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AWARENESS

Basic Auditory Processing Skills and Phonological Awareness in Low-IQ Readers
and Typically-Developing Controls

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Abstract

We explore the relationships between basic auditory processing, phonological awareness, vocabulary and word reading in a sample of 95 children, 55 typically-developing children and 40 children with low-IQ. All children received non-speech auditory processing tasks, phonological processing and literacy measures, and a receptive vocabulary task.

Compared to age-matched controls, the children with low-IQ and low reading skills were significantly impaired in auditory and phonological processing, whereas the children with low-IQ and preserved reading skills were not. There were also significant predictive relations between auditory processing and single word reading. Poor auditory processing was not dependent on low-IQ, as auditory processing was age-appropriate in the low-IQ children who were good readers.

Keywords: garden variety, phonology, auditory processing, reading, reading disability

Basic Auditory Processing Skills and Phonological Awareness in ‘Garden Variety’ Poor Readers and Low-IQ Good Readers

The notion of the “garden variety” or low-IQ poor reader (LIQPR) was first proposed by Gough and Tunmer (1986) to distinguish children with poor word reading abilities who also had poor general cognitive abilities from children who had word reading abilities that were unexpectedly poor given their IQ (children with developmental dyslexia). Stanovich (1988) took the notion of low-IQ poor readers further. In his core phonological deficit model, Stanovich (1988) argued for the *inclusion* of low-IQ poor readers amongst those children regarded as having *specific* reading difficulties. His argument was that IQ was not diagnostic for the presence of specific reading difficulties. Stanovich proposed that whenever a core phonological deficit was present, a child might be expected to have specific difficulties in acquiring literacy skills, and thus might benefit from specific and targeted support. It is also possible that whenever a core phonological deficit is present, a child might be expected to have auditory processing difficulties. Given the growing evidence for a relationship between basic auditory sensory processing of the amplitude envelope and the development of phonological abilities (Corriveau, Pasquini & Goswami, 2007; Goswami, Gerson & Astruc, 2009; Goswami et al., 2002; Hämäläinen, Leppänen, Torppa, Muller & Lyytinen, 2005; Hämäläinen, Salminen & Leppänen, in press; Lorenzi, Dumont & Fullgrabe, 2000; Muneaux, Ziegler, Truc, Thomson & Goswami, 2004; Pasquini, Corriveau & Goswami, 2007; Richardson, Thomson, Scott & Goswami, 2004; Rocheron, Lorenzi, Fullgrabe & Dumont, 2002; Suranyi, Csepe, Richardson, Thomson, Honbolygo & Goswami, 2009; Thomson, Fryer, Maltby & Goswami, 2006; Thomson & Goswami, 2008), we decided here to explore

basic auditory sensory processing in the low-IQ poor reader. Our hypothesis was that low-IQ poor readers might show the same basic auditory processing difficulties as children with developmental dyslexia. If this were to be the case, then it would support the view that basic auditory sensory processing deficits are associated with poor phonological development, whether the child has a diagnosis of a reading difficulty or a language difficulty (Corriveau et al., 2007; Fraser, Goswami & Conti-Ramsden, in press), and whether the child has a low, typical or high full-scale IQ.

Although there are many studies in the literature of auditory processing and reading (see Hämäläinen, Salminen & Leppänen, in press, for a recent meta-analysis of all auditory non-speech studies in developmental dyslexia), there is no consensus concerning the relationship between auditory sensory skills and reading development. This is partly because many studies have measured only one auditory processing variable, because many studies have failed to assess the contribution of IQ, and because studies intended to test associations between auditory processing and dyslexia have failed to require a diagnosis of dyslexia or have failed to verify the current dyslexic status of participants (see Pasquini et al., 2007, for discussion). In their meta-analysis of non-speech auditory processing studies in developmental dyslexia, Hämäläinen et al. noted that at the time of writing, whereas there had been 22 studies of frequency discrimination, there had been 10 or fewer studies of other auditory parameters such as intensity (10 studies), duration (9 studies) and rise time (7 studies at that time). Significant group differences between dyslexics and controls were found for all 7 (100%) of the rise time studies, for 16 (73%) of the frequency discrimination studies, for 6 (67%) of the duration studies, and for one (10%) study of intensity. The median effect sizes in each case (Cohen's *d*) were 1.0 for rise time, 0.6 for frequency, 0.9 for duration, and 0.4 for

intensity. It is also unclear whether auditory processing deficits that are revealed in childhood persist into adulthood, or whether they attenuate as a result of maturation or remediation. For example, it has been claimed that auditory processing deficits are characteristic of at best a sub-group of dyslexics, perhaps around 39% (Ramus, 2003). In his review, Ramus (2003) stated this as a general conclusion about dyslexic populations, and thus encompassing children participants, yet five of the six studies cited as key support for this claim were of adult compensated developmental dyslexics. The auditory processing measures surveyed did not include measures of rise time. By contrast, in their meta-analysis, Hämäläinen et al. concluded that highly consistent associations between auditory processing and reading occurred for rise time discrimination (100% of reviewed studies), and also amplitude modulation detection (100% of reviewed studies). Other auditory variables, such as frequency discrimination, showed less consistent results (associations found in 57% of reviewed studies). In the current study, we were particularly interested in amplitude modulation detection with respect to rates of onset or rise time.

In prior studies of rise time perception and reading (e.g., Corriveau et al., 2007; Fraser et al., in press; Goswami et al., 2002, 2009; Richardson et al., 2004; Thomson & Goswami, 2008), children with reading or language difficulties have been particularly impaired at discriminating the rise time (rate of change) of amplitude envelopes at onset. In these studies, rise time has been a consistently strong predictor of the children's phonological skills, measured at the onset-rime or phoneme level (e.g., Corriveau et al., 2007, Richardson et al., 2004, for detail). Rise time discrimination is also impaired in the majority of children tested (Richardson et al., 2004: 63% of children with dyslexia were below the 5th percentile of age-matched controls; Corriveau et al., 2007: 71% of children

with SLI were below the 5th percentile of age-matched controls). Rise time is also strongly associated with phonological impairments and developmental dyslexia in languages other than English (Hämäläinen et al., 2005, Finnish; Muneaux et al., 2004, French; Suranyi et al., 2009, Hungarian; see Hämäläinen et al., in press, for a review). To our knowledge, however, no-one has yet explored rise time perception in the low-IQ poor reader. This is important to remedy, as the recent speech science literature is demonstrating the central importance for speech intelligibility of the slower modulations that characterise the amplitude envelope (Drullman, Festen & Plomp, 1994; Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995; Smith, Delgutte & Oxenham, 2002; see Goswami, 2009, for a summary).

Although the prior literature on low-IQ poor readers has not explored the perception of amplitude envelope information, it has established comprehensively that LIQPRs have poor phonological skills. The demonstration by Stanovich (1988) that the phonological profiles of low-IQ poor readers were indistinguishable from those of children with developmental dyslexia has been amply supported (Stanovich, Nathan & Vala-Rossi, 1986; Stanovich, Nathan & Zolman, 1988). There has been less research on whether poor phonological development is associated with the same factors for low-IQ poor readers and children with developmental dyslexia. The large literature on potential neural causes of developmental dyslexia (e.g., auditory processing deficits, magnocellular deficits, cerebellar deficits, general sensory processing deficits, e.g., Nicolson, Fawcett & Dean, 1995; Ramus, 2004; Stein & Walsh, 1997; Tallal, 2004) has tended to exclude children with low-IQ. One reason is that poor performance on tasks used to measure sensory or neural deficits could arise from low-IQ (Banai & Ahissar, 2004).

At the same time, it has been suggested that the poorer vocabulary skills associated with having lower IQ could in themselves explain the poorer phonological development of the low-IQ poor reader. For example, Swan and Goswami (1997b) reported that low-IQ poor readers exhibited word finding difficulties in the confrontation naming task, just like children with developmental dyslexia (e.g., Wolf, 1991). However, an object recognition post-test suggested that the errors made by low-IQ poor readers were due to impoverished vocabulary knowledge, as their errors were on words absent from their receptive vocabularies. In contrast, the errors made by children with dyslexia were caused by word finding difficulties, as the target words were in their receptive vocabularies. In a subsequent study, Swan and Goswami (1997a) showed that both the low-IQ poor readers and the children with dyslexia exhibited phonological deficits, and suggested that the antecedents of poor phonological awareness in the low-IQ poor readers could include impaired vocabulary development. Studies of children with nonspecific language difficulty and low-IQ (NLI children) by Bishop and her colleagues also support a link between poor language and poor reading. They reported that NLI children were more likely than matched children with SLI (specific language impairment and normal nonverbal IQ) to go on to develop reading difficulties at 8.5 yrs (Bishop & Adams, 1990) and at 15 yrs (Stothard, Snowling, Bishop et al. 1998). Hence, language factors rather than sensory or neural factors could cause the phonological impairments found in low-IQ samples.

Accordingly, in the current study we manipulated an important structural lexical factor that is known to affect typical phonological development, phonological neighbourhood density (see De Cara & Goswami, 2003; Storkel, 2001; Thomson, Richardson & Goswami, 2005). Phonological ‘neighbourhood density’ is the number of

similar-sounding words to a particular target word in the spoken language. Phonological neighbourhood density was a factor originally proposed by psycholinguists as a metric for describing similarities and differences between words (e.g., Landauer & Streeter, 1973; Luce & Pisoni, 1998). A phonological neighbourhood was defined as the set of words generated by the addition, deletion or substitution of one *phoneme* to a target word. For example, the neighbours of the target *cup* included *culp*, *up*, *cap* and *cut*. When many words resembled the target, the neighbourhood for that word was said to be dense. When few words resembled the target, the neighbourhood for that word was said to be sparse. Studies in both language acquisition and phonological awareness have shown that in general words from dense neighbourhoods are acquired earlier by children and are easier to manipulate in phonological awareness tasks (e.g., De Cara & Goswami, 2003; Metsala, 1999; Storkel, 2001). As neighbourhood density is correlated with vocabulary size, children who are acquiring spoken words at a faster rate and who have larger vocabularies would be expected to show phonological neighbourhood effects earlier than children who are not. Thus neighbourhood density effects in phonological awareness tasks should emerge earlier for children with more rapid vocabulary acquisition (see De Cara & Goswami, 2003, for related empirical evidence).

