NeuroReport 10, 2045–2050 (1999)

Can sensitivity to auditory frequency modulation predict children's phonological and reading skills?

J. B. Talcott,[1,CA] C. Witton,[1,2] M. McClean[3] P. C. Hansen,[1] A. Rees,[2] G. G. R. Green[2] and J. F. Stein[1]

[1]University Laboratory of Physiology, Parks Road, Oxford OX1 3PT; [2]Department of Physiological Sciences, University of Newcastle, Framlington Place, Newcastle upon Tyne NE2 4HH; [3]Meltham CE Primary School, Holmfirth Road, Meltham, Huddersfield HD7 3DA, UK

[CA]Corresponding Author

UNDERSTANDING how letter units represent particular speech sounds is a crucial skill for developing competent reading skills. However it is not known whether such phonological ability is constrained by basic auditory capacities such as those necessary for detecting the frequency modulations characteristic of many phonemes. Here we show that nearly 40% of the variability in normal children's phonological and reading skills can be predicted from their sensitivity to 2 Hz frequency modulated (FM) tones. This relationship does not hold for sensitivity to 240 Hz FM. Because lower but not higher rates of FM provide information important for speech comprehension, dynamic auditory sensitivity is likely to play an important role in children's phonological and reading skill development. *NeuroReport* 10:2045–2050 © 1999 Lippincott Williams & Wilkins.

Key words: Auditory; Development; Frequency modulation; Phonology; Reading; Temporal processing

Introduction

Phonological awareness refers to the knowledge that words can be broken down into combinations of letters that can be mapped to specific speech sounds. Most children develop competent phonological skills without instruction, and in pre-readers this competency can predict their future reading ability [1]. Hence poorer readers often have poorer phonological skills, a finding that is exemplified by the strong evidence for pervasive phonological deficits associated with developmental dyslexia [2]. Phonological ability has been shown to be genetically influenced [3,4] and mediated by particular neural circuits [5], but it is still not known to what extent it is constrained by basic auditory mechanisms. The widely held view is that phonological (dis)abilities are specific to the processing of language stimuli and are unrelated to lower level auditory processing [6].

Whereas several studies have demonstrated lower level auditory deficits, especially for rapid or changing acoustic stimuli, concomitant to phonological deficits in specific language-impaired [7] and dyslexic [8] populations, few studies have explicitly examined the nature of the relationship between phonological awareness and dynamic auditory sensitivity. However, Witton *et al.* [9] demonstrated that pseudoword reading skill, a sensitive measure of phonological ability, of both dyslexic and control adults could be predicted from their sensitivity to 2 Hz auditory FM, where detection is achieved by tracking the actual frequency modulation ('wobble') of the carrier. The same relationship did not hold for a higher FM rate (240 Hz) where detection is achieved by detecting a tone at the pitch of the modulating frequency rather than tracking the modulation of the carrier with time. These two modulation frequencies are probably processed by separate auditory mechanisms: 2 Hz FM sensitivity is determined by cortical mechanisms but 240 Hz is extracted at a lower, peripheral level [10,11].

The important phonetic distinctions within continuous speech are mainly conveyed by temporal changes in acoustic energy rather than by spectral cues [12,13]. An inability to detect temporal auditory changes is also associated with speech perception deficits [14]. We therefore predicted that normal children's sensitivity for 2 Hz FM, but not for 240 Hz FM, would correlate strongly with their phonological skills, and therefore also with their reading and spelling ability. We also predicted a weaker relationship between FM sensitivity and exception word reading skill because irregular word naming is probably less reliant upon phonological skills than upon orthographic abilities [15].

Materials and Methods

Subjects: This study was carried out in accordance with the guidelines of the Declaration of Helsinki. The subjects were 32 unselected children comprising a single primary school class. Sixteen of the children were females. The average age of the sample was 118.4 months (9.9 years) and all of the participants were native English speakers (Table 1). All of the children's cognitive and reading skills as ascertained by standardised tests of achievement were within 2 s.d. of the population mean for their age group.

