Journal of Child Psychology and Psychiatry 46:6 (2005), pp 598–611 doi: 10.1111/j.1469-7610.2004.00379.x

Developmental consequences of poor phonological short-term memory function in childhood: a longitudinal study

Susan E. Gathercole,[1] Claire Tiffany,[2] Josie Briscoe,[3] Annabel Thorn,[2] and The ALSPAC team[2]

[1]University of Durham, UK; [2]University of Bristol, UK; [3]Cardiff University, UK

Background: A longitudinal study investigated the cognitive skills and scholastic attainments at 8 years of age of children selected on the basis of poor phonological loop skills at 5 years. **Methods:** Children with low and average performance at 5 years were tested three years later on measures of working memory, phonological awareness, vocabulary, language, reading, and number skill. **Results:** Two subgroups of children with poor early performance on phonological memory tests were identified. In one subgroup, the poor phonological memory skills persisted at 8 years. These children performed at comparable levels to the control group on measures of vocabulary, language and mathematics. They scored more poorly on literacy assessments, but this deficit was associated with group differences in complex memory span and phonological awareness performance. The second subgroup of children performed more highly on phonological memory tests at 8 years, but had enduring deficits in language assessments from 4 to 8 years. **Conclusions:** Persistently poor phonological memory skills do not appear to significantly constrain the acquisition of language, mathematics or number skills over the early school years. More general working memory skills do, however, appear to be crucial. **Keywords:** Working memory, short-term memory, phonological awareness, vocabulary, language, mathematics, literacy.

There is now substantial evidence linking poor phonological short-term memory skills during childhood with specific difficulties in acquiring language and scholastic abilities. In studies of unselected samples, young children's scores on phonological memory tests such as digit span and nonword repetition have consistently been shown to be closely related to vocabulary knowledge both in the native language (Avons, Wragg, Cupples, & Lovegrove, 1998; Bowey, 2001; Gathercole & Baddeley, 1989; Gathercole, Service, Hitch, Adams, & Martin, 1999; Gathercole, Willis, Emslie, & Baddeley, 1992; Michas & Henry, 1994) and in second languages (e.g., Dufva & Voeten, 1999; Service, 1992; Service & Kohonen, 1995). Children with low phonological memory scores also perform relatively poorly in learning unfamiliar phonological structures under controlled laboratory conditions (Gathercole & Baddeley, 1990a; Gathercole, Hitch, Service, & Martin, 1997; Michas & Henry, 1994).

Links between phonological memory and word learning extend to a number of special developmental populations. Severe deficits on phonological memory tasks are characteristic of Specific Language Impairment, a disorder of language development in the absence of general intellectual or sensory problems (e.g., Bishop, North, & Donlan, 1996; Bishop, Bishop, Bright, James, Delaney, & Tallal, 1999; Gathercole & Baddeley, 1990b; Montgomery, 1995). Down's syndrome is another developmental condition characterised by poor vocabulary knowledge and impairments of phonological memory skills relative to general abilities (Hulme & Mackenzie, 1992; Jarrold, Baddeley, & Hewes, 1999, 2000; Laws, 1998; Mackenzie & Hulme, 1987; Wang & Bellugi, 1994). A complementary profile is provided by William's syndrome. Individuals with this rare genetic disorder have severe deficits in spatial cognition, but perform relatively well on tests of both phonological short-term memory and vocabulary knowledge (Wang & Bellugi, 1994; Jarrold et al., 1999; Grant et al., 1997). On the basis of this evidence and convergent findings from experimental studies of word learning in adults (e.g., Papagno, Valentine, & Baddeley, 1991), it has been proposed that the primary function of phonological short-term memory is to support the long-term learning of the phonological structure of the language (Baddeley, Gathercole, & Papagno, 1998). According to this view, individuals with inadequate short-term memory skills will experience difficulties in learning the sound structure of new words, although the non-phonological aspects of their vocabulary acquisition may be entirely normal.

Compromised phonological short-term memory skills have been linked with several other aspects of language processing and learning. First, there are reports that the spontaneous production of speech in children with poor short-term memory function is characterised by relatively short utterance lengths (Adams & Gathercole, 1995, 1996; Blake, Austin, Cannon, Lisus, & Vaughan, 1994), immature syntax

Published by Blackwell Publishing, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA

(Speidel, 1989) and low vocabulary diversity (Adams & Gathercole, 1995). This raises the possibility that at least in the early years when language production processes may not be fully automatised, phonological short-term memory may play a crucial role in buffering the phonological structure of speech prior to output as well as contributing to the learning of vocabulary and syntax. Second, there is evidence that phonological short-term memory is involved in the storage and processing of sentences, in both adults (Martin, Lesch, & Bartha, 1999) and children (Hanten & Martin, 2001; Willis & Gathercole, 2001). Third, significant associations between short-term memory skills and reading development have frequently been observed (e.g., Dufva et al., 2001; de Jong & van der Leij, 1999; Garlock, Walley, & Metsala, 2001; Griffiths & Snowling, 2002; Muter & Snowling, 1998). Finally, phonological short-term memory has also been linked with the development of mathematical computation skills (e.g., Fazio, 1999; Hecht, Torgesen, Wagner, & Rashotte, 2001), and with mental arithmetic in particular (Lee & Kang, 2002; Seitz & Schumann-Hengsteler, 2000).

Despite this wealth of correlational evidence, the practical consequences of deficits in phonological short-term memory for learning and scholastic attainment during early and middle childhood remain largely unknown. Children with developmental pathologies such as Specific Language Impairment and Down's syndrome that are associated with inadequate phonological memory skills have many other cognitive deficits that may lie at the root of their learning difficulties. And in the majority of studies in which children with no known developmental pathologies are selected for their poor phonological short-term memory skills, there has been little detailed assessment of their other cognitive skills. It is therefore unclear whether the impairments found in language and other learning domains result directly from phonological memory deficits, or are instead the consequences of other associated cognitive deficits.

This article reports findings from a study designed to provide a longitudinal evaluation of language abilities, scholastic attainments, and other cognitive skills of children with low scores on measures of phonological short-term memory at 5 years of age. Children with either very low or normal range performance on tests of phonological memory at 5 years of age were selected to participate in the study. The cognitive skills of the children were tested again at 8 years on measures of short-term memory, working memory and phonological awareness. Their learning achievements were assessed in the areas of vocabulary, language processing, mathematics, and literacy. Retrospective data relating to language and cognitive abilities were also available from previous longitudinal assessments of this cohort. These measures were verbal and performance IQ at 4 years, digit span at 4 and 5 years, nonword repetition at 5 years, language comprehension scores on the Reynell Developmental Language Scales at 5 years (Reynell, 1977), and a test of phonological awareness involving detection of initial consonants at 5 years (Byrne & Fielding-Barnsley, 1993).