Neighbourhood density effects are already known to emerge in the same way in children with developmental dyslexia as in typically-developing children (Thomson et al., 2005). Therefore, if neighbourhood density effects are atypical in low-IQ poor readers, this would suggest a different developmental relationship between vocabulary acquisition and phonological awareness for these children. Neighbourhood density was manipulated in two tasks in the current study, phonological short-term memory (PSTM) and rapid automatized naming (RAN). In the first case, phonological long-term memory

representations for words are known to play an important role in determining the capacity of phonological short-term memory. Phonological short-term memory is usually measured by performance in serial recall tasks, and long-term word representations help with the ‘redintegration’ or reconstruction of decaying traces (Schweikert, 1993). These reconstruction processes work better for words from dense phonological neighbourhoods in both adults (e.g., Roodenrys & Hinton, 2002) and children (e.g., Thomson, Richardson & Goswami, 2005), as words in dense neighbourhoods are better-specified phonologically. Therefore, if language acquisition affects phonological development in the same way in low-IQ poor readers as in typically-developing children, the PSTM task should show an advantage for words from dense phonological neighbourhoods. In contrast, when retrieving words from long-term memory for spoken output under timed conditions, an advantage would be expected for words from sparse phonological neighbourhoods. The higher degree of lexical competition found in denser neighbourhoods should slow the output process (see Guardia & Goswami, 2009; McCrory, 2001; for relevant empirical data). Therefore, if language acquisition affects phonological development in the same way in low-IQ poor readers as in typically-developing children, the RAN task should show an advantage for words from sparse phonological neighbourhoods.

To summarise, in the current study we recruited a sample of 95 children with a mean age of 8 years who were either good or poor readers, and who either had typical or low-IQ (defined as $IQ < 85$). We gave the children standardised measures of reading and vocabulary development, and experimental measures of phonological processing (varying phonological neighbourhood density in some measures) and basic auditory processing. A

large range of auditory processing measures was selected to sample tasks across our prior studies (see Tasks).

Method

Participants

A total of 95 children (46 female, 49 male) participated in this study. The low-IQ poor readers were identified initially during recruitment for a longitudinal study of developmental dyslexia (see Goswami, Fosker, Huss, Mead & Szűcs, in press), with some additions recruited by the first author. All remaining participants were recruited by the first author from local schools. Only children who had no diagnosed additional learning difficulties (e.g., dyspraxia, ADHD, autistic spectrum disorder, speech and language impairments) were included in the study. All participants received a short hearing screen using an audiometer. Sounds were presented in both the left and right ear at a range of frequencies (250, 500, 1000, 2000, 4000, 8000Hz), and all participants were sensitive to sounds within the 20dB HL range.

Thirty children (15 male, 15 female, mean age 94.3 months, mean reading age 80.0 months) were identified as low-IQ poor readers. These children presented with poor reading skills and scored below 85 on the pro-rated full-scale IQ measure (see Sattler, 1982). The majority of these children had been identified by their teachers as struggling readers and were on average 38 months behind age-matched controls on the British Ability Scale measure of single word reading (BAS, Elliott, Smith & McCulloch, 1996). Ten good readers (5 male, 5 female) with similarly low-IQ were identified by the first author during control recruitment. These 10 LIQGR children also had an IQ score of below 85, but scored at a much higher level on the BAS reading test (mean reading age 113 months, 17 months ahead of their age; note however that it is now common in

English samples to find that typical readers are scoring above the putative level on the BAS expected for their age, see Richardson et al., 2004). As will be seen, the typically-developing CA controls were also reading on average 17 months ahead of their age (see Table 1). A control group of 55 typically-developing readers (29 male, 26 female) were also recruited. They were divided at age 92 months in order to create a group equated for mean reading age to the LIQPR group (RL controls, N = 26, mean reading age 86.4 months) and a group equated for mean age to the LIQPR group (CA controls, N = 29, mean reading age 117.2 months). These four groups were created for the purpose of hypothesis-driven comparisons (LIQPR, LIQGR, CA, RL), nevertheless both auditory processing skills and reading skills were continuously distributed in the sample as a whole (see Figures 1 - 7 below).

 Table 1 about here

Standardised tests

Standardised tests of I.Q, receptive vocabulary, reading, mathematics and spelling were administered (for group performance, see Table 1). There were two tests of single word reading (the BAS and the Test of Word Reading Efficiency [TOWRE Sight Word Efficiency, SWE]; Torgesen Wagner & Rashotte, 1999), a nonword reading measure (TOWRE PDE, phonemic decoding efficiency), the BAS spelling measure and the BAS mathematics measure. The British Picture Vocabulary Scale (BPVS, Dunn, Dunn, Whetton & Pintillie, 1982) was used to measure receptive vocabulary. All children were given four subtests of the Wechsler Intelligence Scale for Children (WISC – III, Wechsler, 1992); block design, picture arrangement, similarities and vocabulary. Full

scale IQ scores were then prorated (estimated) from these 4 representative subtests using the procedure adopted by Sattler (1982). Full participant details are presented in Table 1.

Phonological measures

Oddity Onset. The oddity task was administered using digitized speech created from a native female speaker of standard Southern British English. The children listened to sets of three words and had to select the word that began with a different sound (e.g., *cone, pole, comb*). There were 20 trials overall. The trials were varied with respect to the sonority of the sounds in the syllables, but as this factor had no effect on performance, it will not be discussed here. All items are provided in Appendix 1. Test-retest reliability for this task in this sample using a split-half reliability measure was .80.

Phonological Short-Term Memory (PSTM). The memory task was also based on digitised speech from the same female speaker, and consisted of 16 trials of four spoken monosyllables. The children were required to listen to each set of 4 words and then repeat them back to the experimenter. Eight trials used words drawn from dense rime neighbourhoods (e.g., *knit, laid, rack, pub*; mean 18 neighbours) and 8 trials used words drawn from sparse rime neighbourhoods (e.g., *hem, dull, join, song*; mean 7 neighbours). The average rime neighbourhood density for the English language is 12 neighbours (DeCara & Goswami, 2002). The trial types were randomly mixed during computerised presentation. It was expected that the dense neighbourhood items would be easier to recall (see Thomson et al., 2005). Children listened to the stimuli through sound attenuating headphones. Responses were registered by digital voice recorder. The stimuli used are provided in the Appendix. Test-retest reliability for this task in this sample was .75 (simple correlation at the test point reported in the current manuscript and when the task was re-administered to the same sample one year later).

Rapid automatized naming (RAN). The RAN tasks required children to name line drawings of familiar objects selected from either sparse or dense phonological rhyme neighbourhoods. In each case, 4 objects were depicted (dense trials - *Gate, Wheel, Shop, Tie*; sparse trials - *Fire, Cup, Bird, Leaf*). Children were first introduced to the names of the pictures and then shown a page with the same pictures repeated 40 times in random order. In each case, the children were asked to produce the names as quickly as possible. It was expected that words from dense neighbourhoods would take longer to produce. Performance was timed and errors were counted. The presentation order of dense and sparse trials was counterbalanced. As this measure was not readministered a year later, an estimate of reliability for this task was gained by computing the correlation between RAN Dense and RAN Sparse, .68.

Auditory Processing Tasks

General considerations. The auditory processing battery was based on measures that were intended to explore different aspects of auditory perception, particularly of amplitude envelope onset discrimination. Following advice from an auditory expert (Professor Brian Moore, University of Cambridge), the frequency and intensity tasks used a 2IFC “ABABA” delivery format in order to minimise memory demands (see also Thomson & Goswami, 2008). This format was expected to enable a more sensitive estimate of frequency thresholds, as children simply have to listen for a change. As psychoacoustic thresholds are typically calculated over thousands of trials, we sought to optimise our auditory measurements by using a new staircase procedure designed by the second author and by calibrating all our equipment. The psychoacoustic stimuli were presented binaurally through sensitive Sennheiser HD580 headphones at 75 dB SPL. Testing laptops had good Echo Indigo sound cards and were calibrated to ensure that all

laptops were delivering stimuli at the same loudness level. Earphone sensitivity was calculated using a Zwislocki coupler in one ear of a KEMAR manikin (Burkhard & Sachs, 1975). Children's responses were recorded on the computer keyboard by the experimenter.

All tasks were based on a child-friendly "Dinosaur" threshold estimation program, originally created by Dorothy Bishop (Oxford University), which used either an AXB (X as standard, A or B differed from X in one direction, child had to select the different stimulus) or 2IFC (2 stimuli presented which differed on a specified auditory parameter, the child was forced to select one) presentation format. Feedback was given after every trial on the accuracy of performance. The Dinosaur tasks were modified for this study by the second author, who also created the Rhythm task. In all auditory tasks, the child first participated in five practice trials. During the practice period further verbal explanation and reinforcement was provided by the researcher. The child then proceeded to the main activity. Following advice on how to maximise the quality of data collected from children from a number of experts attending the British Acoustical Society meeting in 2005, the amended Dinosaur programme used an adaptive staircase procedure (Levitt, 1971) using a combined 2-up 1-down and 3-up 1-down procedure, where after 2 reversals, the 2-up 1-down staircase procedure changes into 3-up 1-down. The step size halved after the 4th and 6th reversal. A test run typically terminated after 8 response reversals or alternatively after the maximum possible 40 trials. The rationale for this adaptive method is rapidly to place stimuli as close to the individual threshold level of the child as possible, so that threshold can be attained without compromising the estimation of the 79.4 per cent correct point on the psychometric function. Four attention trials were randomly presented during each test run, using the maximum contrast of the respective

stimuli. The threshold score achieved was calculated using the measures of the last four reversals. In addition, as we were testing a low-IQ sample, a Probit function was then fitted using SPSS, by which the 79.4 per cent correct point was calculated. This yielded a threshold value which indicated the smallest difference between stimuli at which the participant could still discriminate with a 79.4 per cent accuracy rate.

Specific Auditory Tasks Used

One amplitude rise time task (1 Rise task). Three 800 ms tones were presented. The second tone was always a standard tone, with a 15 ms linear rise time envelope, 735 ms steady state, and a 50 ms linear fall time. Either the first or third tone was identical to this standard, whereas the third or first tone varied the linear rise time envelope logarithmically along a continuum, with the longest rise time being 300 ms. Children were introduced to three cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child's task was to decide which dinosaur's sound had a softer rising sound than the others (longer rise time). The concept of sound 'softness' was reinforced visually by the researcher contrasting sharp hand taps on the table with a more gentle brushing contact.

