8.000	*−1.975
RYB	7	15.500	3.798	4.000	*−3.028
MAM	7	15.500	3.798	8.000	*−1.975
DAC	8	18.154	4.598	13.000	−1.121
KAM	9	18.333	7.190	13.000	−0.742
DES	10	21.300	5.165	6.000	*−2.962
TID	10	21.300	5.165	17.000	−0.833
Non-word repetition					
STEW	5	19.444	4.558	10.000	*−2.072
ELS	6	22.546	3.417	16.000	*−1.916
JL	6	22.546	3.417	13.000	*−2.794
JOR	6	22.546	3.417	8.000	*−4.257
DUP	7	21.643	1.823	19.000	−1.450
RYB	7	21.643	1.823	16.000	*−3.095
MAM	7	21.643	1.823	18.000	*−1.998
DAC	8	23.769	2.351	23.000	−0.327
KAM	9	22.417	2.021	20.000	−1.196
DES	10	24.000	2.261	17.000	*−3.096
TID	10	24.000	2.261	26.000	0.885
Immediate serial recall					
STEW	5	3.300	0.949	2.000	−1.370
ELS	6	4.182	0.405	4.000	−0.449

Participant	Age	Control group		Participant	
		Mean	*SD*	Raw score	*z*-Score
JL	6	4.182	0.405	2.000	*−5.394
JOR	6	4.182	0.405	2.000	*−5.394
DUP	7	4.357	0.633	3.000	*−2.143
RYB	7	4.357	0.633	3.000	*−2.143
MAM	7	4.357	0.633	4.000	−0.564
DAC	8	5.308	0.480	4.000	*−2.722
KAM	9	4.917	0.669	4.000	−1.371
DES	10	5.600	0.699	3.000	*−3.719
TID	10	5.600	0.699	5.000	−0.858

Table 3

Experimental group

Age	STEW	ELS	JL	JOR	DUP	RYB	MAM	DAC	KAM	DES	TID	Mean Z
	5	6	6	6	7	7	7	8	9	10	10	
WL-Z	−.579	−.774	*−2.009	*−2.132	*− 1.975	*−3.028	*− 1.975	−1.121	−0.742	*−2.962	−.833	−1.648
NWR-Z	*−2.072	*−1.915	*−2.793	*−4.257	−1.450	*−3.095	*−1.998	−.327	−1.196	*−3.096	.885	−1.938
ISR-Z	−1.370	−.449	*−5.394	*−5.394	*−2.143	*−2.143	−.564	*−2.722	−1.371	*−3.719	−.858	−2.375
LEITER-Z	−.533	.667		−.467	1.133	1.400	−.533	−.333	.467	*−2.533	−.400	−.113
PPVT-Z	−1.533	.067		−.600	.533	−.333	−.133	−1.267	−.200	*−1.667	.667	−.447
CELF-RS-Z	−1.333	−.333		*−2.333	−.333	−1.000	−1.000	.333	−1.333	*−1.667	1.000	−.800
CELF-OD-Z	−.333	*− 1.667		−1.333	*−2.000	−.333	*−2.333	−.667	−.667	*−2.000	.333	−1.100
CELF-FS-Z	−1.000	−1.000		*−2.333	*−2.333	−1.333	*−2.000	−1.333	−1.333	*−2.000	2.333	−1.233

Comparison of z-scores in performance on experimental tasks in the present study with z-scores in performance on a variety of standardized tests. Scores on the standardized tests were previously reported in MacWhinney et al. (2000), except for one child (JL), for whom these data were not available.

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Table 4

Correlations between non-word repetition, word learning, and digit span: Comparison of present results with developmental data from Gathercole et al. (1992, for ages 4–8), and Gathercole et al. (1999, for age 13)

Correlation between		Gathercole et al.				Correlation between	Present experiment (5–10 years)	
		4 years	5 years	8 years	13 years		Experimental	Control
Span & CNRep	Simple correlation	0.524[b]	0.667[b]	0.445[a]	0.320[b]	Span & NWR	0.891[d]	0.522[d]
	Age partialled						0.828[c]	0.406*
	Age, non-verbal partialled						0.658[a]	
Span & Vocab	Simple correlation	0.284[a]	0.376[b]	0.355[b]	0.450[b]	Span & WL	0.898[d]	0.447[d]
	Age partialled						0.870[c]	0.305[a]
	Age, non-verbal partialled	0.107	0.122	0.266[a]	0.390[b]		0.804[c]	
Vocab & CNRep	Simple correlation	0.413[b]	0.419[b]	0.284[a]	0.390[b]	WL & NWR	0.798[b]	0.657[d]
	Age partialled						0.752[b]	0.615[d]
	Age, non-verbal partialled	0.397[b]	0.387[b]	0.151	0.370[b]		0.600	

[a] $P < :05$.

[b] $P < :01$.

[c] $P < :005$.

[d] $P < :001$.