A major aim of the study was to establish whether children with poor phonological memory skills have other associated cognitive impairments that could underlie any low achievements found in the domains of language, mathematics, and literacy. One specific issue concerns whether or not their poor short-term performance extends to other components of working memory. A large body of evidence converges on the view that short-term memory is fractionated into a number of separable but interacting subsystems (for reviews, see Baddeley & Logie, 1999; Vallar & Papagno, 2002). The most complete account of short-term memory is provided by Baddeley and Hitch's (1974) working memory model, comprising three temporary memory systems. The central executive is a limited capacity system responsible for the coordination of storage and retrieval within working memory and long-term memory systems, and has been suggested to contribute to tasks that place concurrent demands on processing and storage (e.g., Just & Carpenter, 1992). The phonological loop is specialised for the temporary storage of phonological material, and is assumed to support performance on measures of phonological short-term memory such as digit span and nonword repetition (e.g., Gathercole, Willis, Emslie, & Baddeley, 1994). The visuo-spatial sketchpad maintains material in terms of its visual or spatial characteristics. Recently, Baddeley (2000) has added a fourth component to the model: the episodic buffer, responsible for integrating memory representations across different domains and memory systems.

Previous studies of children with poor performance on measures of phonological memory typically have typically not assessed either central executive or visuo-spatial memory skills. Although phonological and visuo-spatial memory skills are uncorrelated in the middle childhood years (Pickering, Gathercole, & Peaker, 1998), measures of phonological loop and central executive function are typically highly associated although functionally separable (Gathercole & Pickering, 2000a; Gathercole, Pickering, Ambridge, & Wearing, 2004; Pickering & Gathercole, 2001). Thus children with low phonological memory scores are likely also to perform poorly on tasks tapping the central executive. Impairments on complex memory span tasks associated with the central executive have been found in children with poor attainments in mathematics (Hitch & McAuley, 1991; Mayringer & Wimmer, 2000; Siegel & Ryan, 1989) and in literacy (de Jong, 1998; Siegel & Ryan, 1989; Swanson & Alexander, 1997; Gathercole & Pickering, 2000b), and in children recognised by their schools as having special educational needs (Gathercole & Pickering, 2001; Pickering & Gathercole, 2004). It is therefore possible that impairments of the central executive rather than the phonological loop may lie at the root of the learning and language processing difficulties of children who score poorly on measures of phonological short-term memory.

Phonological short-term memory skills have also consistently been found to be closely associated with phonological awareness, the ability to represent and manipulate the phonological structure of language (Bowey, 1996; Gathercole, Willis, & Baddeley, 1991; McDougall, Hulme, Ellis, & Monk, 1994; Metsala, 1999). Interpretation of this relationship has been the subject of considerable debate. According to one view, phonological memory and awareness measures tap a common phonological coding or processing substrate (e.g., Bowey, 1996; Dufva et al., 2001; Garlock, Walley, & Metsala, 2001; Griffiths & Snowling, 2002; Metsala, 1999). An alternative view is that the two types of measures are distinguished in that verbal short-term memory tasks provide more direct indices of the quality of underlying phonological representations whereas awareness tasks rely on a more general metalinguistic awareness of phonological structure (Windfuhr & Snowling, 2001). A third account is that phonological memory and awareness are both constrained by the adequacy of phonological processing skills, but that they also tap distinctive mechanisms involving the phonological loop and metalinguistic analysis, respectively (e.g., Gathercole et al., 1991; Hecht et al., 2001; Muter & Snowling, 1998). Aside from these detailed theoretical considerations, it is crucial for interpretation of the findings of the present study to establish whether children with poor phonological memory scores also have weak phonological awareness skills that may be in part at least the cause of their learning difficulties.

The study also provided the opportunity to test whether the developmental period over which poor phonological short-term memory performance extends has direct consequences for children's attainments in the areas of language, mathematics and literacy. It was anticipated that children selected on the basis of low scores on phonological memory tests at 5 years would vary in their performance on corresponding measures administered at 8 years: while some children may show enduring memory deficits spanning the three-year period, other children may show marked improvements in phonological memory function. If phonological memory skill is a significant determinant of learning during these middle childhood years, attainment levels at 8 years should be lower for children with poor phonological memory skills that extended over the three-year period from 5 to 8 years. This phonological memory severity hypothesis was tested by assessing the relationships between attainment scores and phonological memory scores at age 8 in this group.

Method

Participants

The participating children were members of the Children in Focus study, a subgroup of approximately 10% of the cohort participating in the Avon Longitudinal Study of Parents and Children (ALSPAC). ALSPAC is an in-depth prospective longitudinal study of 14,150 children and parents that started in pregnancy, with the aim of monitoring the child's health and development through childhood (http://www.alspac.bris.ac.uk/ALSPACext/Default.html). Detailed demographic data on the children and their families have been recorded in the course of the study. The mother's highest educational qualification at the time of initial recruitment to the Children in Focus study was recorded for the majority of the children, and coded as either 0 (no qualifications), 1 (CSE or GSCE grades D, E, F or G), 2 (qualifications in shorthand/typing or other skills, e.g., hairdressing/apprenticeships/City & Guilds intermediate technical), 3 (O-level or GCSE grades A, B or C), 4 (1 or more A-levels/registered nurse/City & Guilds final or full technical/teaching qualification), or 5 (university degree).

Each child participated in a day of testing at two specific Children in Focus clinics (48 and 60 months) at which they were tested on a variety of physical and intellectual tasks. The tasks for which data are reported in this article are outlined below. The assessments at the age 4 clinic included the Wechsler Preschool & Primary Scale of Intelligence R -UK (WPPSI, Wechsler, 1990), and digit span (WPPSI). At age 5 clinic, the children were tested on the comprehension subtest of the Reynell Developmental Language Scales (1977) and two measures of phonological short-term memory: digit recall and nonword repetition. The digit recall procedure involved the presentation of spoken sequences of digits for immediate serial recall, using the stimuli and method employed by Gathercole and Pickering (2000a). Following a practice session, a maximum of four lists were presented at each length, starting with two-item sequences; if the first three lists at a particular sequence length were correctly recalled, the list length was increased by one. Items were presented at a rate of one every 750 ms. The number of lists correctly recalled by the child (with credit for three lists at a particular length being given if the child correctly recalls the first two) was scored. A test–retest reliability correlation coefficient for digit span of .68 was obtained in a study of 70 four- and five-year old children (Gathercole, 1995). The Children's Test of Nonword Repetition (Gathercole & Baddeley, 1996) involves the spoken presentation (via an audio cassette) of 40 nonwords ranging in length from two to five syllables. The child attempts to repeat each nonword following its presentation, and the total number of nonwords correctly repeated is scored. The test–retest reliability correlation coefficient in a sample of five- and six-year-old children was .81.