Two amplitude rise time task (2 Rise task). Forty stimuli of 3573 ms (2.5 cycles) in duration were created using a sinusoidal carrier at 500 Hz amplitude modulated at the rate of 0.7 Hz (depth of 50 percent). A square wave was the basis of the underlying envelope modulation. Presentation format was 2IFC. Rise time was again varied logarithmically from 15ms to 300 ms with a fixed linear fall time of 350 ms. The longest rise time was used as the standard. The child was asked to choose the dinosaur that had the sharper beat. This corresponded to the sound with the shorter rise time.

One amplitude rise time task with intensity roving (Rise rove). The stimuli were the same as those used in the 1 Rise task, but the intensity of each stimulus was varied randomly in each trial. This meant that intensity could not be used as a cue to rise time. Children were again asked to choose the dinosaur making the softer rising sound.

Duration discrimination task. A continuum of 40 stimuli was created using pure tones. Presentation format was AXB. The duration of the standard tone, presented second, was 400 ms. The first or third tone could be identical to this standard, and the third or first tone was longer than the standard, ranging logarithmically up to 600 ms. Each tone was presented at 500Hz with a 50ms rise and fall. Children were asked to choose the cartoon sheep which made the longest sound.

Frequency discrimination task (Frequency ABABA). Presentation format was 2IFC. Two sequences of 5 tones were presented. In each sequence five 25ms sine tones were used with 10ms rise time, 10ms fall time and inter-stimuli intervals of 100ms. In one sequence the tones were all of constant frequency (600Hz; 'AAAAA') whilst in the other sequence, alternate tones had higher frequency ('ABABA'). The task used a continuum of 60 stimuli which increased in frequency at constant 2.6 Hz intervals from the standard 600Hz tone. The task was introduced by explaining to children that each cartoon bird would make a series of sounds and that their task was to decide which bird made a mixture of high pitch and low pitch sounds.

Intensity discrimination task (Intensity ABABA). This task similarly employed two tone sequences and was matched for presentation format to the frequency measure. In each sequence five 200ms sine tones were presented with 50ms rise time, 50ms fall time and inter-stimuli intervals of 100ms. In one sequence the tones were all of constant intensity 75dB ('AAAAA') whilst in the other sequence, alternate tones had

reduced intensity ('ABABA'). The task used a continuum of 40 stimuli which decreased in intensity at constant 1.7% steps from the standard 75dB tone. It was explained to children that each cartoon monkey would make a series of sounds and that their job was to decide which monkey made the mixture of loud and soft sounds.

Rhythm discrimination task (Rhythm). As rise time difficulties are theoretically linked to difficulties in perceiving rhythmic timing, this task was expected to be related to poor phonology and hence poor reading. Children were again presented with two sequences of sounds in a 2IFC format. In one sequence a 500 Hz sinusoid 1600 ms in duration was manipulated to present five identical tones with equal 150 ms ISIs. The second sequence had a linearly modified interval between the third and fourth tones ranging from 150 ms to 15 ms. Children were told that one penguin walked in a steady rhythm while one walked in an unsteady rhythm and had a skip in its step. This distinction was supported by the experimenter tapping examples of each on the desk. Children were asked to identify the penguin which did not make a steady rhythm.

Analysis Strategy

One major focus of interest in this paper is basic auditory processing, a sensory measure that might be expected to depend on physical maturation only. On a maturation hypothesis, the appropriate control group for the LIQPRs would be the CA controls (see Ramus, White & Frith, 2006, for this argument "a reading age [and therefore younger] control group could only have poorer sensorimotor performance", p. 266). Alternatively, on a developmental hypothesis, auditory sensory processing skills might also be expected to be affected by being taught to read (see Goswami et al., 2009, for this argument). Therefore, the performance of a RL-equated group is also of interest. Accordingly, we explore the performance of younger reading level-matched children on the auditory

sensory tasks, but base our statistical comparisons on the CA controls. Our theoretical position is that children with poor reading skills represent the lower end of a continuum of ability rather than comprising a heterogeneous group (Goswami, 2008). Accordingly, while group mean performance is of interest in understanding the effects of age versus reading level on auditory and phonological skills, we explore associations between auditory and phonological abilities and reading using the whole sample of children tested. Following other investigations of LIQPR groups, we include Group as a categorical variable in these analyses (e.g., Shaywitz et al., 1992). Significant associations between individual differences in sensory processing abilities and an outcome measure like reading will be more likely in samples with a broader range of reading abilities. For example, if sensory skills such as rise time discrimination follow a threshold model, similar to other physiological variables (e.g., blood pressure), it might be that the physiological variable only has a critical effect once a certain level (here, of inefficient auditory processing) is reached. Blood pressure varies continuously in the population but is only detrimental to health once a certain threshold is attained. When the range of reading ability is relatively narrow and sample sizes are small, associations with physiological and sensory variables are less likely to reach conventional levels of significance. This point can be illustrated with the current data set. Whereas the association between the 1 Rise measure and reading was significant for the whole sample ($r = -.45, p < .001$), it was not significant when the sample was truncated by reading ability, so that for example only good readers were considered (CA controls, $r = -.16, p = .39$) or only LIQPRs were considered ($r = -.30; p = .10$).

Results

To check that the grouping of the children as shown in Table 1 was appropriate, the LIQPR and control children were compared in a series of one-way ANOVAs. As can be seen from Table 1, the parametric analyses confirmed the groupings used. In view of the small number of LIQGR children, non-parametric Mann Whitney U tests were used to compare this group to the CA controls. No significant difference was found in age ($U = 125.50$, $N1 = 10$ $N2 = 29$, $p = .54$), BAS reading age ($U = 130$, $N1 = 10$ $N2 = 29$ $p = .65$), BAS reading ability ($U = 137$, $N1 = 10$ $N2 = 29$, $p = .81$), TOWRE SWE ($U = 118$, $N1 = 10$ $N2 = 29$ $p = .40$), TOWRE PDE ($U = 106.5$, $N1 = 10$ $N2 = 29$, $p = .212$), Spelling ($U = 143.5$, $N1 = 10$ $N2 = 29$ $p = .96$) and BAS Maths ($U = 99$, $N1 = 10$ $N2 = 29$, $p = .15$). There was a significant group difference for BPVS ($U = 50.5$, $N1 = 10$ $N2 = 29$ $p < .01$) and also for FSIQ ($U = 0$, $N1 = 10$ $N2 = 29$, $p < .001$).

The LIQGR group was also compared to the LIQPR group. No significant difference was found with respect to age ($U = 132$, $N1 = 10$ $N2 = 30$, $p = .59$), BPVS ($U = 145.50$, $N1 = 10$ $N2 = 30$, $p = .89$) and FSIQ ($U = 107.50$, $N1 = 10$ $N2 = 30$, $p = .19$), but a significant difference was found for BAS reading age ($U = 24$, $N1 = 10$ $N2 = 30$ $p < .001$), BAS reading ability ($U = 0$, $N1 = 10$ $N2 = 30$, $p < .001$), TOWRE SWE ($U = 12$, $N1 = 10$ $N2 = 30$ $p < .001$), TOWRE PDE ($U = 20.5$, $N1 = 10$ $N2 = 30$, $p < .001$), Spelling ($U = 9.5$, $N1 = 10$ $N2 = 30$ $p < .001$) and BAS Maths ($U = 67.50$, $N1 = 10$ $N2 = 30$, $p < .01$). In summary, it can be seen that the LIQGR group was comparable to the CA control group in all of the standardised measures except for the receptive vocabulary measure and IQ. Receptive vocabulary development was depressed for both the LIQGRs and the LIQPRs. When the LIQGRs were compared to the LIQPRs, the LIQPRs showed significantly poorer performance on the standardised literacy and mathematics measures, but not on the test of receptive vocabulary (BPVS). Hence lower cognitive ability is

associated with poorer vocabulary development, but not necessarily with poorer literacy development.

Table 2 around here

Group performance in the phonological measures is shown in Table 2. As expected, a phonological deficit is apparent for the LIQPR group in all measures, and high neighbourhood density shows a facilitatory effect for word recall and an inhibitory effect for rapid naming, as predicted. For the oddity task, a one-way ANOVA for the LIQPR, RL and CA groups taking the number of trials correct out of 20 as the dependent variable showed a significant effect of Group, $F(2,80) = 9.4$, $p < .001$, $\eta_p^2 = .19$. Post-hoc comparison (Newman-Keuls) showed that the LIQPR group were equivalent to the RL controls, but that both groups were significantly less successful than the CA controls. The LIQPR group was again compared to the CA and RL controls to explore the effects of neighbourhood density in the PSTM and RAN tasks. Here a pair of 3 x 2 repeated measures ANOVAs (Group x Density) were used, taking the number of items recalled correctly (PSTM) and the time taken to read the lists (RAN) as the dependent variables respectively. The ANOVA for PSTM revealed a main effect of Density, $F(1,70) = 8.52$, $p < .01$, $\eta_p^2 = .11$, and a main effect of Group, $F(2,70) = 11.55$, $p < .001$, $\eta_p^2 = .25$. There was no interaction between Group and Density, $F(2,70) = .75$, $p = .76$, $\eta_p^2 = .01$. All groups remembered significantly more words from dense phonological neighbourhoods. The CA controls remembered significantly more items than the RL group, who remembered significantly more items than the LIQPR group. The ANOVA for RAN also revealed a main effect of Density, $F(1,79) = 51.72$, $p < .001$, $\eta_p^2 = .40$, and a main effect

of Group, $F(2,79) = 7.63$, $p = .001$, $\eta_p^2 = .16$, with no interaction, $F(2,79) = 1.54$, $p = .22$, $\eta_p^2 = .04$. All groups were faster at naming items from sparse neighbourhoods. The CA controls were significantly faster at naming than the RL and LIQPR groups, who were equivalent.