Auditory stimuli: Detection thresholds were measured for both 2 Hz and 240 Hz FM of a 1 kHz carrier tone. The duration of each test tone was 1000 ms, with a 500 ms interstimulus interval between tones. Tones were gated on and off with 20 ms rise/fall times. All stimuli were generated by Tucker Davis Technologies System II equipment, and presented through headphones (Sennheiser HD 40) in a quiet room.

The psychophysical procedure was a standard two-alternative forced choice paradigm. The order in which the two modulation frequencies were tested was randomized between subjects to control for potential order effects. Prior to data collection, subjects were given a short period of practice to familiarise them with the stimuli. Each subject was deemed able to perform our tasks based upon this practice period. Pure tone detection thresholds were also measured for all subjects to ensure that they had no hearing loss at 1 kHz. Stimuli were then presented at a comfortable 50–60 dB hearing level, as determined by the child's pure tone audiogram. In each trial, pairs of sounds were presented: one was a pure tone, the other a sinusoidally frequency modulated tone (the target tone). Subjects reported verbally which tone ('first' or 'second') was the target. Ten trials were performed at each of six depths of FM, chosen to span the threshold in equal intervals. In each trial the modulation depth and order of presentation of the tones was randomly assigned by computer. The number of trials in which the subject correctly identified the target was plotted as a function of the frequency modulation depth, and fitted with a Weibull function [16]. Detection threshold (Table 1) was defined as the modulation index at which subjects reached a criterion of 75% correct. Threshold modulation index was obtained by dividing the subject's threshold in Hz by the modulation rate of the carrier frequency. FM thresholds were $\log_{10}$ transformed in order to normalize the data prior to statistical analysis.

Table 1. Group means and standard deviations for the psychometric and linguistic measures in 32 subjects

Measured variable (units)	Mean (s.d.)
Age (months)	118.4 (4.6)
Bass (T-score)	55.4 (7.9)
Basm (T-score)	55.5 (8.5)
Basd (T-score)	44.7 (7.4)
Read (T-score)	55.8 (10.7)
Spell (T-score)	52.5 (7.4)
Non (% correct)	73.6 (20.4)
Irr (% correct)	65.0 (15.8)
Spoon (% correct)	62.3 (22.6)
FM 2 Hz (mod. index)	4.4 (2.8)
FM 240 Hz (mod. index)	4.1 (2.8)

BAS similarities T-score (Bass), BAS matrices T-score (Basm), BAS digit span T-score (Basd), BAS reading T-score (Read), BAS spelling T-score (Spell), Castles and Coltheart non-word naming accuracy (Non), Castles and Coltheart irregular word naming accuracy (Irr) and proportion correct on the Spoonerisms section of the Phonological assessment battery (Spoon). Thresholds for 2 and 240 Hz FM are reported in modulation index (mod. index) units, defined as the detection threshold in Hz divided by the modulation rate.

Psychometric measures: Cognitive, reading and spelling ability were estimated using British Abilities Scales (BAS) subtests [17]. Cognitive measures were chosen to sample both verbal (Similarities: Bass) and non-verbal performance (Matrices: Basm), as well as short-term verbal memory (Digit Span: Basd). BAS single word reading (Read) and spelling (Spell) were also administered. Children's abilities were scored and converted to age adjusted T-scores prior to statistical analyses (Table 1). The sample distributions for reading and spelling were normally distributed as were the distributions for each of the BAS cognitive measures and our other language measures (described below) as ascertained by Kolmogorov–Smirnov Z tests. Individual differences in performance on Bass, Basm and Basd were accounted for by removing variance attributable to these factors by hierarchical multiple regression analysis.