A total of 926 children completed both the digit recall and the nonword repetition tests. *Z*-scores for each measure were averaged to produce a composite phonological short-term memory score at 5 years. Ninety-five children met the following criteria for inclusion in the phonological memory deficit group: i) a *z*-score score of

−1.33 or less on one of the individual measures, ii) a composite score of −1.00 or below, iii) gestational age at birth at least 37 weeks; iv) English as the child's first language, v) maternal education levels recorded, vi) WPPSI (Wechsler, 1990) scores at 4 years recorded. The target number of children in the phonological memory deficit group was 40, and a 50% success rate in recruitment was anticipated. On this basis 85 children were invited to attend a day of further testing at the University of Bristol at 8 years of age. The first 42 children whose parents/guardians consented to participation attended the testing sessions. The data from three children who failed to complete all of the assessments were not included in the statistical analyses. The mean phonological memory scores at 5 years of the remaining 39 children were as follows (with data from the larger group of 95 initially identified as having low phonological memory scores in parentheses): for digit recall, mean = 8.97 with *S.D.* 2.18 (mean 7.91, *S.D.* 2.41); for nonword repetition, mean = 5.82 with *S.D.* 4.26 (mean 7.21, *S.D.* = 4.44). The mean level of maternal education was 3.15 (*S.D.* .99) for the 39 children tested at 8 years, and 3.05 (*S.D.* 1.07) for the larger group of 95. The participating children were therefore representative of the larger sample of children identified as having low phonological memory scores at 5 years.

In order to distinguish children with poor phonological memory performance at 5 years only from those with deficits persisting from 5 to 8 years, the children with low phonological memory scores at 5 years were classified as belonging to one of two subgroups on the basis of their performance on the Working Memory Test Battery for Children (WMTB-C, Pickering & Gathercole, 2001) at 8 years of age. In order to maintain comparability with the selection criteria applied to the memory scores at 5 years, children were assigned to the 'persistent phonological memory deficit' subgroup (persistent PMD) if they obtained standard scores of 85 or less (equivalent to 1 S.D. or more below the mean) on at least two of the four phonological loop measures.[1] Fifteen children met this criterion: 5 girls and 10 boys, with a mean chronological age at testing of 8 years 7 months (*S.D.* = 1.66 months, range = 8 years 2 months to 8 years 8 months). Of this subgroup, one child had no recorded verbal IQ score at 4 years, and four children failed to complete the digit span test at 4 years. The mean maternal education level of the group was 3.20 (*S.D.* = 1.01).

The remaining 24 children who failed to meet the criterion were assigned to the 'early phonological memory deficit only' subgroup (early PMD only). This subgroup consisted of 12 boys and 12 girls, with a mean age at testing of 8 years 5 months (*S.D.* = 1.71 months, range = 8 years 1 month to 8 years 9 months). Two of the children failed to complete the digit span test at 4 years. The mean maternal education level of the group was 3.13 (*S.D.* = .99). All children in both PMD subgroups (early and persistent) obtained standard score of 86 or greater calculated the Raven's Progressive Matrices test of nonverbal ability (Raven, 1986) administered at 8 years.

The control group was selected from the children participating in the Children in Focus clinic at 5 years who met the following criteria: i) digit recall and nonword repetition *z*-scores above −1.00 (for both measures), ii) standard scores of 85 or above on all four phonological loop measures of the WMTB-C (Pickering & Gathercole, 2001), iii) gestational ages at birth of at least 37 weeks, iv) English as their first language, v) maternal education levels recorded, vi) performance IQ score at 4 years recorded. The parents/guardians of 80 children were invited to participate in the testing at 8 years, and the first 46 children for whom consent was obtained were tested. For the purposes of analysis, a control group of 15 children matched with the persistent PMD subgroup on the basis of sex, age in months, maternal education level, and performance IQ at 4 years were selected. Matching on performance IQ provided a means of equating general nonverbal ability in the two groups. The mean chronological age of the control group was 8 years 5 months (*S.D.* = 2.54 months, range = 8 years 2 months to 8 years 9 months). The mean maternal education level of the group was 3.13 (*S.D.* = .83).

Procedure

Each child, accompanied by a caregiver, attended a one-day testing session in the Child Development Laboratory at the University of Bristol at 8 years of age. The child was tested in a quiet room free from distractions. The schedule of testing was held constant for each child as far as possible, although some *ad hoc* reordering of tests was occasionally necessary to engage the child's attention. The procedures for individual tests are described below.

Working memory. Six tests from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) were administered to each child. The three phonological loop tests were word list recall (recall of spoken lists of monosyllabic words), nonword list recall (recall of spoken lists of monosyllabic nonwords), and digit list recall (recall of spoken lists of digit names).

Two measures of the central executive were also included: backwards digit recall, and listening recall. The backwards digit recall task involved the child attempting to repeat a spoken sequence of digits in reverse order on each trial. In the listening recall test, the child heard on each trial a sequence of simple spoken statements to which they had to reply 'true' or 'false', and then attempted to recall the final word of each sentence in the sequence in which the sentences were presented. The final test was block recall, a test of visuo-spatial short-term memory. The children saw the experimenter tap a sequence of blocks arranged unsystematically in a three-dimensional array, and attempted to reproduce the sequence in the same order.

In each of these tests, sequence lengths increased across trials until the child made more than one error in the four trials at a particular level of difficulty. Testing was then discontinued. The number of trials correct was scored in each case.

[1] For comparison, the proportions of children from the standardisation sample of 636 children for the WMTB-C (Pickering & Gathercole, 2001) obtaining standard scores of 85 or less on the four measures were as follows: digit recall, .15; word recall, .15; nonword recall, .17, word list matching, .17.

