females: correct body mass = 53.4 kg)). The sex-specific formula was used when possible; otherwise the mean of the male and female formulae was used. Before applying these formulae, skeletal bi-iliac breadth was converted to living bi-iliac breadth using the equation (both dimensions in cm):

$$\text{living BI} = 1.17 \times \text{skeletal BI} - 3 \quad (5)$$

derived from comparisons within modern humans[16]. Bi-iliac breadth of the Pleistocene specimens was either measured directly or estimated from closely related fossils and/or from known clinal variation in bi-liiac breadth[16,17]. Stature was estimated from preserved long bone lengths using equations derived from appropriately proportioned modern reference samples. Details are given in Supplementary Information.

Combined body mass estimates. When both an intact femoral head and bi-iliac breadth were available, the mean of the femoral head and stature/bi-iliac estimates was used ($n = 26$). Otherwise, either the femoral head, when available ($n = 67$) or the estimated stature/bi-iliac ($n = 70$) estimate was used.

Brain mass and EQ. Brain mass was derived from cranial capacity using a least-squares regression of 27 primate species that had data available for both parameters[26,27], corrected for logarithmic transformation bias:

$$\text{brain mass} = 1.147 \times \text{cranial capacity}^{0.976}\ (r^2 = 0.995) \quad (6)$$

Encephalization quotient was derived from Martin's[28] relationship between brain mass (g) and body mass (kg) in mammals:

$$\text{EQ} = \text{brain mass}/(11.22 \times \text{body mass}^{0.76}) \quad (7)$$

Encephalization quotients (EQ) relating brain mass to body mass were derived in two ways, using individually associated crania and postcrania, and using mean brain mass and body mass within temporally defined groups. The EQs derived using the group means are based on many more specimens, but because they do not use individually matched data they could potentially be biased in several ways. However, other methods of limiting these samples, for example by using only individuals from the same sites and/or sex, produce similar results. Also, where they can be compared, the individually associated and mean data values for the same temporal periods are similar (Table 1). For associated specimens, sex and latitudinal biases in EQ should be minimal: within the Pecos and Pleistocene EAM samples sex differences in EQ average less than 2%, and among modern humans higher- and lower-latitude populations appear to average less than a 4% difference in EQ (mean data from Beals *et al.*[29] and our worldwide sample[16]).

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Deficits in auditory temporal and spectral resolution in language-impaired children

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Between 3 and 6 per cent of children who are otherwise unimpaired have extreme difficulties producing and understanding spoken language[1]. This disorder is typically labelled specific language impairment. Children diagnosed with specific language impairment often have accompanying reading difficulties (dyslexia)[2], but not all children with reading difficulties have specific language impairment[3]. Some researchers claim that language impairment arises from failures specific to language or cognitive processing[4–6]. Others hold that language impairment results from a more elemental problem that makes affected children unable to hear the acoustic distinctions among successive brief sounds in speech[7–11]. Here we report the results of psychophysical tests employing simple tones and noises showing that children with specific language impairment have severe auditory perceptual deficits for brief but not long tones in particular sound contexts. Our data support the view that language difficulties result from problems in auditory perception, and provide further information about the nature of these perceptual problems that should contribute to improving the diagnosis and treatment of language impairment and related disorders.

We measured the detection threshold for a brief tone presented before, during or after two different masking noises in eight children diagnosed with specific language impairment, and in eight control children with normal language skills who matched the others in age and non-verbal intelligence (Table 1). Before beginning the tests with the brief tones, we introduced the children to the listening task by measuring their detection thresholds for a long tone presented in the temporal centre of a 'bandpass' noise that included frequencies at and near the tone frequency. The points above the schematic

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illustration of the stimuli in Fig. 1a show that the same mean tone level was required by specifically language-impaired (filled squares) and control (open squares) children to detect the long tone in this masking condition ($F(1,14) < 1$, $P > 0.05$).

Figure 1b shows the results of our subsequent measurements in the same children of the detection threshold for a brief tone presented with the bandpass noise at each of four temporal positions shown along the abscissa. The performance pattern of control children (open squares) was just as expected from previous work on normal auditory masking[12,13]: the tone was easier to detect when it was presented just before or just after, as opposed to during, the noise, and was easiest to detect when it preceded rather then followed the noise. In comparison to controls, children with specific language impairment (filled squares) needed a higher tone level for detection in every condition. Most remarkably, impaired children had as much or more difficulty detecting the tone when it was presented before the noise (the backward-masking condition) as when it was presented during or after the noise. There was no overlap in performance between the two groups in the backward-masking condition.

We also measured detection thresholds in the same children for a brief tone presented at each of the four temporal positions in a spectrally 'notched' noise that excluded frequencies at and near the tone frequency. Figure 2 shows the mean tone thresholds for each group for both the bandpass (squares, replotted from Fig. 1b) and notched (triangles) noises. The conditions are shown at the bottom of Fig. 2. For both impaired and control children, the tone was typically easier to detect with the notched rather than with the bandpass noise. This is expected for normal hearing[14,15]. However, in contrast to most adults[16,17], neither group of children showed a clear threshold difference between the two masker types when the tone and noise started simultaneously.