Nonparametric Mann-Whitney tests were used to compare the LIQGRs with the CA controls. No significant difference was found between the LIQGRs and the CA controls on any of the phonological measures (Oddity [$U = 112$, $N1 = 10$ $N2 = 27$, $p = .45$], PSTM dense [$U = 137$, $N1 = 10$ $N2 = 29$ $p = .81$], PSTM sparse [$U = 114.5$ $N1 = 10$ $N2 = 29$ $p = .33$], RAN dense [$U = 93$ $N1 = 10$ $N2 = 29$, $p = .10$], RAN sparse [$U = 107$ $N1 = 10$ $N2 = 28$ $p = .29$]). Similar non-parametric analyses comparing the LIQGR and LIQPR groups found a significant group difference for the Oddity task ($U = 79.50$, $N1 = 10$ $N2 = 30$, $p < .05$), the PSTM dense ($U = 44$, $N1 = 10$ $N2 = 18$, $p < .05$) and PSTM sparse items ($U = 47.50$, $N1 = 10$ $N2 = 18$, $p < .05$), but no significant differences for the RAN measures (RAN dense $U = 143.50$, $N1 = 10$ $N2 = 30$, $p = .84$; RAN sparse $U = 135$, $N1 = 10$ $N2 = 30$, $p = .66$). For phonological awareness and phonological short-term memory, it seems that the LIQGR group has developed phonological skills in line with their reading abilities.

The auditory discrimination data were explored by group using the SPSS boxplot function as well as measures of kurtosis and skew to check that assumptions of normality were met. Outliers were defined as scores falling outside 3 inter-quartile ranges from the further edge of the box and were removed. There were three outliers for the intensity measure (1 RL, 2 LIQPR), two outliers for the rhythm measure (1 LIQGR, 1 RL), one outlier for the 1 Rise measure (LIQGR), one for Rise Rove (RL), and one for frequency (RL). The distributions for Frequency ABABA were found to be bimodal. Children were

either very sensitive to frequency, or very insensitive, with a cut-off at around a threshold of 25 (1.18 semitones). In prior work using the AXB task with a dyslexic population, frequency was also found to be dichotomous with a similar cut-off around 1.18 semitones (see Goswami, Wang, Cruz, Fosker, Mead & Huss, 2009). Accordingly, frequency was coded dichotomously for the correlation and multiple regression analyses (see below). A score of 1 was assigned for thresholds above 25, and a score of 0 for thresholds of 25 or below.

Figures 1 - 7 here

Mean performance thresholds for the auditory tasks by group are provided in Table 3. Scatterplots of auditory thresholds for the whole sample, with the CA means and standard deviation included in each case, are provided in Figures 1 to 7. Overall, inspection of Table 3 suggests that low-IQ poor readers usually have higher auditory thresholds than CA control children, but not than RL control children. In accordance with the maturation hypothesis prevalent in the field (discussed earlier), the LIQPR thresholds were compared statistically with the CA controls only. A series of one-way ANOVAs confirmed that the difference in thresholds reached significance for the Intensity ABABA task, $F(1,55) = 14.43, p < .001, \eta_p^2 = .21$ the Rhythm task, $F(1,57) = 7.64, p < .01, \eta_p^2 = .12$, the One Rise task, $F(1,57) = 16.91, p < .001, \eta_p^2 = .23$, the Two Rise task, $F(1,57) = 4.06, p < .05, \eta_p^2 = .07$, and the Frequency ABABA task, $F(1,57) = 11.86, p = .001, \eta_p^2 = .17$; but not the Duration task, $F(1,55) = 3.74, p = .06, \eta_p^2 = .06$, or the Rise Rove task, $F(1,57) = 3.85, p = .06, \eta_p^2 = .06$. This pattern also held when controlling the overall

false discovery rate (FDR) for the series of tests below a level of 5%. In fact, applying a two-stage adaptive linear step-up procedure, as advocated by Benjamini, Krieger & Yekutieli (2006), would lead us to reject all seven null hypotheses, thus finding a significant group difference between the LIQPRs and the typically-developing controls in all of the auditory tasks.

To determine whether the group-level auditory processing deficits were due to a small sub-set of the LIQPR children, the performance of the CA control group was also used to calculate the 5th percentile for each auditory task following the criteria suggested by Ramus, Pidgeon and Smith (2003). For the rise time tasks, 16 LIQPR children fell below the 5th percentile of the CA controls in the 1 Rise task (55%), and 15 in the 2 Rise task (52%). No LIQPR children were below the 5th percentile of CA performance for the Rise Rove, Frequency or Intensity tasks, but for the Duration task, 8 LIQPR children (28%) fell below the 5th percentile and for the Rhythm measure it was 11 children (38%).

Group differences between the LIQGRs and the CA controls were again explored using non-parametric tests. A series of Mann-Whitney U tests confirmed that there were no significant differences between the LIQGRs and the CAs on any of the auditory tasks (Intensity [$U = 141.50$, $N1 = 10$ $N2 = 29$ $p = 0.91$]; Rhythm [$U = 116$, $N1 = 9$ $N2 = 29$ $p = 0.64$]; Two Rise [$U = 96.50$, $N1 = 10$ $N2 = 29$ $p = 0.12$]; One Rise [$U = 114$, $N1 = 9$ $N2 = 29$ $p = 0.59$]; Duration [$U = 115.50$, $N1 = 10$ $N2 = 29$ $p = 0.35$]; Rove [$U = 119$, $N1 = 10$ $N2 = 29$ $p = 0.42$]), although Frequency came very close ($U = 84$, $N1 = 10$ $N2 = 29$, $p = .05$). Again, when a two-stage linear adaptive set-up procedure was applied, none of the null hypotheses were rejected. Hence there were no significant differences between the GRLIQs and the typically-developing controls on any of the auditory tasks.

Tables 3, 4 and 5 about here

The LIQGRs and the LIQPRs were also compared for the auditory variables. Mann-Whitney U tests showed that the LIQGRs performed significantly better in the Intensity ($U = 63.50$, $N1 = 10$ $N2 = 28$, $p = .01$) and One Rise tasks ($U = 64.50$, $N1 = 9$ $N2 = 30$, $p < .05$) compared to the LIQPRs. This suggests that having a low-IQ does not affect the discrimination of single amplitude envelope onsets nor of sound intensity. The two groups were not significantly different for the remaining auditory tasks; (Rhythm $U = 99$, $N1 = 9$ $N2 = 30$, $p = .24$; Two Rise ($U = 139.50$, $N1 = 10$ $N2 = 30$, $p = .75$); Duration ($U = 128.50$, $N1 = 10$ $N2 = 30$, $p = .51$); Rove ($U = 129.50$, $N1 = 10$ $N2 = 30$, $p = .53$) and Frequency ($U = 149$, $N1 = 10$ $N2 = 30$, $p = .99$), suggesting that having a low-IQ may affect auditory thresholds for these measures. Again, however, as the LIQGRs were a small group, these findings are suggestive only.

To explore the relationships between auditory processing and literacy in this sample, we used correlation and multiple regressions, using data from the entire sample. The raw and partial (controlling for Group) correlations between the standardised measures, the phonology measures and the auditory processing measures are shown in Table 4. Once group status is controlled, the partial correlations show that the children's auditory thresholds in all tasks are related to reading age in months on the British standardised single word reading task (BAS), and that most auditory measures are also related to single word reading on the U.S. standardised measure (TOWRE SWE), with the exception of 2 Rise and Frequency. As shown, the pure measure of rise time discrimination (Rise Rove) was significantly correlated with all the literacy measures (BAS reading, TOWRE real word and nonword reading, and BAS spelling).

To calculate the unique variance in reading ability accounted for by each auditory task, a series of two-step fixed entry multiple regression equations were computed, entering Group as a categorical variable at step 1, and then each auditory processing measure in turn at step 2 (seven equations in total). The results are shown in Table 5. The dependent variable was reading ability (BAS age-equivalent in months, as BAS standard scores were not normally distributed). As can be seen, all of the auditory measures accounted for significant unique variance in single word reading (all p 's < .001). The Intensity ABABA measure accounted for the largest absolute amount of unique variance in reading (20%), followed by the 1 Rise measure (17%). In a final 2-step multiple regression equation predicting reading age in months (not shown in the Table), taking Group as step 1, measures of sensitivity to sound rise time (1 Rise), frequency (dichotomous), intensity and duration were all entered together at Step 2. By this method, only those variables which predict unique variance emerge as significant equation coefficients. All four auditory variables together accounted for 33% of unique variance in reading ability (p < .001). When the Standardised Betas were inspected, the significant predictors of reading were 1 Rise ($Beta = -0.24$, $p = .013$), Duration ($Beta = -0.22$, $p = .016$), and Intensity ABABA ($Beta = -0.26$, $p = .012$). Frequency ABABA was not a significant predictor of reading in these analyses.

The correlational and multiple regression analyses are hence consistent with prior findings regarding relations between rise time, duration and reading, and suggest that auditory processing has unique relations with word reading even when children with lower IQ are studied. However, the current study also had a number of limitations. A theoretically important group was the LIQGRs, but only ten such children were available for this study. This small sample limits the strength of the conclusions that can be drawn.

The dataset reported here is also cross-sectional, hence the predictive relations revealed by the multiple regression analyses are ambiguous with respect to direction of causality. Longitudinal analyses are required, and we are currently carrying out such analyses for the children in this study (Unpublished PhD thesis Kuppen, 2009).

Discussion

The results reported here suggest that the reading difficulties experienced by low-IQ poor readers are associated with poor basic auditory processing and poor phonological skills rather than with poor vocabulary development or lower IQ scores. The low-IQ poor readers exhibited significantly impaired auditory processing, and auditory processing skills predicted unique variance in single word reading skills even when group status was controlled in multiple regression equations. The inclusion of a group of low ability good readers (the LIQGR group) revealed that children with lower IQ scores who learn to decode words without difficulty also have age-appropriate auditory processing and phonological skills. However, they do not have age-appropriate vocabulary skills. Together, these data suggest that the poor phonological abilities found here for the low-IQ poor readers are associated with impairments in auditory processing rather than with impairments in vocabulary development. This contrasts with our previous assumptions (Swan & Goswami, 1997a,b).