Phonological awareness. Two tests of phonological awareness were given, onset oddity detection and end oddity detection. On each trial of the onset oddity detection task, the child viewed an array of four black and white line drawings each depicting a familiar monosyllabic word. The child's task was to identify the word that did not share the same initial phoneme as the three remaining items. On each trial, three of the four words belonged to a common semantic category; the odd word out was always a member of this category. Four practice trials preceded 12 experimental trials. The first eight experimental trials used the stimuli constructed by Stuart and Coltheart (1988), such as *cow*, *cup*, *cat*, *dog*. A further four more difficult trials were added in which the child needed to detect either an initial consonant cluster versus no cluster (e.g., *twenty*, *ten*, *twelve*, *twig*) or to differentiate initial consonant clusters (e.g., *climb*, *creep*, *crawl*, *crow*). Stimuli are listed in the Appendix.

The end oddity task developed by Kirtley, Bryant, Maclean, and Bradley (1989) was also administered to each child. Children received two practice trials and eight experimental trials were given, in each of which the experimenter spoke aloud three familiar CVC words, each of which shared a common vowel and two of which shared a common consonant (e.g., *hat*, *fat*, *man*). The child's task was to identify the word that did not share the common final consonant. The number of correct trials was scored for each child.

Attainment measures

Vocabulary. Two measures of vocabulary knowledge were administered to each child. The Long Form of the British Picture Vocabulary Scale II (BPVS, Dunn, Dunn, Whetton, & Burley, 1997) provides a measure of receptive vocabulary in which the child on each trial has to point to the picture (from a choice of four) that corresponds to a word named by the experimenter. Both raw and standard scores (with a mean of 100 and a standard deviation of 15) were obtained for each child.

The Word Definitions subtest of the Wechsler Intelligence Scales for Children-Revised^{UK} (Wechsler, 1986) requires the child to explain the meaning of words named by the experimenter. The quality and specificity of the definition is scored. Raw and scaled scores (with a mean of 10 and a standard deviation of 3) were obtained for each child.

Language. The Listening Comprehension and Oral Expression subtests of the Wechsler Objective Language Dimensions (WOLD; Wechsler, 1996a) were administered to each child. The Listening Comprehension subtest has two components: receptive vocabulary (assessed by picture pointing) and passage comprehension. The Oral Expression subtest is designed to assess the child's use of non-imitative expressive language. This involves, for example, detailed descriptions and logical sequences of information. Both raw and standard scores (mean of 100, standard deviation of 15) are calculated for each subtest.

Number. Knowledge and skills relating to number were assessed using the Wechsler Objective Numerical Dimensions (WOND; Wechsler, 1996b). Two subtests, Mathematical Reasoning and Numerical Operations, were administered to each child. The Mathematical Reasoning subtest involves both visual and verbal presentation of problem information, and assesses problem solving relating to number, numeration and number concepts, and a variety of more advanced mathematical abilities. The Numerical Operation subtest is visually based, and assesses skills in mathematical computation; it involves addition, subtraction, multiplication, and division. Both subtests yield a raw score and a standard score with a mean of 100 and a standard deviation of 15 are calculated for each subtest.

Reading. Each child was tested on the Wechsler Objective Reading Dimensions (WORD; Wechsler, 1993). The test has three components. Basic Reading involves the child reading aloud single words of increasing difficulty, and measures decoding and word recognition skills. The Spelling subtest requires the child to spell words spoken by the experimenter. Reading Comprehension involves reading one or more passages of text, and answering printed questions related to the text. Each of the three subtests yields a raw score and a standard score with a mean of 100 and a standard deviation of 15.

Results

Cognitive skills measures

Table 1 summarises scores on the principal measures for the three groups (early PMD, persistent PMD, and control). The probability values yielded by the univariate *F*-tests for each pairwise group comparison are also shown in the table. Mean standard scores on the WMTB-C (Pickering & Gathercole, 2001) as a function of group are shown in Figure 1.

Consider first comparisons between the two phonological memory deficit groups: early PMD (with deficits only at 5 years) and persistent PMD (deficits at both 5 and 8 years). The early PMD group performed significantly better than the persistent PMD group on all phonological loop measures ($p < .05$ in each case), with a phonological loop standard score of 95.10 compared to 82.13. The two groups did not differ significantly on any other memory scores. More surprisingly, the early PMD group obtained lower verbal IQ scores at 4 years (with a mean standard score of 87.96) than the persistent PMD group (mean 96.14). This difference was significant by univariate *F*-test ($p < .05$). The two PMD groups did not differ significantly on either of the two nonverbal ability measures, performance IQ at 4 years, and Raven's CPM at 8 years ($p > .05$). No other group differences were found in measures at ages 4, 5 or 8 years.

The early PMD group differed from the control group on a range of measures. First, group differences were found on the majority of phonological memory measures: digit recall at ages 4, 5 and 8 years ($p < .001$ in each case), nonword repetition

Table 1 Descriptive statistics (means and SDs) for the three groups on cognitive assessments at 4, 5 and 8 years, with probability values for subgroup comparisons

			Group						Group comparison (p)		
			Early PMD n = 15		Pers. PMD n = 24		Control n = 15				
Age	Area of assessment	Measure	Mean	S.D.	Mean	S.D.	Mean	S.D.	Early & pers. PMD	Early PMD & control	Pers. PMD & control
4	IQ	Verbal IQ∞	87.96*†	12.68	96.14	7.63	99.13	14.56	.035	.018	ns
		Performance IQ∞	99.63	9.69	101.07	7.49	100.87	10.75	ns	ns	ns
	Phon. STM	Digit recall	7.64†	3.39	7.18†	1.78	11.42	4.81	ns	.000	.012
5	Language	Reynell Language	57.61	5.41	60.60	3.29	60.07	3.03	ns	ns	ns
	Phon. STM	Digit recall	8.55†	2.61	8.16†	2.66	13.13	2.90	ns	.000	.000
		Nonword rep.	5.55†	3.90	6.87†	4.67	22.33	5.14	ns	.000	.000
	Phon. Awareness	Init.con.det.	7.33	1.88	7.13	2.56	7.87	2.67	ns	ns	ns
8	Nonverbal ability	Raven's CPM	23.75	4.11	25.00	3.57	25.53	4.05	ns	ns	ns
	Phon. STM	Digit recall	25.42*†	2.57	22.07†	1.39	30.40	5.42	.000	.000	.000
		Word recall	17.29*†	1.99	15.07†	2.18	20.93	4.28	.002	.001	.000
		Nonword recall	11.54*†	2.45	8.87†	1.96	13.47	3.33	.001	.045	.000
		Word matching	22.37*	6.10	18.20	3.57	22.53	8.25	.022	ns	ns
		Phon. Loop∞	95.10*†	5.33	82.13†	5.25	107.00	14.38	.000	.001	.000
	Complex span	Listening recall	9.58†	2.72	10.67	2.72	11.73	2.03	ns	.027	ns
	(working memory)	Back. digit recall	10.83	2.82	10.20	2.70	13.00	6.15	ns	ns	ns
		Complex memory∞	93.39†	11.05	94.23†	8.50	103.33	14.91	ns	.022	.050
	Spatial STM	Block recall	23.87	4.82	22.33	4.37	23.47	4.56	ns	ns	ns
	Phon. Awareness	Onset oddity	9.42†	1.61	8.87†	2.13	10.53	1.51	ns	.038	.020
		End oddity	6.58	1.28	6.00	1.13	7.07	1.75	ns	ns	ns