We also measured the children's phonological and orthographic word decoding skills. The phonological measures included a test of non-word naming, which taps children's ability to use the rules that specify the relationship between letter units and speech sounds to decode and pronounce a pseudo-word string (e.g. 'torlep') [18] and a test of spoonerisms [19]. This measures children's ability to manipulate phonemes in words presented to them orally. It has three sections with increasing task difficulty: simple phoneme deletion and substitution ('dog' '/l/' = 'log'), complex phoneme deletion and substitution ('dog' 'lick' = 'log') and spoonerisms ('lazy dog' = 'daisy log'). Total number of items correct out of a maximum of 40 was recorded and converted to percentage correct.

An irregular word (e.g., 'yacht') naming test from the same test battery as the non-words [18] was used as a measure of orthographic reading skill. This test measures orthographic more than phonological word identification processes because the correct words need to be decoded and identified by a direct lexical procedure based upon retrieving graphemic information visually from memory, hence the words cannot be read simply by sounding words out by applying phonological knowledge [15,18]. For the irregular word (IRR) and non-word (NON) naming tests, the children were instructed to name each item, which was presented to them visually in a list, while proceeding as quickly as possible without making errors. The number correct was recorded for each 30 item list. The total number of items correct was then converted to percentage correct.

Results

Pearson product moment correlations between our tests are shown in Table 2. The BAS tests of cognitive ability accounted for up to 20% of the intersubject variability in our auditory measures. These cognitive scores were similarly correlated with the children's performance on the reading and language tasks, so the impact of these factors was controlled by removing the variance attributable to these cognitive abilities as the first step in a hierarchical regression analysis. This enabled more direct comparison between our sensory and linguistic variables in subsequent correlation analyses.

Our most important finding was that phonological skill, as assessed by non-word naming (Fig. 1b) and spoonerisms decoding, strongly covaried with sensitivity to 2 Hz FM. Forty percent of the variance in non-word naming performance and nearly 29% of the variance in individuals' ability to decode spoonerisms could be accounted for by 2 Hz FM thresholds, whereas thresholds for 240 Hz FM were not significantly correlated with either variable. This suggests an important influence of low frequency FM detection on the development of the phonological skills necessary for reading.

Children's reading skills were also strongly predicted from their sensitivity to 2 Hz modulation of a 1 kHz tone, but not from sensitivity to 240 Hz modulation of the same carrier frequency. As shown in Fig. 1a, 34% of the variance in BAS reading ability could be predicted from sensitivity to FM at 2 Hz. 240 Hz FM could account for another 10% but this was not statistically significant. A similar, but less strong effect was found between FM sensitivity and spelling ability. Twenty-eight percent of the variance in individuals' spelling scores could be predicted from 2 Hz FM thresholds, whereas a non-significant proportion (7%) was accounted for by sensitivity to 240 Hz FM. 2 Hz FM sensitivity was less predictive of orthographic coding skill as assessed by irregular word naming than it was for non-word naming (Fig. 1c) although the administration and scoring of these measures were identical. This suggests that low modulation rates of FM mediate the individual variations in phonological ability rather than affecting other aspects of word recognition such as orthographic analysis.