In the subgroups analysis, over half of the LIQPRs performed below the 5th percentile typical for their age on the 1 Rise and 2 Rise measures. This suggests that the accurate perception of rise time is important for both phonological development and for the development of literacy. Impaired auditory sensory thresholds for rise time may be indicative of a temporal processing difficulty with respect to the slowly-varying envelope cues that are crucial for speech intelligibility (e.g., Boemio, Fromm, Braun, & Poeppel,

2005; Poeppel & Luo, 2007). Our basic hypothesis has been that early difficulties in perceiving these slower amplitude modulations affect the development of the entire phonological lexicon, via a primary difficulty with syllable segmentation that leads to onset-rime and phoneme difficulties (e.g., Goswami et al., 2002; Richardson et al., 2004; Goswami, 2009). Recently, and in line with this hypothesis, Abrams, Nicol, Zecker and Kraus (2009) demonstrated using neuroimaging, that children who are poor readers show impaired phase locking of cortical responses to the amplitude envelope of speech. This impaired phase locking may be marked by the higher auditory thresholds to rise time revealed in studies such as the current one. Phase locking to the amplitude envelope of speech requires sensitivity to the onsets of changes in amplitude modulation. Indeed, neural coding of amplitude modulation in lower frequency regions has been shown via single cell recording data to preferentially involve the rising phases of the envelope (i.e., rise time, see Malone, Scott & Semple, 2007). Malone et al.'s cortical physiology data suggested that the sensory processing of slow modulations was best described as envelope shape discrimination. A developmental impairment with envelope shape discrimination, measured here by the 1 Rise and 2 Rise tasks, could hence affect the development of both phonological representation and of reading.

Regarding developmental relationships between rise time perception and the development of phoneme awareness, we have hypothesised that an initial difficulty with syllabic representation leads developmentally to difficulties in segmenting the syllable into smaller phonological units (the typical developmental sequence across languages being syllable – onset-rime - phoneme, see Ziegler & Goswami, 2005). Indeed, we have shown recently that discriminating phonetic contrasts based on rise time is difficult for children with dyslexia, whereas discriminating phonetic contrasts based on formant

transition duration is not (Goswami, Fosker, Huss, Mead & Szűcs, in press). Goswami, Fosker et al. (in press) found that children with dyslexia were significantly *better* than CA controls in distinguishing a phonetic contrast (ba/wa) based on formant transition duration, suggesting that sensory weaknesses in rise time perception are compensated for developmentally by enhancing speech perception on the basis of complementary cues (see Serniclaes, Van Heghe, Mousty, Carre & Sprenger-Charolles, 2004). We also found that the children with dyslexia showed similar auditory thresholds when discriminating “ba” from “wa” on the basis of rise time as younger RL-matched controls. This suggests that auditory sensory processing develops *both* via maturation and as literacy is acquired, the latter because orthographic learning helps children to refine the acoustic contrasts that are reflected by the alphabet. With respect to maturation, if age was the only determinant of sensory development, then the LIQPR group tested here should show auditory thresholds equivalent to the CA controls. In the current study, the auditory sensory thresholds shown by the low-IQ poor readers were usually equivalent to those of younger children who were reading at the same level as them (the RL controls). This implies that developmentally, there could be a reciprocal causal relationship between progress in reading and children’s auditory thresholds, at least for the measures used here. We are currently preparing a report on the longitudinal progress of the LIQPRs and their controls, which will provide some data relevant to testing this hypothesis (Unpublished PhD thesis, Kuppen, 2009).

The finding that low-IQ poor readers have impaired phonology is a familiar finding in the reading acquisition literature (Stanovich, 1988; Stanovich et al., 1986; Stanovich et al., 1988, Stanovich & Siegel, 1994). Here, we explored the development of phonological representations in low-IQ poor readers by utilising a phonological

neighbourhood density manipulation (e.g., De Cara & Goswami, 2003; Storkel, 2001; Thomson et al., 2005). The low-IQ poor readers were both more accurate in recalling words from dense phonological neighbourhoods and slower to name words from dense phonological neighbourhoods, as were all other participating groups. This suggests that, despite their impaired vocabulary development, phonological development is dependent on the same lexical factors for the low-IQ poor readers as for the typically-developing children. As structural lexical factors impact performance in the same way for LIQPRs, impaired vocabulary per se is unlikely to be the source of their impaired phonological development.

Furthermore, the low-IQ good readers, who had vocabulary development that was similarly impaired to the low-IQ poor readers, did not differ from the typically-developing controls with respect to their phonological skills. In addition, the LIQGR group showed the same phonological neighbourhood density effects as everyone else. In fact, the LIQGR group, showed very similar performance to the typically-developing children in all measures of interest except for vocabulary, frequency discrimination and IQ. As they were a small group (10 children), the data are suggestive only, nevertheless non-parametric analyses showed that the LIQGR group had age-appropriate phonology, age-appropriate auditory processing abilities with the exception of frequency, and good single word reading skills. They even had mathematical skills that were comparable to the typically-developing controls, although it should be noted that the BAS mathematics subtest involves components of verbal arithmetic and hence may benefit from intact phonological processing. The good phonological skills possessed by the LIQGR children, despite their low general IQ and low vocabulary, may be linked developmentally to their intact auditory processing abilities. The finding that frequency discrimination was poor in

all children with low-IQ (LIQGRs and LIQPRs) supports Bishop's view that impaired frequency discrimination is an associate rather than a cause of phonological difficulties (Halliday & Bishop, 2006). While the current data set cannot establish whether intact auditory processing enables normative phonological development, or whether good phonological skills enhance auditory processing abilities, longitudinal data from pre-readers suggest that auditory processing of rise time predicts the development of both phonological and literacy abilities (Corriveau, Goswami & Thomson, 2010).

Multiple regression analyses with the entire sample controlling for group status showed significant associations between reading and auditory processing. The multiple regression analyses indicated that significant unique variance in single word reading skills was accounted for by all of the auditory measures. The data suggest that the different auditory measures created for this study are contributing to individual differences in reading performance. Also of interest in this dataset are the ABABA measures, first used by Thomson and Goswami (2008), and designed to minimise memory load. These measures do not require rapid processing, but are potentially more relevant to perception of the speech envelope, within which rises and falls in fundamental frequency and also in intensity are important. This data set is the first to find a link between individual differences in perception of intensity and reading in English-speaking children. Thomson and Goswami (2008) did not find a significant association between Intensity ABABA and reading in their sample of English children with developmental dyslexia, although their regression analyses included children with dyslexia and CA controls only. Wang, Huss, Hämäläinen and Goswami (2009) recently reported a significant relationship between auditory thresholds in the same Intensity ABABA measure used here and reading (a character recognition measure) for Chinese children

with developmental dyslexia, in regression analyses including both CA and RL controls (as here).

Finally, the finding that the novel Rhythm measure, which theoretically measures children's sensitivity to rhythmic timing, was also a significant predictor of word reading suggests that general sensitivity to the rhythmic structure of acoustic signals is linked to language and literacy outcomes (see Corriveau & Goswami, 2008; Goswami et al., 2009; Thomson et al., 2006; Thomson & Goswami, 2008). This is consistent with other data concerning rhythmic timing and reading development. For example, children with developmental dyslexia are impaired in metrical musical perception compared to typically-developing controls (Huss, Verney, Fosker, Mead & Goswami, 2009). Both children with developmental dyslexia (Thomson & Goswami, 2008) and children with specific language impairments (Corriveau & Goswami, 2009) are impaired in tapping in time with a rhythmic beat compared to typically-developing control children. Difficulties in tapping to a rhythm were also found for compensated adults with developmental dyslexia attending a world top-ranked university (Thomson et al., 2006). Historically, individual differences in auditory rise time perception have been of interest because rise time is a major cue to producing and perceiving rhythmically-timed speech (Hoequist, 1983; Scott, 1998). Developmentally, there may be important relations between rhythmic timing and rhythmic co-ordination, language development and phonology (Goswami, 2010).

The current findings therefore add to the growing literature suggesting a relationship between accurate perception of the slowly-varying amplitude envelope information in speech and the development of a well-specified phonological lexicon. The data presented here suggest that this relationship is not dependent on IQ Accurate

perception of these slower modulations appears to be more important for developing phonological awareness than sensitivity to the rapid changes in frequency and intensity that were previously believed to link auditory temporal processing to literacy (Tallal, 1980, 2004). This can be explained by adopting a historical perspective on the relationship between temporal processing and phonology. Classical models of speech perception recognised a link between auditory temporal structure and phonology, but assumed that invariant acoustic features in the speech signal such as spectral energy peaks (formants) were the auditory correlates of phonemes (e.g., Blumstein & Stevens, 1981). Although phonemes were classically assumed to be the fundamental units underpinning speech-based representations, there is growing evidence that this is incorrect (Port, 2007). Port has argued that there is no ‘universal phonetic inventory’ or inventory of elemental speech sounds upon which all languages depend. Adult listeners can understand speech even when no formant structure is present (Remez, Rubin, Pisoni & Carrell, 1981). Furthermore, phoneme awareness seems to be a product of becoming literate rather than a fundamental aspect of phonological development (Port, 2007; Ziegler & Goswami, 2005). Developmentally, phonological awareness is rooted in syllables and rhymes (e.g., Anthony et al., 2002; Goswami & Bryant, 1990; Goswami, 2002). Therefore, measures of the accuracy with which the child can perceive the slowly-varying temporal envelope of speech rather than the rapidly varying fine time structure may offer the most utility in understanding the relationship between auditory temporal perception, phonological development and learning to read and to spell, both across languages and across the IQ range.

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Table 1.

Participant Characteristics by Group

	LIQPR	LIQGR	CA Controls	RL Controls
Age (months)	98.93 (12.35) ^a	96.00 (16.06) ^a	99.41 (5.42)	80.19 (5.39) ^b
BAS (reading age equivalent in months)	80.03 (11.26) ^b	113.00 (18.16) ^a	117.2 (17.98)	86.38 (15.37) ^b
FSIQ (standard score)	73.92 (6.57) ^b	76.60 (6.77) ^b	107.44 (13.23)	106.99 (14.11)
BAS reading (standard score)	84.73 (8.29) ^b	117.10 (8.99) ^a	115.86 (11.26)	109.58 (15.37) ^a
TOWRE SWE (standard score)	87.17 (11.66) ^b	109.70 (9.30) ^a	111.24 (11.31)	106.69 (11.97) ^a
TOWRE PDE (standard score)	85.80 (9.96) ^b	105.10 (9.00) ^a	109.86 (14.75)	108.54 (10.96) ^a
Spelling (standard score)	85.60 (10.24) ^b	111.80 (11.63) ^a	112.97 (13.46)	109.00 (14.77) ^a
Maths (standard score)	91.63 (11.89) ^b	103.90 (10.59) ^a	110.34 (15.26)	106.23 (19.29) ^a
BPVS (standard score)	91.43 (8.99) ^b	91.40 (6.92) ^b	106.28 (13.61)	102.27 (12.46) ^a

Note. ^a equivalent to CA, ^b significantly different from CA. Standard deviations in parentheses. LIQPR = low-IQ poor reader, LIQGR = low-IQ good readers, CA = age-equated typically-developing readers, RL = reading level-equated typically-developing readers, BAS = British Ability Scales, FSIQ = pro-rated full scale IQ, TOWRE SWE = Test of Word Reading Efficiency Sight Word Efficiency, TOWRE PDE = Test of Word Reading Efficiency phonemic decoding efficiency, BPVS = British Picture Vocabulary Scale.