∞Standard score.
*$p < .05$, compared with persistent PMD group.
†$p < .05$, compared with control group.

at 5 years ($p < .001$), word recall at 8 years ($p < .005$), and nonword recall at 8 years ($p < .05$). No significant group difference was found on the word list matching task at 8 years ($p > .05$). The early PMD group also obtained significantly lower scores on the listening recall complex memory task ($p < .05$), and overall on the complex span composite measure ($p < .05$). Verbal IQ scores were significantly lower in the early PMD than control group (87.96 compared and 99.13, respectively, $p < .05$). A final task on which the early PMD group showed significantly poorer performance than the control group was the onset oddity phonological awareness measure administered at 8 years ($p < .05$).

Comparisons of the persistent PMD and control groups established that the persistent PMD children scored more poorly on all phonological loop measures at 4, 5 and 8 years (at the 5% level or below) with the exception of word list matching ($p > .05$). Composite complex span scores were also lower for the persistent PMD than the control group (94.23 and 103.33, respectively, $p = .05$), although neither of the two individual complex span measures yielded a significant group difference ($p > .05$ in both cases). Finally, the persistent PMD group performed at a significantly lower level on the onset oddity task at 8 years ($p < .05$). The persistent PMD and control groups did not differ significantly on either verbal IQ at 4 years or the nonverbal ability measure (Raven CPM) at 8 years ($p > .05$ in both cases).

Relationships between cognitive skills and attainment scores

It is evident from the results reported above that although the persistent PMD group showed a greater deficit in scores on phonological memory measures at 8 years than the early PMD group, some aspects of the performance of the two groups on other measures did not reflect a simple gradient of severity of phonological memory deficit. In particular, the early PMD group (who performed more highly on the phonological loop measures at 8 years than the persistent PMD group) had lower verbal IQ scores at 4 years than both the persistent PMD and control groups, and also performed more poorly than the control group on the listening recall complex memory task, whereas no significant corresponding deficit was found for the persistent PMD group. Lower phonological memory scores at 8 years were therefore associated with higher performance on these measures. In order to check on potential non-linearities in the relationship between phonological memory scores at 8 years in the two PMD groups and attainment levels, a correlation matrix was constructed for the two PMD subgroups combined ($n = 39$). This matrix included the composite phonological loop and complex memory scores, language and nonverbal ability measures, and standard scores on the attainment measures. In addition, an interaction term for the two PMD groups was obtained from the product of the phonological standard scores and

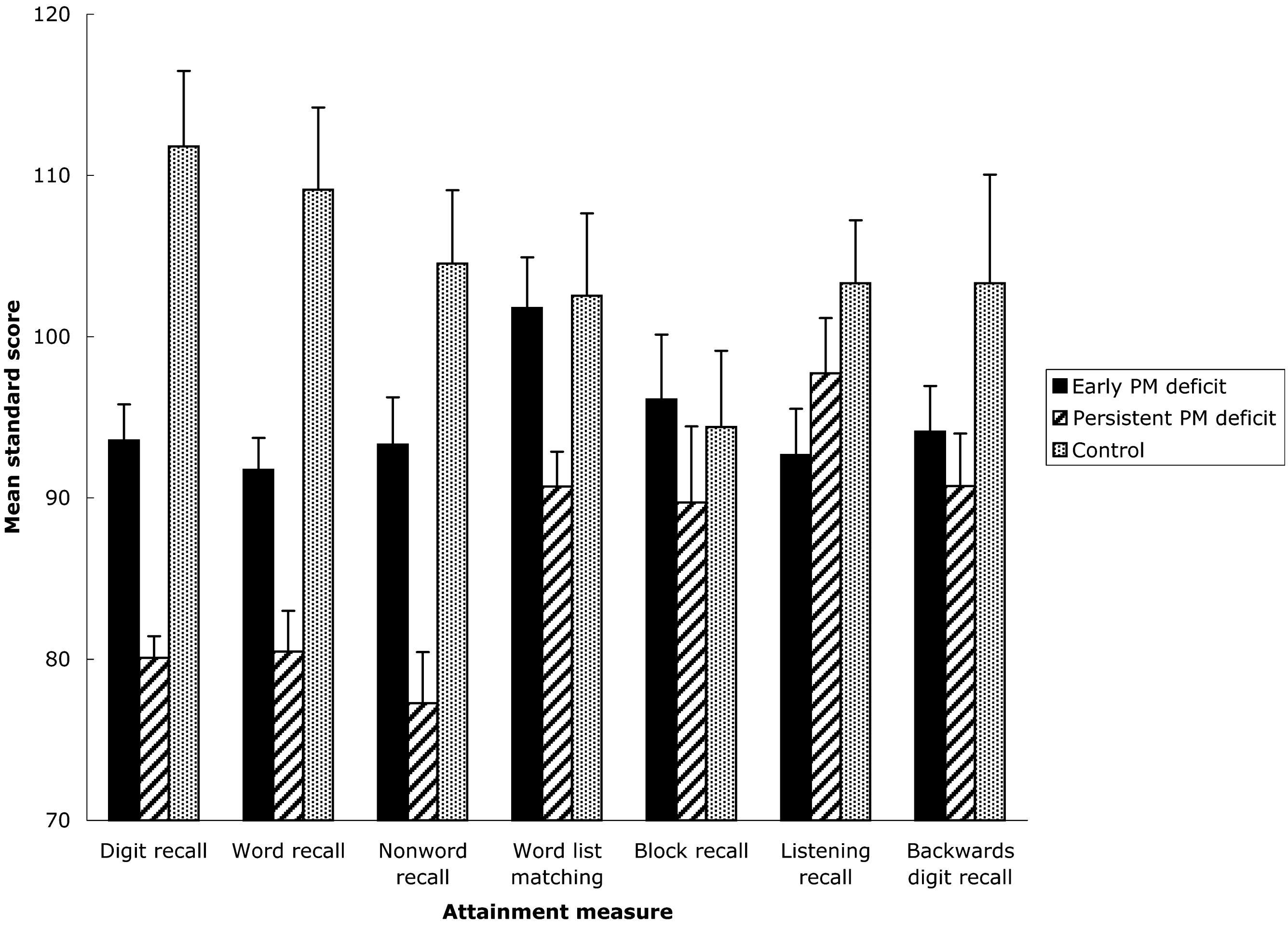

Figure 1 Mean standard scores on the working memory subtests as a function of group, with standard error bars