Two aspects of the performance of impaired children with the notched noise are particularly important. First, language-impaired children were better at hearing the tone presented before (the backward-masking condition) the notched than the bandpass noise. Their severe perceptual deficit for tones presented in this temporal position was worst when the tone and following noise had similar frequencies. Follow-up tests on four additional impaired children showed that the detection threshold in the backward-masking condition reached control values when the spectral notch in the masker was made sufficiently wide. Thus, impaired children had perceptual difficulties in certain temporal and spectral sound contexts, but did not display a general deficit in the perception of rapidly presented sounds. Second, the mean threshold difference between the notched and bandpass noises was smaller for impaired than for control children in both the simultaneous-delay (10.5 dB compared to 18.6 dB) and forward (15.7 dB compared to 20.5 dB) masking conditions. This indicates that impaired children were less able than controls to take advantage of a frequency separation between the tone and noise to aid detection of the tone.

A $2 \times 2 \times 4$ analysis of variance performed on the data in Fig. 2 revealed significant main effects for subject group ($F(1,112) = 102.70$, $P < 0.0001$), noise type ($F(1,112) = 43.94$, $P < 0.0001$), and tone position ($F(3,112) = 41.93$, $P < 0.0001$). There were also significant interactions between subject group and tone position ($F(3,112) = 16.72$, $P < 0.0001$) and noise type and tone position ($F(3,112) = 3.53$, $P = 0.017$), but not between the subject group and the noise type ($F(1,112) = 0.08$, $P > 0.05$), nor among the three factors ($F(3,112) = 1.07$, $P > 0.05$). A Scheffé post hoc analysis indicated that the thresholds of the two subject groups differed significantly only in the two backward-masking conditions ($P < 0.0001$ for the bandpass masker and $P = 0.0002$ for the notched-noise masker).

In summary, these results suggest that children with specific language impairment are severely impaired in their ability to (1) separate a brief sound from a rapidly following sound of similar frequency, and (2) enhance the detection of a brief tone by exploiting a frequency difference between the tone and a longer co-occurring or preceding masking sound. These auditory perceptual deficits could

Table 1 Mean of standard scores in the TONI-2 and CELF-R tests

	Language-impaired	Control
Age	8.1 (6.3)	8.0 (7.1)
Sex	6 M, 2 F	3 M, 5 F
TONI-2	101 (5.3)	105.1 (6.5)
CELF-R		
Receptive language	83.4 (6.9)*	112.5 (7.8)
Linguistic concepts	7.4 (1.5)*	10.6 (2.3)
Sentence structure	6.9 (1.6)	12.4 (2.0)
Oral directions	7.5 (2.1)	13.0 (2.1)
Expressive language	70.7 (4.8)*	98.1 (5.2)
Word structure	5.5 (1.6)	8.8 (1.6)
Formulated sentences	4.9 (1.3)	8.6 (1.1)
Recalling sentences	6.3 (2.1)	12.0 (1.3)
Total language	75.3 (4.5)*	105.3 (5.4)

Results in the Test of Nonverbal Intelligence (TONI-2; ref. 25) and in the Clinical Evaluation of Language Fundamentals Revised (CELF-R; ref. 26) are shown for the 8 specifically language-impaired and 8 control children. The mean age (in years and months) and sex distribution of both groups is also shown. The standard deviation of each mean value is given in parentheses.

* Values are based on the mean of 7 of the 8 impaired children as test results were missing.

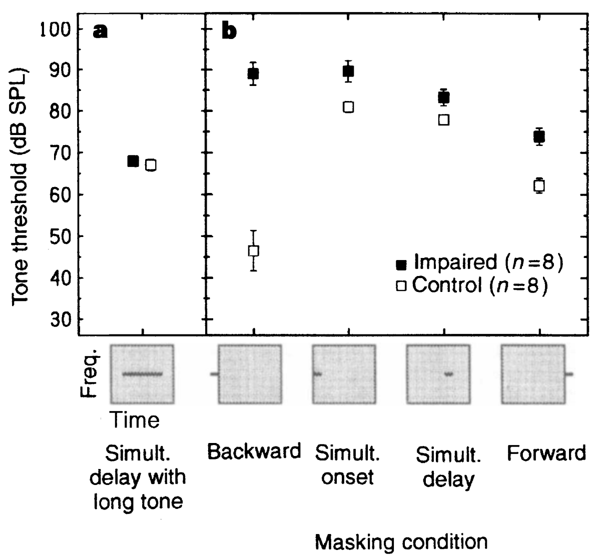

Figure 1 Average tone level required by eight language-impaired (filled squares) and eight control (open squares) children to just detect a long tone temporally centred in a bandpass noise (**a**), or a brief tone presented before, during or after that noise (**b**). Error bars indicate plus and minus one standard error of the mean across subjects. The stimuli are represented schematically along the abscissa. SPL, sound pressure level.