Table 2.

Performance in the Phonological Processing Tasks

	LIQPR	LIQGR	CA Controls	RL Controls
Oddity onset task no. correct (max 20)	11.37 (4.47) ^b	15.10 (4.07) ^a	16.37 (3.22)	13.27 (5.20) ^b
PSTM Dense words correct (max 32)	15.44 (6.21) ^{b 1}	22.00 (8.27) ^a	23.48 (5.99)	19.73 (7.44) ^a
PSTM Sparse words correct (max 32)	12.83 (5.74) ^{b 1}	18.70 (7.69) ^a	22.10 (5.98)	17.92 (7.87) ^b
RAN Dense (secs)	51.31 (16.11) ^b	47.87 (11.13) ^a	40.9 (5.3)	50.7 (12.9) ^b
RAN Sparse (secs)	41.43 (10.10) ^b	39.79 (10.98) ^a	35.51 (4.09)	42.33 (7.55) ^b

Note. ^a equivalent to CA, ^b significantly different from CA, ¹. Density data from 12 children was not recorded so only mean scores were computed for these children. Standard deviations in parentheses. LIQPR = low-IQ poor readers, LIQGR = low-IQ good readers, CA = typically-developing age-equated children, RL = reading level-equated typically-developing readers, PSTM = phonological short-term memory, RAN = rapid automatized naming, secs = seconds.

Table 3.

Mean Auditory Thresholds by Group in the Psychoacoustic Tasks

	LIQPR	LIQGR	CA Controls	RL Controls
Intensity ABABA	34.79 (8.51) ^b	23.90 (12.41) ^a	24.07 (12.36)	30.64 (10.79)
Equivalent in dB SPL	5.20 (1.15) ^b	3.52 (1.73) ^a	3.53 (1.73)	4.54 (1.51)
Rhythm	18.67 (12.44) ^b	12.00 (4.39) ^a	11.59 (6.07)	15.21 (10.29)
Equivalent in ms	63.9 (40.9) ^b	39.4 (13.0) ^a	37.6 (18.2)	50.9 (33.2)
2 Rise	27.97 (11.40) ^b	29.20 (11.30) ^a	22.31 (10.09)	29.38 (12.10)
Equivalent in ms	265.2 (164.7) ^b	268.1(161.2) ^a	245.9 (145.2)	268.6 (181.2)
1 Rise	23.2 (13.41) ^b	11.78 (5.93) ^a	11.41 (7.77)	21.27 (12.12)
Equivalent in ms	162.3 (87.7) ^b	75.3 (36.0) ^a	73.0 (43.8)	148.5 (80.4)
Duration	24.87 (11.29)	22.10 (9.71) ^a	19.45 (10.18)	23.27 (10.82)
Equivalent in ms	121.9 (52.9)	107.9 (44.8) ^a	94.2 (46.2)	114.6 (48.8)
Rise Rove	29.57 (12.23)	27.10 (11.79) ^a	23.62 (10.98)	28.20 (12.63)
Equivalent in ms	207.9 (82.1)	190.8 (75.9) ^a	165.6 (73.1)	198.5 (84.9)
Frequency ABABA	31.33 (8.99) ^b	30.20 (11.95) ^a	21.38 (12.92)	30.52 (12.56)
Equivalent in semitones	0.39 (0.10) ^b	0.37 (0.14) ^a	0.26 (0.15)	0.38 (0.15)

Note. ^a equivalent to CA, ^b significantly different from CA. Standard deviations in parentheses. Threshold equivalents to Probit values provided. LIQPR = low-IQ poor readers, LIQGR = low-IQ good readers, CA = age-equated typically-developing readers, RL = reading level-equated typically-developing readers.

Table 4.

Raw Correlations (above the diagonal) and Partial Correlations (controlling for Group, below the diagonal) between Standardised Scores and Experimental Measures

Task	BAS Reading Age (m)	TOWRE SWE (SS)	TOWRE PDE (SS)	BAS Spelling (SS)	BAS Maths (SS)	BPVS (SS)	Oddity Onset	RAN Dense	RAN Sparse	PSTM	1 Rise	2 Rise	Rise Rove	Dur'n	Freq	Inten	Rhythm
BAS Reading Age (m)		.567***	.402***	.600***	.486***	.351***	.588***	-.417***	-.445***	.514***	-.454***	-.293**	-.350***	-.394***	-.269**	-.496***	-.434***
TOWRE SWE (SS)	.491***		.806***	.803***	.504***	.484***	.383***	-.385***	.310**	.384***	-.246*	-.109	-.197	-.291**	-.167	-.338**	-.278**
TOWRE PDE (SS)	.289**	.739***		.646***	.375***	.481***	.299***	-.248*	-.145	.380***	-.200	-.100	-.184	-.209*	-.183	-.209*	-.231*
BAS Spelling (SS)	.502***	.715***	.506***		.593***	.411***	.482***	-.267**	-.200	.449***	-.202	-.039	-.173	-.278**	-.125	-.310**	-.227*
BAS Maths (SS)	.388***	.407***	.249*			.272**	.423***	-.306**	-.367***	.373***	-.033	-.206*	-.166	-.248*	-.110	-.372***	-.215*
BPVS (SS)	.325*	.511***	.534***	.392***	.233*		.241*	-.182	-.092	.281**	-.284**	-.245*	-.119	-.147	-.228*	-.377***	-.172
Oddity Onset	.523***	.320**	.244*	.378***	.325**	.183		-.359***	.427***	.524***	-.204	-.101	-.223	-.276**	-.022	-.266*	-.399***

RAN Dense	-.431***	-.444***	-.274*	-.293**	-.292**	-.180*	-.348**	.682***	-.301**	.291**	.087	.242*	-.327**	.192	.226*	.291**
RAN Sparse	-.480***	-.341**	-.151	-.203	-.361**	-.057	-.465***	.687***	-.253*	.176	.077	.068	.348**	.059	.284**	.290**
PSTM	.457***	.327**	.327**	.373**	.273*	.314**	.454***	-.285**	-.264*	-.329**	-.257*	-.407***	-.111	-.183	-.288**	-.317**
1 Rise	-.440***	-.221*	-.138	-.112	.064	-.217*	-.134	.280*	.193	-.310**	.286**	.491***	.205*	.228*	.445***	.343**
2 Rise	-.317**	-.185	-.155	-.088	-.201	-.266*	-.091	.070	.081	-.268*	.273*	.363***	.160	.205*	.449***	.256*
Rise Rove	-.390***	-.298**	-.241*	-.242*	-.175	-.117	-.213	.260*	.132	-.416***	.484***	.343**	.305**	.371***	.299**	.362***
Duration	-.372***	-.288**	-.150	-.249*	-.198	-.138	-.282*	.337**	.347*	-.086	.175	.144	.325**	.233*	.336**	.315**
Frequency (Dichot.)	-.277*	-.215	-.211	-.167	-.094	-.274*	-.017	.189	.065	-.181	.231*	.167	.376***	.209	.212*	.275**
Intensity	-.486***	-.252*	-.093	-.211	-.345**	-.334**	-.244*	.253*	.306**	-.305**	.455***	.473***	.297**	.310**	.211	.355**
Rhythm	-.392***	-.255*	-.215	-.138	-.162	-.096	-.343**	.328**	.332**	-.248*	.337**	.258*	.329**	.425***	.298**	.336**

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

BAS = British Ability Scales; m = months; TOWRE = Test of Word Reading Efficiency; SWE = Single Word Efficiency; SS = standard score; PDE = Phonemic Decoding Efficiency; BPVS = British Picture Vocabulary Scales; RAN = Rapid Automatised Naming; PSTM = phonological short-term memory; Dur'n = Duration; Freq = Frequency (dichotomous measure); Inten = Intensity.

Table 5.

*Stepwise Regressions Showing the Unique Variance in BAS Reading Age(in months)
Contributed by the Different Auditory Processing Measures (Standardised Beta
coefficients and R^2 change)*

	DV	BAS Reading
Step	Beta	R^2 change
1. Group	-.27	.07**
2. Intensity ABABA	-.46	.20***
2. Rhythm	-.40	.15***
2. 2 Rise	-.32	.10**
2. 1 Rise	-.42	.17***
2. Duration	-.38	.14***
2. Rise Rove	-.34	.12***
2. Frequency ABABA	-.28	.08**

* $p < .05$, ** $p < .01$, *** $p < .001$

Figure Captions.

1. Scatterplot of Probit thresholds (maximum = 40) for the 1 Rise task, identifying group membership as CA, LIQGR, RL or LIQPR.
2. Scatterplot of Probit thresholds (maximum = 40) for the 2 Rise task, identifying group membership as CA, LIQGR, RL or LIQPR.
3. Scatterplot of Probit thresholds (maximum = 40) for the Rise Rove task, identifying group membership as CA, LIQGR, RL or LIQPR.
4. Scatterplot of Probit thresholds (maximum = 40) for the Rhythm task, identifying group membership as CA, LIQGR, RL or LIQPR.
5. Scatterplot of Probit thresholds (maximum = 40) for the Duration task, identifying group membership as CA, LIQGR, RL or LIQPR.
6. Scatterplot of Probit thresholds (maximum = 40) for the Frequency ABABA task, identifying group membership as CA, LIQGR, RL or LIQPR.
7. Scatterplot of Probit thresholds (maximum = 40) for the Intensity ABABA task, identifying group membership as CA, LIQGR, RL or LIQPR.

Figure 1.