Table 2 Correlations between princiapl measures for children with poor phonological memory scores at 5 (n = 39)

No.	Measure	1	2	3	4	5	6	7	8	9	10	11
1	Verbal IQ 4	–										
2	Perf. IQ 4	.274**	–									
3	Reynell language 5	.666**	.277	–								
4	Raven nonverbal 8	.130	.396*	.273	–							
5	Vocab composite 8	.471**	.275	.478**	.315	–						
6	WOLD language 8	.366*	.075	.403**	.213	.694**	–					
7	WOND number 8	−.128	.279	.124	.541**	.300	.222	–				
8	WORD reading 8	−.028	.219	.223	.299	.482**	.283	.382*	–			
9	Phon. STM 8	−.154	.002	-.089	.051	−.023	.025	.115	.295	–		
10	Phon. STM8*gp	.387*	.080	.350*	.202	.516**	.439**	.039	−.036	-.625	–	
11	Complex memory 8	−.029	.171	.243	.290	.204	.330*	.486**	.564**	.154	.081	–
12	Phon. awareness 8	.098	.132	.051	.181	.250	.269	.211	.479**	.309	−.194	.247

*$p < .05$.
**$p < .01$.

group membership (1 for early PMD, 2 for persistent PMD). A composite phonological awareness score was also calculated by averaging *z*-scores for the onset and end oddity measures. The correlation matrix is shown in Table 2. It is notable that although the phonological memory scores at 8 years show no significant correlations with other measures, the interaction term (PhonSTMgp) was significantly correlated with a range of language measures: verbal IQ at 4 ($r = .387$, $p < .05$), Reynell language scores at 5 ($r = .350$, $p < .05$), vocabulary at 8 ($r = .516$, $p < .001$), and WOLD language scores at 8 years ($r = .439$, $p < .01$). This pattern of results indicates a strong non-linear relationship between phonological memory scores at age 8 and language abilities between 4 and 8 years, such that children with poorest phonological memory scores at 8 years scored disproportionately well on these language measures. It was therefore not appropriate to pursue regression-based analyses of the phonological memory data for this group, due to their dependence on a linear model. Instead, subsequent analyses were based on treatment of the children satisfying the early and persistent PMD criteria as separate groups.

A further important feature of the correlation matrix is the contrast between the patterns of correlations between phonological memory and complex memory scores at 8 years and the various attainment measures at the same age. The phonological memory coefficients were all nonsignificant and close to zero, possibly due to the restricted range of scores. In contrast, strong and significant associations were found between the complex memory scores and WOLD language scores ($r = .330$, $p < .05$), WOND number scores ($r = .486$, $p < .01$) and WORD reading scores ($r = .564$, $p < .001$). Phonological awareness scores at 8 years were also significant predictors of WORD reading scores ($r = .479$, $p < .01$) but not of any of the other attainment measures.

Partial correlation coefficients were calculated in order to determine the extent to which the associations with attainment scores of the phonological awareness and complex memory span scores were unique. The partial correlation coefficients for complex memory scores (partialling out the phonological awareness measure) were as follows: WOLD language, $r = .282$, $p = .05$; WOND number, $r = .447$, $p < .01$; WORD reading, $r = .524$, $p < .001$. The corresponding coefficients for the phonological awareness score (partialling out the complex memory score) were: WOLD language, $r = .205$, $p = .05$; WOND number, $r = .108$, $p = .05$; WORD reading, $r = .425$, $p < .01$. The complex memory and phonological awareness measures therefore were each uniquely associated with literacy scores, and complex memory span scores also shared specific links with both the language and number-based assessments at 8 years.

Scores on the attainment measures at 8 years for each of the three groups are summarised in Table 3. Standard and scaled scores (as appropriate) are shown in the table in order to provide normative comparisons, although statistical analysis was performed on the raw scores. An important feature of the attainment data is that both the early and persistent PMD groups performed at expected levels for their age on the standardised tests of vocabulary, language, mathematics and literacy, with scores close to 100 in each case. The lowest mean score of either group, of 94, was obtained for the early PMD group on the BPVS vocabulary test; this score is within half a standard deviation below the population mean. The performance of the control group on all these measures exceeded average levels for age, with standardised test scores falling in the range 103 to 114.

Table 3 Descriptive statistics for scores on attainment measures at 8 years by group, with probability values for pairwise group comparisons by univariate *F*-tests

	Group						Group comparison probability			Group comparison probability covarying complex memory (phon. awareness) scores		
	Early PMD		Persistent PMD		Control							
Area: measure	Mean	S.D.	Mean	S.D.	Mean	S.D.	Early & pers. PMD	Early PMD & control	Pers. PMD & control	Early & pers. PMD	Early PMD & control	Pers. PMD & control
Vocabulary												
BPVS	94.38*†	8.88	102.27	8.90	103.40	7.44	.006	.001	ns	.006 (.001)	.009 (.005)	ns
WISC∞	8.83*†	4.13	11.20	2.37	11.73	4.13	.042	.045	ns	.046 (.014)	ns	ns
Language (WOLD)							ns	ns	ns	ns	ns	ns
Comprehension	98.92*†	12.07	108.40	8.85	111.20	11.78	.016	.007	ns	.016 (.013)	ns (.040)	ns
Oral expression	99.00	10.03	103.00	9.56	104.40	9.88	ns	ns	ns	ns	ns	ns
Mathematics (WOND)							ns	ns	ns	ns	ns	ns
Math. reasoning	102.33	12.52	106.87	10.40	110.27	14.27	ns	ns	ns	ns	ns	ns
Number operations	99.67	11.20	96.00	17.10	108.80	3.83	ns	ns	ns	ns	ns	ns
Literacy (WORD)							ns	ns	ns	ns	ns	ns
Basic reading	102.58†	11.65	100.27†	12.96	114.00	15.63	ns	.020	.022	ns	ns	ns
Reading comp.	99.60†	11.02	98.07†	11.06	107.87	12.05	ns	.027	.033	ns	ns	ns
Spelling	100.87†	11.57	98.67†	11.92	114.13	17.45	ns	.007	.013	ns	ns (.020)	ns

∞Scaled score.
*$p < .05$, compared with persistent PMD group.
†$p < .05$, compared with control group.