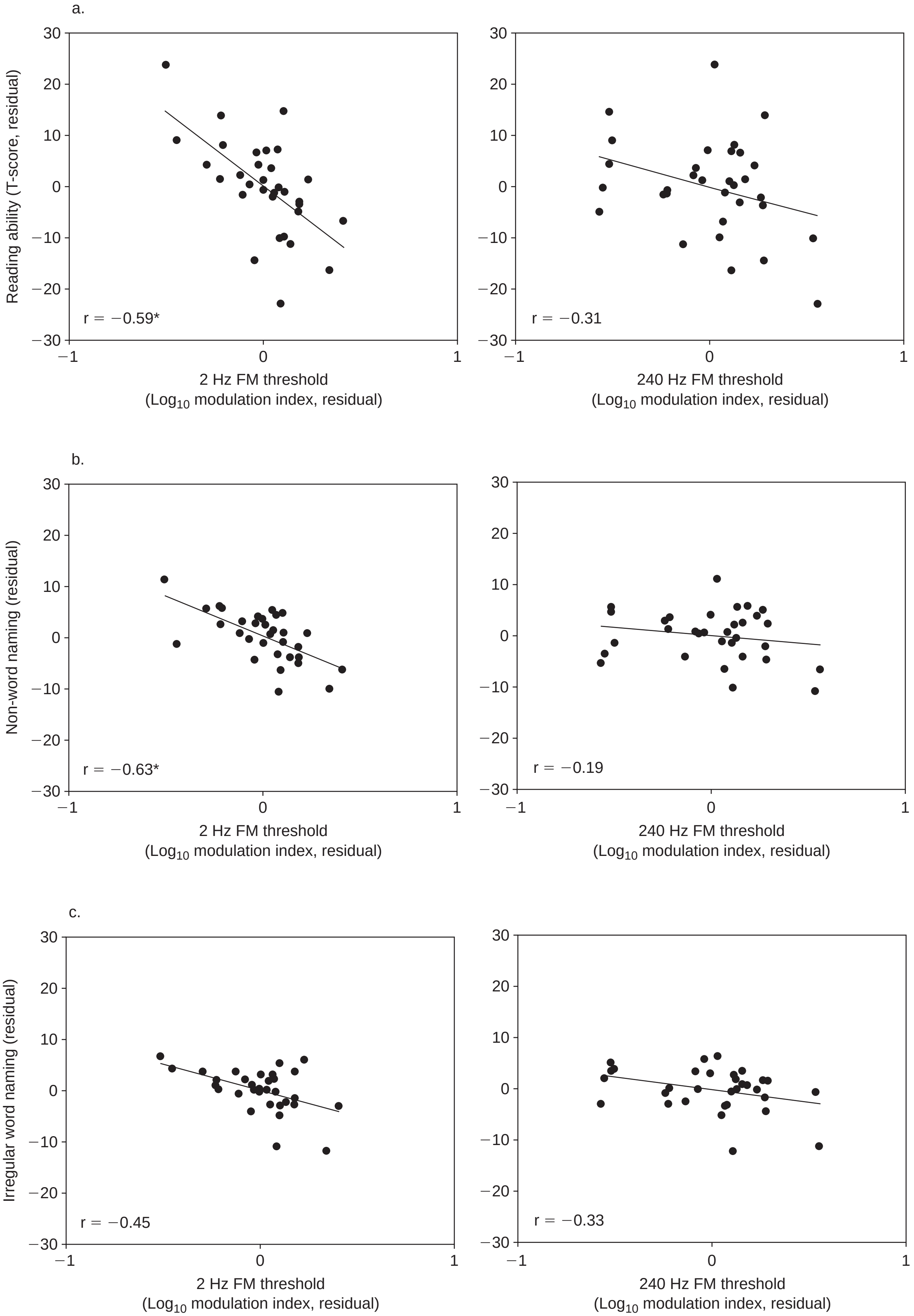
Discussion

Our results show that *normal* children's phonological and reading skills, but to a lesser extent their orthographic abilities, covary with their basic sensitivity for the temporal (or 'dynamic') properties of FM in sound. Such a finding suggests that basic auditory skills can constrain phonological development and therefore also reading ability. It also implies that the phonological problems of language impaired populations may also result from impaired acoustic perception rather than deficits specific to linguistic processing.

Table 2. Correlations between test battery items

	FM2	FM240	Read	Spell	Non	Irr	Spoon	Bass	Basd
FM2									
FM240	0.34								
Read	−0.70*	−0.44							
Spell	−0.67*	−0.43	0.79*						
Non	−0.74*	−0.42	0.82*	0.79*					
Irr	−0.59*	−0.48	0.83*	0.67*	0.71*				
Spoon	−0.68*	−0.40	0.69*	0.71*	0.83*	0.63*			
Bass	−0.48	−0.28	0.44	0.39	0.37	0.38	0.38		
Basd	−0.36	−0.41	0.25	0.35	0.45	0.34	0.44	0.24	
Basm	−0.45	−0.33	0.43	0.41	0.48	0.32	0.48	0.54	0.23