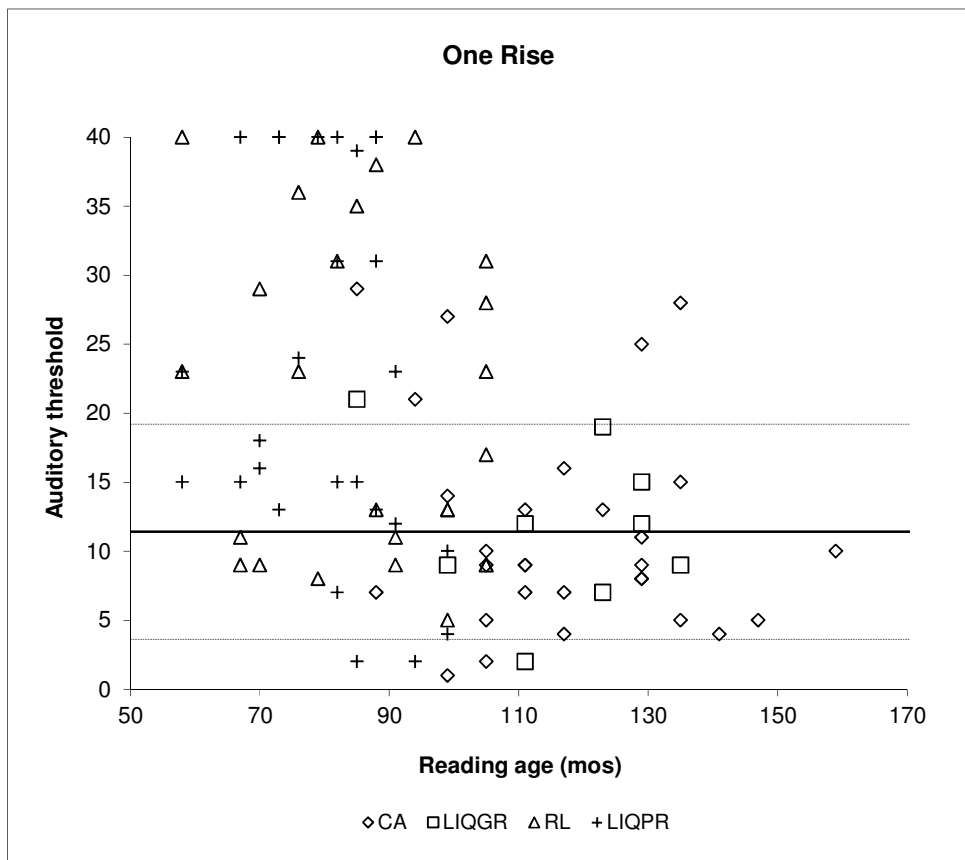


Figure 2.

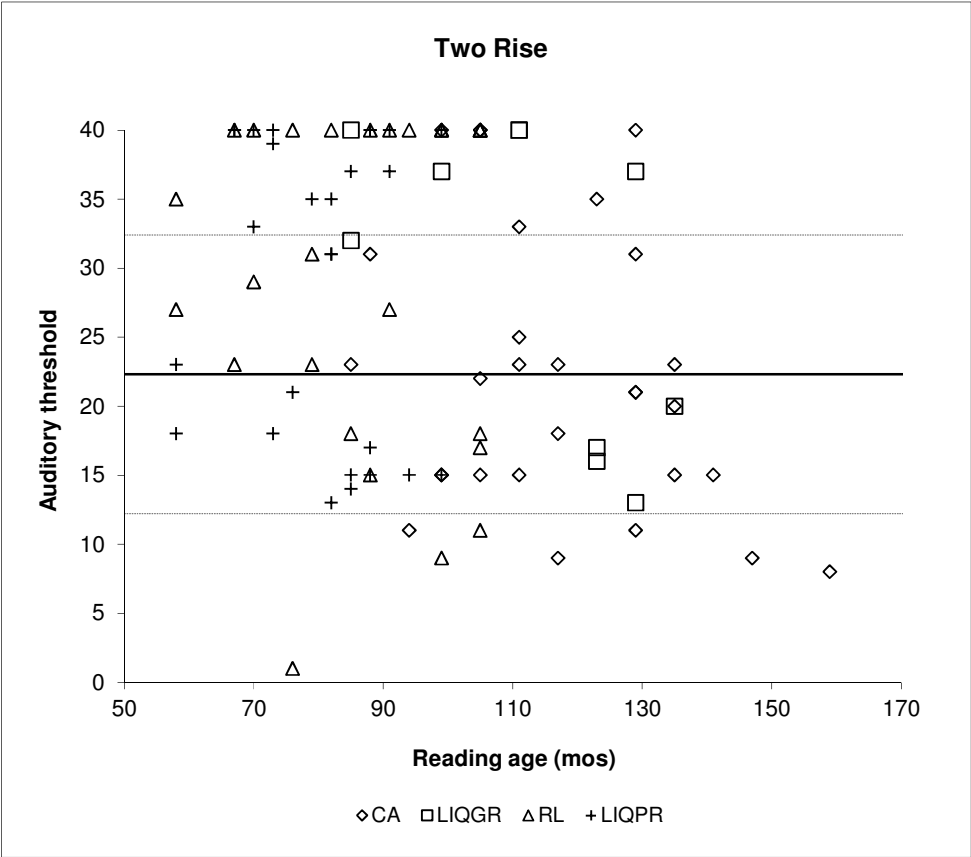


Figure 3.

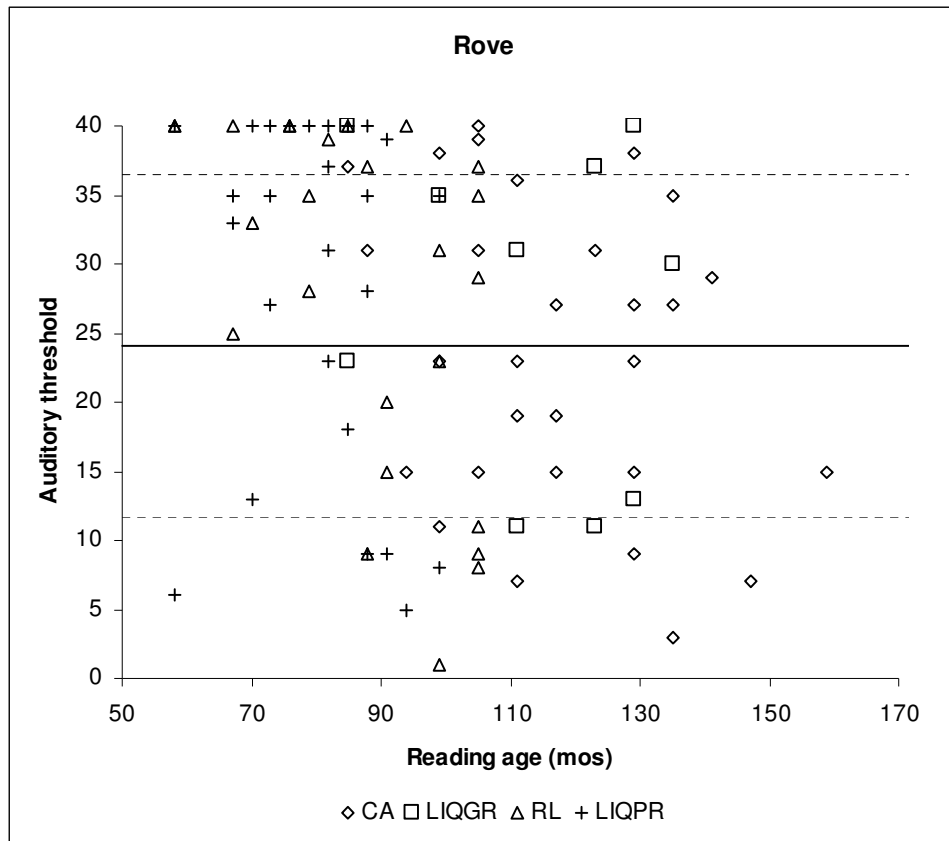


Figure 4.

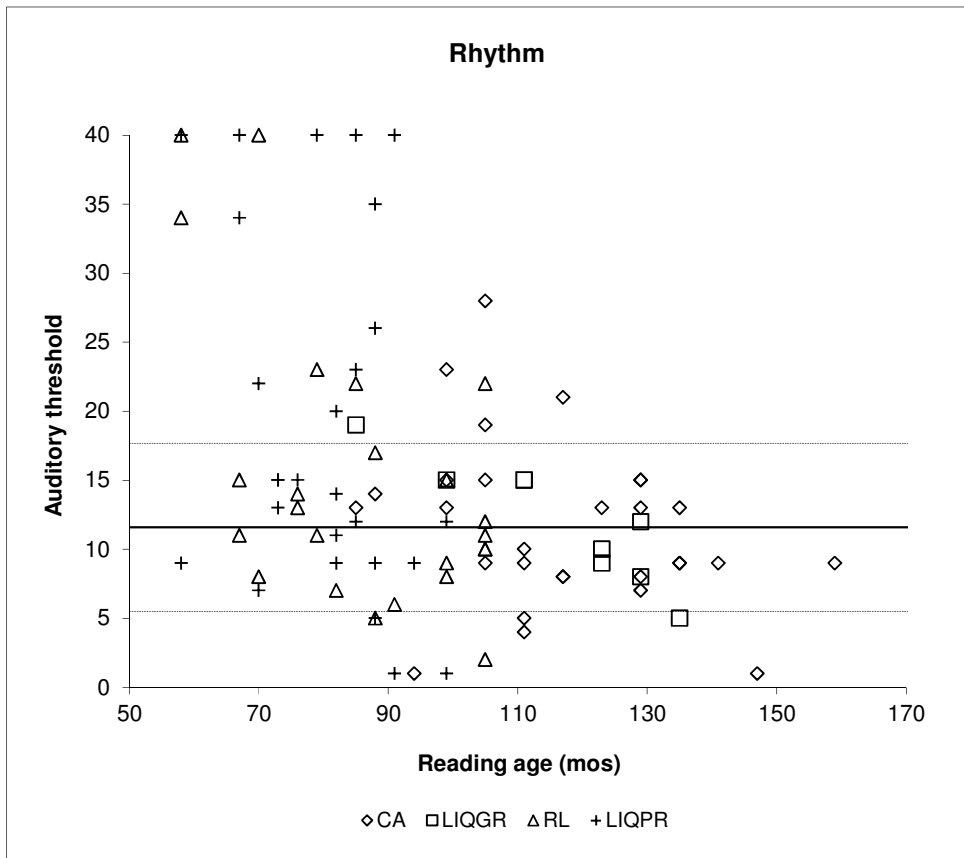


Figure 5.