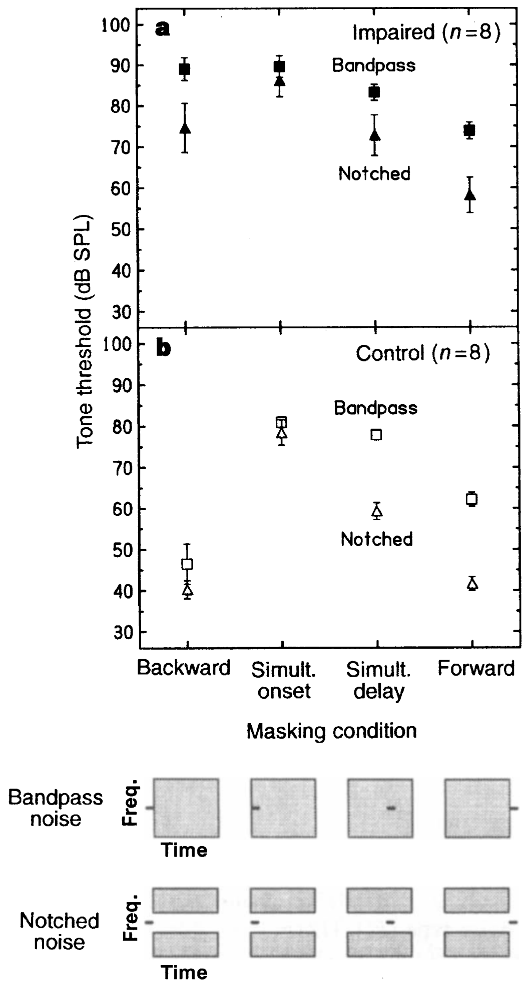

Figure 2 Average tone level required by eight language-impaired (**a**) and eight control (**b**) children to just detect a brief tone presented before, during or after a bandpass (squares, replotted from Fig. 1b) or notched (triangles) noise. Error bars indicate plus and minus one standard error of the mean across subjects. The stimuli are represented schematically along the bottom.

clearly degrade the perception of the brief acoustic elements of speech. Many individuals with language impairment and other disorders related to spoken language might benefit from diagnoses incorporating the auditory tests used here, and from auditory training that focuses on their most severely impaired abilities[18,19]. The present auditory tests might also aid in the diagnosis and treatment of persons with reading difficulties. We have preliminary data on twelve such individuals. Five had excessive amounts of auditory backward masking, but none had as much masking as the children with specific language impairment. Our results are in accord with the conclusion of a recent review that some, but not all, children with reading problems have difficulties accurately perceiving rapidly presented stimuli[20]. Our data are also consistent with a previous report showing that children with reading difficulties are particularly poor at discriminating words that differ only in their first sound[21]. Finally, the temporal and spectral specificity of the auditory perceptual deficits reported here may serve to guide the search for the underlying neural bases of language disorders[22]. □

Methods

Stimuli. All stimuli were generated digitally. Tone: 1,000 Hz, 20 or 200 ms onset-to-offset. Noises: 600–1,400 Hz (bandpass noise) or 400–800 Hz and 1,200–1,600 Hz (notched noise), 300 ms onset-to-offset, 40 dB SPL spectrum level. Gating envelope: 10-ms cosine squared for all stimuli. Masking conditions: The 20-ms tone was turned on at four different times defined relative to the onset of the 300-ms noise: − 20 ms (backward masking), 0 ms (simultaneous-onset masking), 200 ms (simultaneous-delay masking), or 300 ms (forward masking). The 200-ms tone was turned on 50 ms after noise onset.

Procedure. We used a standard, adaptive[23], two-interval, forced-choice procedure to estimate the tone level required for 94% correct detections. The observation intervals were separated by 800 ms. Visual displays on a computer screen marked the observation intervals and gave feedback. Each reported brief-tone threshold was based on the mean of two or three 30-trial measurements per child. Three measurements were always collected, but the most deviant estimate was omitted if the standard deviation of the three was greater than 15 dB. The average within-subject standard error was 3.7 dB for impaired children and 2.5 dB for control children. Because the long-tone condition was used to acquaint the children with the task, we report only the last threshold estimate of the one to three obtained from each child in that condition; in total, the eight impaired children completed 14 threshold estimates and the eight control children 13 estimates in the long-tone condition. We collected the data with the long tone first, and then presented the four brief-tone conditions in pairs (bandpass then notched noise) in a digram balanced latin square[24]. We tested each child individually in a sound-attenuated room. Stimuli were delivered to the right ear over Sennheiser HD450 headphones. All children were paid for their participation.

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