Asterisks depict significant Pearson product moment correlations ($p < 0.05$) after Bonferroni correction for multiple comparisons. Legend is the same as for Table 1 except for the FM thresholds which have been $\log_{10}$ transformed for statistical analysis.


a.
Reading ability (T-score, residual)
r = −0.59*
2 Hz FM threshold
(Log10 modulation index, residual)
r = −0.31
240 Hz FM threshold
(Log10 modulation index, residual)
b.
Non-word naming (residual)
r = −0.63*
2 Hz FM threshold
(Log10 modulation index, residual)
r = −0.19
240 Hz FM threshold
(Log10 modulation index, residual)
c.
Irregular word naming (residual)
r = −0.45
2 Hz FM threshold
(Log10 modulation index, residual)
r = −0.33
240 Hz FM threshold
(Log10 modulation index, residual)

Subjects' thresholds for 2 Hz and 240 Hz FM detection, although obtained using the same psychophysical method, were poorly correlated with each other (Table 2). This result reflects the likelihood that different mechanisms mediate their detection [10,11]. Successively higher levels in the auditory pathway respond most effectively to progressively lower modulation rates [20]. Thus, higher rates are analysed preferentially by brainstem mechanisms whereas lower rates are analysed more by central structures. Whitfield and Evans [21] have shown that units in the auditory cortex respond to sinusoidal FM tones at rates up to 15 Hz.

The different relationships between the two FM rates and the phonological tasks also suggest that slow frequency modulations are important for coding information required for comprehending speech. The strong correlations that we found between basic linguistic abilities and FM sensitivity at 2 Hz imply that accurate detection of slower frequency changes is needed for discriminating speech sounds in order to develop precise phonological representations, and that this is an important prerequisite for successful reading. Our observation that sensitivity to 2 Hz rather than 240 Hz FM predicts normal children's reading and phonological ability shows that tracking frequency changes, rather than spectral cues, is likely to be the crucial processing skill. The modulation rate we used (2 Hz) more directly signals syllabic identity than phonemic identity, as the latter is more likely to be conveyed by frequency modulations in the 30–40 Hz range. However, such values are measures of instantaneous frequency change; and in continuous speech these rapid changes are frequently separated by steady state vowels where the frequency is relatively constant. It is possible therefore that the effective rates of modulation in speech are lower than those estimated from consonants in isolation. Our data suggest that accurate encoding of rate of change of frequency may be important for phoneme identification in all readers. Although it is unlikely that FM sensitivity is directly responsible for reading and spelling ability, the effects of FM could mediate individual differences in speech perception. This could determine phonological ability, which in turn impacts upon reading skill.

It has been argued that poor phonological skills may result from a basic inability to segment acoustic stimuli that rapidly follow one another or those that have very brief stimulus durations [22]. Our study differs substantially from recent reports that demonstrated such acoustic deficits in special populations [13,23,24], however, because we assessed subjects who spanned the normal range of reading abilities rather than classifying subjects into dichotomous groups. We then related these lower level sensory skills directly to our subjects' literacy skills by correlation analyses. Our FM stimuli also measured auditory temporal processing more directly than most previous studies because we measured subjects' ability to detect stimuli that were defined by their changes in time. Previous studies have primarily used stimuli that were temporal only in the sense that subjects' processing time was restricted by short stimulus durations or short interstimulus intervals.

Conclusion

We have shown that both phonological and reading ability covary strongly with a child's sensitivity to slow modulations in auditory frequency. Although we have not proven that this relationship is causal, the sensitivity of the auditory system for FM [25], but not for modulations in amplitude (AM) [26], shows marked improvement from infancy to at least 10 years of age at the same time when phonological and reading skills are also developing. Thus, our FM measures might be used to identify children at risk of both dyslexia and other receptive language problems at early ages prior to any reading experience. Moreover, these FM measures, which exploit the apparent plasticity of FM detection mechanisms at young ages, could also be included in educational programmes designed to improve the phonological skills of all children.