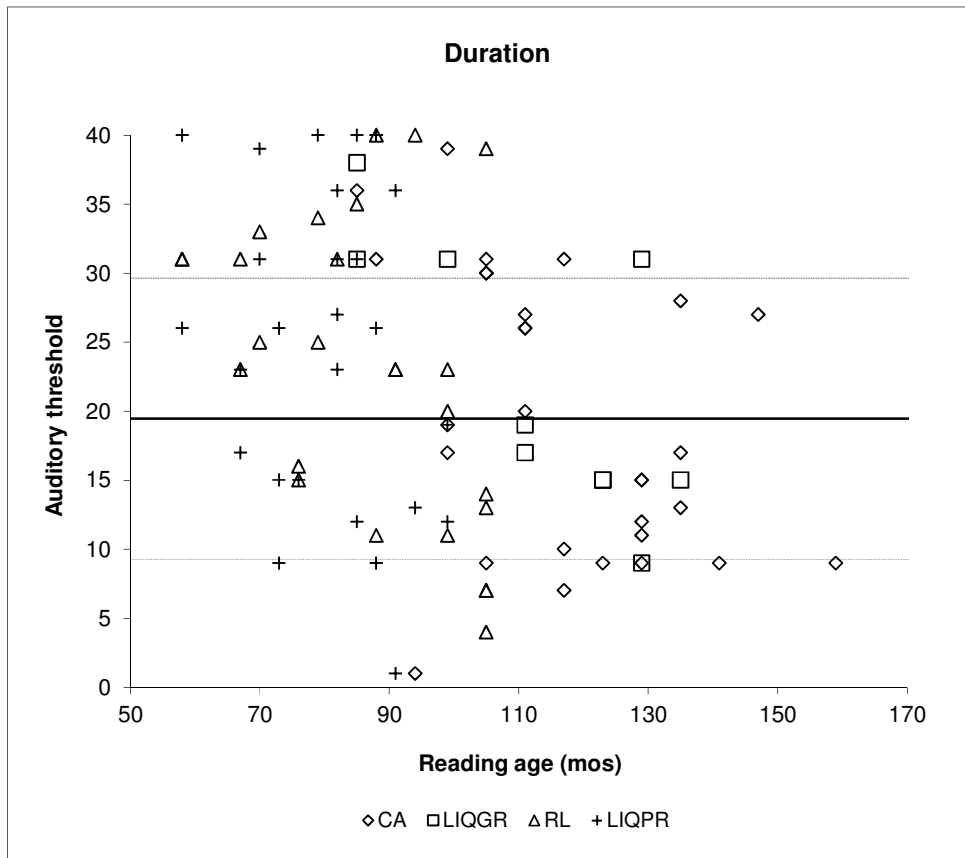


Figure 6.

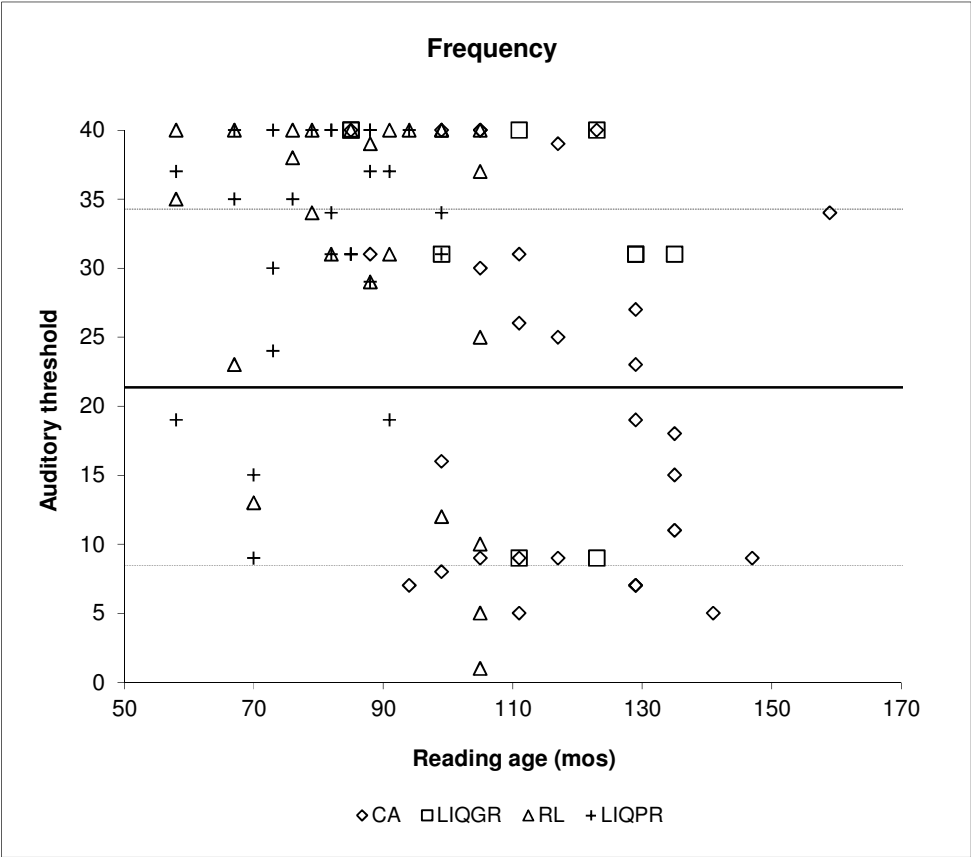
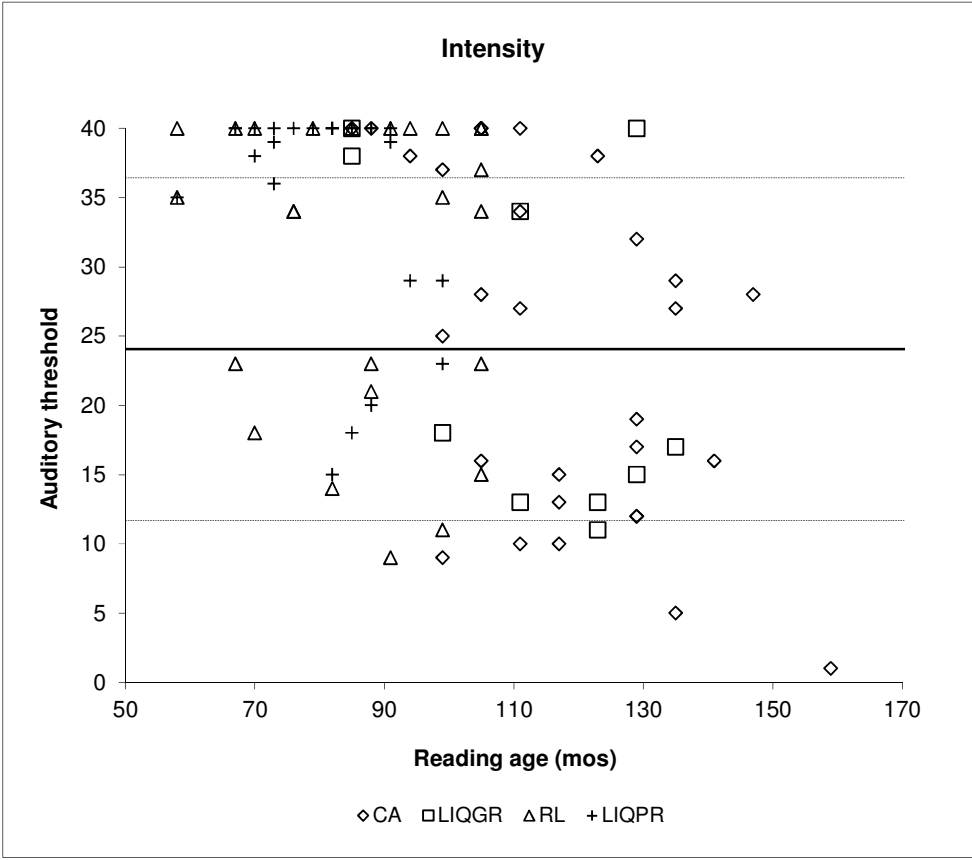


Figure 7.



Appendix

Words Used in the Onset Oddity task

Sonority profile of onset	Word 1	Word 2	Word 3
poor	bike	tight	type
good	laid	make	mate
good	nib	rig	rid
poor	pin	pill	king
good	mode	wrote	mope
good	rat	rack	map
good	ran	rang	lamb
good	mine	rime	mile
poor	cap	cat	pack
poor	gate	take	tape
poor	kick	kit	tip
good	rain	name	nail
good	light	ripe	like
poor	pan	pal	gang
poor	cope	poke	coat
poor	cone	pole	comb
poor	tile	pine	time
good	rim	ring	mill
good	moan	roam	mole
poor	came	pail	pain

Words Used in the PSTM task

Density	Word 1	Word 2	Word 3	Word 4
sparse	type	rib	nook	bud
sparse	tong	curl	dome	gown
dense	rule	tone	boom	thing
sparse	peg	shook	fib	road
dense	jug	shop	hat	weak
dense	king	gum	bone	pale
dense	knob	lake	root	map
dense	doom	ball	ping	fun
dense	scene	ring	thumb	hale
dense	shake	lip	fed	tub
sparse	wool	wrong	home	down
sparse	hook	leg	wipe	bird
dense	rack	pub	knit	laid
sparse	comb	pull	gong	turn
sparse	join	song	hem	dull
sparse	word	league	ripe	nib

Correction to “Basic Auditory Processing Skills and Phonological Awareness in Low-IQ Readers and Typically Developing Controls” by Sarah Kuppen, Martina Huss, Tim Fosker, Natasha Fegan, and Usha Goswami.

It has come to our attention that the Article “Basic Auditory Processing Skills and Phonological Awareness in Low-IQ Readers and Typically Developing Controls” 15(3), 211-243 describes an older version of the Frequency ABABA task (Thomson & Goswami, 2008) which used stimuli that are 25 ms long. In fact the task used 200 ms stimuli, as described in the ABABA Frequency task from Wang, Huss, Hämäläinen and Goswami. (2011). This does not affect the data reported in the paper, which used the conversion metric for the correct 200 ms Frequency ABABA task. We apologise for this error.

Thomson, J., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: auditory and motor rhythms link to reading and spelling. *Journal of Physiology - Paris*, 102, 1-3, 120-129.

Wang, H-L., Huss, M., Hämäläinen, J., & Goswami, U. (in press). Basic auditory processing and developmental dyslexia in Chinese. *Reading and Writing*. Advance online publication. doi: 10.1007/s11145-010-9284-5