In order to establish whether differences in attainment scores were statistically significant, a series of MANOVAs was performed on each variable set, for each of the three pairwise group combinations. The analyses were performed on raw scores, and the probability values associated with *Hotelling's T*-test were calculated in each case. The probability values for the associated univariate *F*-tests are also shown in Table 3. On the vocabulary measures, the early PMD group performed at significantly lower levels than both the persistent PMD group and the control group ($p < .05$, in both cases). No significant difference was found between the severe PMD and control groups ($p > .05$). This pattern of findings was reflected in the univariate tests performed on both vocabulary measures. The early PMD group also scored significantly more poorly on the WOLD language measures than the control group ($p < .05$), with the group difference reaching significance only the Language Comprehension subtest by univariate *F*-test. Although the corresponding overall group comparison in the MANOVA was nonsignificant for the two PMD groups ($p > .05$), the early PMD group showed a significant deficit relative to the persistent PMD group on the Language Comprehension subtest, by univariate *F*-test ($p > .05$, in each case). No significant differences were found between the persistent PMD and control groups on the language subtests.

In the MANOVAs performed on the number subtests from the WOND, the only overall group term that reached significance was the comparison between the early and late PMD groups ($p < .05$). As neither of the univariate *F*-tests approached significance, it appears that the group term reflected minor fluctuations in subtest scores in opposing directions across the two groups, and does not require theoretical interpretation. On the WORD reading measures, significant differences were found between each of the two PMD groups and the control group ($p < .05$, in both cases), reflecting the lower performance of the two PMD groups. The two PMD groups did not themselves differ significantly ($p > .05$).

A further set of MANCOVAs was carried out in order to establish whether group differences in attainment tests scores were associated with variation in complex memory span scores, which were significantly lower for both PMD groups than the control group. In these analyses, in which complex memory span score was the covariate, the group effects reflecting the poorer vocabulary scores of the early PMD group than either the persistent PMD or control groups remained significant ($p < .05$, in both cases). The lower performance of the early than persistent PMD group on the language subtests was marginally nonsignificant ($p = .054$), although the group difference was significant by univariate *F*-test on the Language Comprehension subtest. No other group differences were significant at the .05 level in the remaining analyses.

A final corresponding set of MANCOVAs was performed in which the two phonological awareness measures at 8 years (onset and end oddity detection) were included as covariates. Significant overall group effects were as follows. Differences between the early and persistent phonological memory deficit groups were significant in the analyses of both the vocabulary measures ($p < .005$) and language subtests ($p = .01$); by univariate *F*-test, the group term was significant only on the Listening Comprehension subtest ($p < .05$). In the MANCOVA performed on the vocabulary measures for the early phonological memory deficit group and control group, the group term was significant ($p < .05$), with univariate *F*-tests showing significance only for the BPVS measure ($p = .005$). In the remaining MANCOVAs carried out on these two groups the overall group terms were nonsignificant. Note, though, that group differences by univariate *F*-tests were significant on the Language Comprehension subtest of the WOLD and the Spelling subtest of the WORD ($p > .05$, in each case).

Discussion

This study investigated the consequences of poor phonological short-term memory skills at 5 years for children's attainments in vocabulary, language, literacy and mathematics three years later. One subgroup of the children appeared to have a specific deficit of the phonological loop component of working memory. These children scored poorly on all measures of phonological short-term memory administered between 4 and 8 years. On verbal complex memory span tests associated with the central executive and a spatial memory measure, however, they performed in the low average range. This group were impaired relative to controls on one of the two measures of phonological awareness administered at 8 years of age, although not on the phonological awareness test completed at 5 years.

In terms of more general attainments at 8 years, this group performed at appropriate levels for their age in all assessed areas: vocabulary, language, number skills, and literacy. Relative to the matched control group they performed poorly on the literacy tests; this pattern of findings arose because of the above-average performance of the matched controls on the literacy tests. The group difference was, however, accounted for by differences in both complex memory span and phonological awareness performance. These children therefore did not experience learning difficulties in key domains over the early school years that could be attributed to their poor phonological memory function.

The finding that enduring deficits in phonological short-term memory were not accompanied by poor vocabulary knowledge at 8 years may initially appear to challenge claims that learning the phonological forms of new words is mediated by the phonological loop (e.g., Baddeley et al., 1998). In fact, the data are consistent with previous evidence suggesting that vocabulary acquisition may be most sensitive to phonological memory constraints in the earlier childhood period. Strongest links between phonological memory skills and the native vocabulary knowledge have been found at younger ages, and in particular between 4 and 6 years of age (e.g., Bowey, 2001; Gathercole, 1995; Gathercole & Baddeley, 1989; Gathercole et al., 1997). Furthermore, in a longitudinal study of a cohort of children studied between 4 and 8 years of age, Gathercole et al. (1992) found that the association between nonword repetition (an index of phonological memory) and vocabulary knowledge was strongest at 4 years, declining to a nonsignificant level by 8 years (see also, Gathercole, 1995). On this basis, it was suggested that by the middle childhood years when language abilities approach adult levels and exposure to spoken language has been extensive and highly redundant, the contribution of the phonological loop to the phonological learning of new words may be overshadowed by other factors such as conceptual abilities and exposure to print (Stanovich & Cunningham, 1993). Prior influences of the phonological loop on vocabulary acquisition may therefore have been masked in the persistent phonological memory deficit group in the present study by other more potent current factors operating at 8 years. This view is reinforced by findings that paired associate learning of verbal items in a laboratory setting is relatively slow in this group (Gathercole et al., 2003), indicating that these children do have specific difficulties in phonological long-term learning that are detectable under conditions that minimise the contribution of other mediating and compensating factors.

The second subgroup of children drawn from the larger sample of children selected on the basis of poor phonological memory test scores at 5 years had an unexpectedly contrasting profile. These children obtained higher scores on phonological memory tests at 8 years than the persistent phonological memory deficit group described above. The two groups were originally distinguished in order to test the phonological memory severity hypothesis, according to which children with less severe deficits in phonological memory function by 8 years should outperform the persistent deficit group in any area of attainment that shares a developmental association with phonological memory skill. Counter-intuitively, the results showed a converse pattern of findings. Of the low memory group at 5 years, the children with better phonological memory scores at 8 years performed more poorly than the persistent memory deficit group on verbal IQ at 4 years, with a mean verbal IQ score of 89 (96 for the persistent phonological memory group) compared with a performance IQ of 100. They also performed more poorly on vocabulary and language assessments at 8 years than both the persistent phonological memory group and the controls. Like the persistent phonological memory group, they also showed deficits relative to controls on reading measures at 8 years, although this difference was eliminated when variation in either complex memory span or phonological awareness scores were taken into account.