References

1. Bradley L and Bryant P. *Nature* **301**, 419–421 (1983).
2. van Ijzendoorn M and Bus A. *Read Res Q* **29**, 267–275 (1994).
3. Grigorenko E, Wood F, Mayer M *et al. Am J Hum Genet* **60**, 27–39 (1997).
4. Fisher S, Marlowe A, Lamb J *et al. Am J Hum Genet* **64**, 146–156 (1999).
5. Rumsey J, Horwitz B, Donohue B *et al. Brain* **120**, 739–759 (1997).
6. Studdert-Kennedy M and Mody M. *Psychon Bull Rev* **2**, 508–514 (1995).
7. Tallal P. *Brain Lang* **9**, 182–198 (1980).
8. McAnally K and Stein J. *Proc R Soc Lond B Biol Sci* **263**, 961–965 (1996).
9. Witton C, Talcott J, Hansen P *et al. Curr Biol* **8**, 791–797 (1998).
10. Kay R. *Physiol Rev* **62**, 894–975 (1982).
11. Kay R. *Prog Biophys Mol Biol* **28**, 109–187 (1974).
12. Shannon R, Zeng F, Kamath V *et al. Science* **27**, 303–304 (1995).
13. Remez R, Rubin P, Pisoni D and Carrell T. *Science* **212**, 947–950 (1981).
14. Stefanatos G, Green G and Ratcliff G. *Arch Neurol* **46**, 871–875 (1989).
15. Olson R, Forsberg H, Wise B, and Rack J. Measurement of word recognition, orthographic and phonological skills. In Lyon G, ed. *Frames of Reference for the Assessment of Learning Disabilities: New Views on Measurement Issues.* Baltimore: Paul H. Brookes Publishing, 1994: 243–277.

FIG. 1. Correlations between literacy skills and auditory FM thresholds. (**a**) BAS reading performance as a function of log transformed FM threshold for 2 Hz (FM2) (left panel) and for 240 Hz (FM240) (right panel). (**b**) Non-word reading accuracy as a function of log transformed FM threshold for 2 Hz (FM2) (left panel) and for 240 Hz (FM240) (right panel). (**c**) Irregular word reading accuracy as a function of log transformed FM threshold for 2 Hz (FM2) (left panel) and for 240 Hz (FM240) (right panel). Plotted data are the Pearson product moment correlations between variables after removing the effects of intelligence (see text for details). Asterisks depict significant correlations ($p < 0.05$) after Bonferroni correction for multiple comparisons.

16. Macmillan N and Creelman C. *Detection Theory: A Users Guide*. Cambridge: Cambridge University Press, 1991.
17. Elliot C, Murray D and Pearson L. *British Abilities Scales, Manual 4.* Windsor: NFER-Nelson Publishing, 1983.
18. Castles A and Coltheart M. *Cognition* **47**, 149–180 (1993).
19. Gallagher A and Frederickson N. *Educ Child Psych* **12**, 53–67 (1995).
20. Rees A and Møller A. *Hear Res* **10**, 301–330 (1983).
21. Whitfield I and Evans E. *J Neurophysiol* **28**, 655–672 (1965).
22. Tallal P, Merzenich M, Miller S and Jenkins W. *Exp Brian Res* **123**, 210–219 (1998).
23. Wright B, Lombardino L, King W *et al. Nature* **387**, 176–178 (1997).
24. Merzenich M, Jenkins W, Johnston P *et al. Science* **27**, 77–81 (1996).
25. Hall J and Grose J. *J Acoust Soc Am* **96**, 150–154 (1994).
26. Levi E, Folsom R and Dobie R. *Hear Res* **89**, 21–27. (1989).

ACKNOWLEDGEMENTS: We thank all of the teachers, pupils and parents associated with Meltham Primary School for their willing participation and Professor Burton Rosner for helpful comments and discussion. This work was supported by the Wellcome Trust, the Medical Research Council and the Oxford MRC Centre for Cognitive Neuroscience.

Received 21 April 1999; accepted 12 May 1999