The most parsimonious account of the performance profile of this subgroup is that it reflects a general language deficit rather than a primary impairment of phonological short-term memory. This deficit may correspond to an impairment of semantic processing similar to that documented by Nation, Adams, Bowyer-Crane, and Snowling (1999). It is widely accepted that performance on short-term memory tasks involving the serial recall of verbal material reflects not only the contents of temporary storage mechanisms such as the phonological loop, but also the contribution of long-term lexical representations primed by the initial input (e.g., Hulme, Maughan, & Brown, 1991; Hulme et al., 1997; Gathercole, Frankish, Pickering, & Peaker, 1999; Roodenrys & Quinlan, 2000; Walker & Hulme, 1999). Specifically, lexical phonological representations appear to be used to reconstruct the identity of degraded representations in the phonological loop. The proposal here is that the low memory scores of this subgroup arise from weak lexical support for temporary memory representations, possibly due to deficits in semantic processing, and not from an impairment of the phonological loop.

An underlying language deficit also provides an explanation for the significantly poorer performance of this subgroup on the listening recall measure of complex memory span. Based on the listening span task developed by Daneman & Carpenter (1980), this task requires semantic analysis of sentences in order to judge veracity in addition to temporary storage. Previous developmental research has shown that children with language processing difficulties of a non-phonological origin do indeed typically perform poorly on working memory tasks such as listening span that involve sentence processing (Nation et al., 1999).

An important finding from the study concerns the influence of more general working memory abilities on learning during the early school years. According to the current working memory view, scores on the two verbal complex memory span measures involve both storage in the phonological loop and also tap the processing resources associated with the central executive component (e.g., Baddeley & Logie, 1999). Other theorists have linked complex span tasks with a more general concept of working memory whose operation is constrained by limited attentional resources (e.g., Cowan, 1998; Engle, Tuholski, Laughlin, & Conway, 1999). Results from the present study strongly reinforce other reports that scores on complex span tasks are highly related to learning achievements across the curriculum (e.g., de Jong, 1998; Jarvis & Gathercole, 2003; Swanson & Alexander, 1997' Swanson & Ashbaker, 2000). Within the larger group of children selected as having low phonological memory scores at 5 years, complex memory performance was a significant predictor of performance on measures of language, mathematics and literacy; the association with literacy was particularly high ($r = .56$). Furthermore, the significant differences in the scores of both the persistent phonological memory deficit subgroup and the language deficit subgroup compared with controls on the literacy assessments was eliminated when differences associated with complex memory scores were taken into account. Together, these data provide substantial support for claims that capacities to process and store material in working memory significantly constrain a child's ability to acquire complex skills during the early period of formal education.

In contrast to the pervasive association between complex memory skills and attainments in the areas of language, mathematics and literacy, a highly specific link was found between phonological awareness abilities at 8 years and the literacy scores of the children with low phonological scores at 5 years. This finding converges with a large body of evidence that development of literacy skills is closely related with abilities to analyse and demonstrate metalinguistic awareness of phonological structure (Bradley & Bryant, 1983; Griffiths & Snowling, 2002; Morais, Content, Bertelson, Cary, & Kolinsky, 1988). It should be noted that children in both the persistent phonological memory deficit and language deficit groups scored more poorly than controls on the onset oddity detection measure of phonological awareness of 8 years. Furthermore, when differences in phonological awareness scores at 8 years were controlled statistically, the disparity in literacy test scores of these two groups was no longer significant. This result may reflect either the contribution to the acquisition of literacy of phonological processing abilities (e.g., Hecht et al., 2001; Muter & Snowling, 1998) or the converse influence of learning to read and spell on awareness of phonological form demonstrated by Morais et al. (1988). More importantly for the present concerns, the presence of a strong correlational association between phonological awareness but not phonological memory scores and reading ability in the low memory group at 5 years provides substantial evidence for the separability of the two domains of phonological skill (e.g., Gathercole et al., 1991; Hecht et al., 2001; Muter & Snowling, 1998).

In summary, children with poor phonological short-term memory skills that persisted from 4 to 8 years achieved normal levels of attainment in the areas of vocabulary, language, mathematics and literacy at 8 years. The scholastic achievements of this group and of other children with low phonological memory performance resulting from a more pervasive language deficit were, however, strongly influenced by more general working memory capacities. In terms of impact for the acquisition of complex skills and knowledge during the early school years, the impact of working memory function associated with the central executive appears to exceed that of the more specialised phonological loop.

Acknowledgements

This project was funded by a Wellcome Trust of Great Britain awarded to S.E. Gathercole, D. Gadian, F. Vargha-Khadem, and J. Golding. The research reported in this article benefited greatly from discussions with D. Gadian and F. Vargha-Khadem. Earlier longitudinal data collection was supported by a variety of funding agencies, including the Medical Research Council, the Wellcome Trust, the Department of Health, the Department of the Environment, British Gas, Smith's Charities, and the Hearing Research Trust. The ALSPAC study is part of the WHO-initiated European Longitudinal Study of Pregnancy & Childhood. We acknowledge also the contribution of many collaborators who contributed to the scientific development of this project, and extend our special thanks to the children and their families who participated in the project.

Correspondence to

Susan E. Gathercole, Department of Psychology, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK; Tel: +191 3742625; Fax: +191 3747474; Email: s.e.gathercole@durham.ac.uk

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Manuscript accepted 17 March 2004

Appendix Stimuli employed in onset oddity detection task, by trial

P1	bread	cake	crisps	cot
P2	key	comb	brush	clip
P3	foot	fish	leg	face
P4	bird	bee	bell	fly
T1	cow	cup	cat	dog
T2	moon	sun	saw	star
T3	pink	blue	purple	pen
T4	pear	grapes	peach	purse
T5	spade	bone	bricks	ball
T6	shoe	sun	sock	shirt
T7	bed	bus	car	bike
T8	door	duck	dog	pig
T9	twenty	ten	twelve	twig
T10	stand	staple	sew	stick
T11	black	brown	blue	blind
T12	climb	creep	crawl	crow